



Center for Innovation in Construction Safety & Health Research



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Table of Contents

LIST OF TERMS AND ABBREVIATIONS	6
1. TRAINING NEEDS ANALYSIS OF INFORMAL WORK SYSTEMS	9
ABSTRACT	9
Section 1: Training Needs Analysis of Informal Work Systems	11
Highlights/Significant Findings	11
Translation of Findings.....	12
Outcomes/Relevance/Impact.....	12
Section 2: Training Needs Analysis of Informal Work Systems	13
Background	13
Specific Aims	16
Methodology	18
Results	23
Discussion	30
Impact on the Construction Industry.....	32
Publications	39
Inclusion of Gender and Minority Study Subjects	40
2. QUANTIFICATION OF AND SOLUTIONS TO THE IMPEDIMENTS TO SPEECH COMMUNICATION AND SIGNAL DETECTION IN THE CONSTRUCTION INDUSTRY	42
ABSTRACT	42
Section 1: Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry	45
Highlights/Significant Findings	45
Translation of Findings.....	46
Outcomes/Relevance Impact.....	46
Section 2: Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry	48
Background: Noise in Construction	48
Research Goals and Objectives.....	50
Research Results	52
Experiment 1: Backup alarm detection using ascending and descending method of limits.	93
Rationale and Objectives	93

Methodology	94
Results and Discussion	95
Experiment 2: Determination of backup alarm masked thresholds in construction noise with augmented and passive HPDs.	98
Rationale and Objectives	98
Methodology	99
Results and Discussion	114
Experiment 3: Backup alarm localization.....	132
Rationale and Objectives.....	132
Methodology	132
Procedure	139
Results and Discussion	141
Conclusions: Backup Alarm Localization Study	170
Recapitulation and Overall Conclusions.....	175
References Cited	181
3. NOISE AND VIBRATION CONTROL OF HAMMER DRILLS	184
Abstract	184
Section 1: Noise and Vibration Control of Hammer Drills	186
Highlights/Significant Findings	186
Translation of Findings.....	187
Outcomes/Relevance/Impact.....	187
Section 2: Noise and Vibration Control of Hammer	189
Background	189
Project Specific Aims	191
Project Procedure	192
Overview of Main Results	195
Materials Available for Other Investigators.....	246
Publications	246
References	247
4.DECISION SUPPORT TOOL FOR ERGONOMIC CONSTRUCTION DESIGN.....	252
Abstract	252
Section 1: Decision Support Tool for Ergonomic Construction Design	254
Highlights/Significant Findings	254
Translation of Findings.....	255

Outcomes/Relevance/Impact.....	255
Section 2: Decision Support Tool for Ergonomic Construction Design	257
1. Background	257
2. Specific Aims	264
3. Input from End Users	265
4. Taxonomy, Task Identification, and Input from Workers.....	277
5. Development of Decision Support Tool.....	304
6. Laboratory-based Ergonomic- and Risk-Assessment.....	333
7. Panelization Construction Design and Planning Algorithms	354
8. Software Development, Demonstration, and User Feedback	379
Inclusion of Gender and Minority Study Subjects	399
Inclusion of Children	400
Materials Available for Other Investigators.....	400
5. ADMINISTRATIVE CORE.....	401
Abstract	401
Section 1: Administrative Core	402
Highlights/Significant Findings	402
Translation of Findings.....	402
Outcomes/Relevance/Impact.....	403
Section 2: Administrative Core	405
(Logic Model-based) Scientific Report	405
A. Major Occupational Health and Safety Challenges	405
B. Driving Goals and Objectives	405
C. Inputs.....	407
D. Activities.....	409
E. Outputs	412
Sample Outputs from Graduate Research Studies Affiliated with the Administrative Core	415
F. Intermediate Outcomes	417
Sample Intermediate Outcomes from Graduate Research Studies affiliated with the Administrative Core	420
G. End Outcomes	431
Major Subproject Brief Summaries (detailed earlier in this report):.....	433
Pilot Project Summaries.....	438

Kevin P. Granata Occupational Safety and Health Pilot Program Projects.....	439
Sample Results from Pilot Studies.....	440
External Pilot Study Examples	443
Funded Students	471
Abstracts for Thesis and Dissertation Research Projects.....	475
Examples of Outreach to Professionals and Practitioners.....	483
ISOES Construction Safety Symposium Participants.....	484
ISOES Symposium Abstracts	485
Examples of Recognition, Awards and Service	488
Conclusion.....	488
Works Cited	490
Publications	491
Material Available for Other Investigators.....	496
APPENDICES	497
Appendix A: Project Co- Investigators' Affiliations.....	498
Appendix B: Construction Industry Questionnaire	502
Appendix C: Informed Consent Forms	513
Appendix D: Amplitude-Sensitive Earmuffs Measures in Pink Noise.....	518
Appendix E: Comfort and Alarm Detectability Rating Scales.....	523
Appendix F: Procedures for the Backup Alarm Detection Study.....	525
Appendix G: Chipping Hammer Operation	529
Appendix H: Calculation of Stack Drop-Off Locations	534

LIST OF TERMS AND ABBREVIATIONS

BLS – Bureau of Labor Statistics

CISCH/CSC – Center for Innovation in Construction Safety and Health/Construction Safety Center

CPWR – The Center for Construction Research and Training, formally known as Center to Protect Worker Rights, the NIOSH National Center

dB - decibels

DBIS – Discoveries and Breakthroughs Inside Science

ETD – Electronic Thesis and Dissertations

GPP – Kevin P. Granata Occupational Safety and Health Pilot Research Program

HL - hearing level (for audiometry)

HPD – Hearing protection device

Hz - Hertz, cycles per second

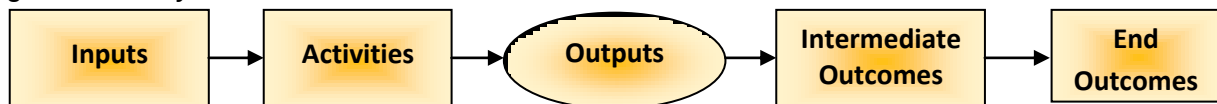
ICTAS – Institute for Critical Technology and Applied Science

IOM – Institute of Medicine, National Academies

ISO - International Organization for Standardization

ISOES – International Society for Occupational Ergonomics and Safety

Logic Model Key



Inputs: Planning: Stakeholder, surveillance, intervention data; Production: Funding, staffing, facilities; Structure: Director, Associate Director, Advisory Board, Industry Board, Leadership Team.

Activities: Research studies, technology transfer activities.

Outputs: Recommendations, reports, workshops, databases, training and education materials, demonstration programs, trained professionals, tools and methods, best practices, licenses, patents.

Intermediate Outcomes: Policy impact, training, educations, implemented guidelines, technology, standards, trade/media releases, websites.

End Outcomes: Improvements in safety and health workplaces.

****Table Formatting for Logic Model Entities***

Type	Title	Author	PI/Advisor	Entity	Location	Nora Goals

Type: (Type of work completed)

T = Student Thesis

D = Student Dissertation

R = Report

UGR = Undergraduate Research

A = Article

M = Meeting

R01 Project

R21 Project

Location: (Location where document can be found)

ETD = Virginia Tech's Electronic Thesis and Dissertation Database

<http://scholar.lib.vt.edu/theses/> – General web link

** Individual ETD links in logic model table take you directly to that student's thesis or dissertation*

MEAD – Macroergonomic Anal^ysis and Design

MLSoC – Myers-Lawson School of Construction

NIOSH - National Institute for Occupational Safety and Health

NORA – National Occupational Research Agenda

OSH – Occupational Safety and Health

OSHA – Occupational Safety and Health Administration or Act

p2r2p – Practice-to-Research-to-Practice

PPT – Personal Protective Technology

PtD – Prevention through Design

r2p – Research to Practice

rms - root mean square

ROCK – Repository for Occupational Construction Knowledge

SAE - Society of Automotive Engineers

SME - Subject Matter Expert

S/N - signal-to-noise ratio

SPL - sound pressure level

“sub-project” – A project within the larger cooperative agreement

“the Center” – Center for Innovation in Construction Safety and Health Research

TWA - Time-Weighted Average

VT – Virginia Tech

1. TRAINING NEEDS ANALYSIS OF INFORMAL WORK SYSTEMS

(Smith-Jackson and Kleiner) Start Date: 9/15/04 - End Date: 12/31/07

ABSTRACT

This project focused on identifying the needs and barriers that influence the ability of small construction companies to conduct worker safety and health training. Small construction companies make up a large proportion of the construction industry, and account for a significant number of injuries and fatalities. In addition, small companies (less than 11 employees) that have informal organizational structures and that tend to employ family members and close friends are often overlooked in accident research because they are not required to report data to the Bureau of Labor Statistics unless selected randomly from among all businesses that do not fall under the authority of CFR 1926.

Thus, the knowledge domain relevant to small construction firms consists of a number of gaps, including a lack of a general understanding of the nature and structure of the work systems and work environments used by small construction firms. There is also a lack of knowledge on the use of safety training or safety interventions, safety climate and workers' perceptions of risk and safety, and potential safety barriers related to the prevalence of close familial ties or friendship ties within these informal work systems. This research effort was focused on identifying the barriers and understanding the needs.

The research effort began with an analytical assessment of the small construction industry, with a focus on companies with 20 or fewer employees. The Macroergonomics Analysis and Design method was used to identify attributes that either support or hinder the use of safety and health training within small companies. Several important factors were identified that impact the safety environment. These included low literacy rates, language barriers, time pressure, lack of information on safety, and very few resources and time for formal training. It was also discovered that there were very few formal lines of authority among small contractors, so safety information was diffused in an unorganized way with no verification of who received safety information and what information was communicated. These were barriers we considered when developing interview questions for the next phase of the study.

Ninety construction workers in small construction firms that were predominantly populated by family members and close friends were interviewed, and companies employed 2 – 10 employees. In addition, four focus groups of family-based construction companies were conducted as well. These interviews and focus groups revealed a number of work-family and family-work conflicts that served as barriers to safety in the workplace and that could interfere with formal training, given a pattern of owners being perceived as the source of the problem. But also, about half of the construction workers preferred working in a family-based environment and found it to be helpful in facilitating safety. In addition, the types of hazards experienced by small firms to some extent paralleled those reported by national BLS statistics for all construction firms. One striking finding was the high degree of poor safety attitudes and the extent to which employees reported "bosses" and time pressure to be the main barriers to training and practicing safety in the workplace. In general, the focus groups supported the same findings.

The final study was a prospective study where employees were given incident logs to report on-the-job information related to safety. Fourteen construction workers in small family-owned businesses completed logs for 4 weeks. The logs indicated a pattern across worksites. The main barriers to safety on the workplace included the requirement to work during illnesses or medical problems, having no personal protective technologies (i.e., fall protection harnesses), worksite clutter, and time pressure.

This research has revealed a need to develop effective informal training mechanisms to ensure workers can be trained in small construction firms within a context that fits their informal

organization structure, and the significant barriers faced by the nature of their work that is mainly influenced by time, resource, and personnel constraints.

Section 1: Training Needs Analysis of Informal Work Systems

Highlights/Significant Findings

This study had two aims. The first aim was to conduct an overall needs analysis using the MEAD method, interviews, and focus groups to identify attributes of small construction firms that employ family members and close acquaintances. The second aim was to translate the results into requirements for training in informal construction work systems.

The attributes of small construction firms that may impact safety training were identified as follows:

- Time pressure: Challenging time lines in the context of small numbers of employees undermine the feasibility of using formal training systems.
- Resource limitations: Small construction firms are limited in personnel, physical, and financial resources. In these types of environments, formal safety training is given a low priority.
- Few formal lines of authority: The informal nature of these work systems makes it difficult to determine who is accountable for training and ensuring training is done in a timely and consistent manner. In addition, informality is increased when authority is linked to familial or social relationships.
- Little-to-no access to personal protective technology: Employees revealed the difficulty in getting personal protective technology (PPT) such as goggles and fall arrest harnesses as significant barriers to being safe in the workplace and identified a strong need to have training in how to use PPT if it were made available.
- Little-to-no access to formal trainers: Workers reported having no access to people who were qualified to train them. This also reflects a lack of knowledge of some of OSHA's training outreach programs.
- Lack of recognition of the importance of safety training, and this may reflect the poor safety climate among small contractors/firms. A common refrain in the interviews was that "safety is common sense."
- Supervisors were perceived as placing low priority on safety training.

Other important factors were identified that address the overall safety climates of small construction firms and their readiness for safety training.

- Construction workers had very strong preferences for hands-on training, and minimal preferences for formal training, especially if it involved "classroom" training.
- The safety climate was recognized as poor. Relationships in the workplace were perceived as negative factors and seemed to undermine the safety climate because workers believed that some owners were too lenient.
- Workers reported that inappropriate behaviors such as horseplay, allowing young children on the worksite, and use of alcohol and drugs. Some reported that the closeness of the relationships led to leniency in enforcing safety practices.
- Contrary to the interviews, focus groups revealed that conflicts involving family and work life did not exist.

- Workers in the focus groups did not see a problem with having underage workers on the construction sites because they believed it helped children gain essential jobs skills and independence at an early age.
- Most of the workers interviewed stated that training had never been done in their work environments.
- Those reporting that some training had been done reported the most common methods as hands-on, meetings, and OSHA materials, respectively.

Translation of Findings

These findings were translated into design requirements to support the adoption and use of safety training within small construction firms whose employees consist mainly of family members and close friends. The recommendations can be used to develop either informal or formal training systems that are compatible with the limitations and preferences of these workplace environments. Effective training systems must consider the following requirements in their design:

1. Family dynamics will impact safety training effectiveness, so 'train the trainer' programs should consider including conflict as a potential contributor to workplace hazards.
2. Training programs must be integrated into the day-to-day work practices so they are situated and informal.
3. Since there are few lines of formal authority in small construction companies, training formats should focus on peer training and informal training.
4. Safety training activities should be short and concrete.
5. Formal training opportunities such as classes or meetings should only be done if they can be incorporated into scheduled breaks such as lunch breaks.
6. Individual training, as opposed to group training, is more compatible with these workplace environments.
7. The use of labels such as 'training' and 'trainer' should be avoided so the power dynamics inherent among family members and close friends does not interfere with implementation or effectiveness of the training.
8. Since most workers believe family and social ties are important in the workplace, these beliefs should be integrated in training programs.

Outcomes/Relevance/Impact

The outcomes of this research describe the specific characteristics of small construction firms that consist of family members and close social acquaintances. The outcomes reveal a number of attributes that impact safety climate and that must be considered when exploring ways to affect the delivery of effective safety training. In addition, the specific barriers and needs relevant to small construction work systems will be helpful in understanding how to design safety training and organizational interventions to enhance productivity and safety. This work is relevant to NIOSH initiatives of surveillance, social and economic consequences of work, and work organization.

Section 2: Training Needs Analysis of Informal Work Systems

SCIENTIFIC REPORT

Background

NIOSH defines small businesses as consisting of 100 or fewer employees (NIOSH Safety and Health Resource Guide). We have focused on a smaller population within this definition that will be henceforth referred to as “informal construction work systems.” We define informal construction work systems as those consisting of 20 or fewer employees with little-to-no formalized organizational structures communicated or archived explicitly through written documentation, articles of incorporation, or through other systematic tools or procedures. These informal construction work systems typically employ family members or close acquaintances, often without a formalized hiring or orientation procedure. Most of the research on safety within informal work systems has focused on the Agricultural industry, and the same concerns about familial relationships have arisen from the research in this area. Farm safety advocates and the Centers for Disease Control and Prevention have focused on familial systems that comprise many agricultural work systems. Power structures and roles within family systems contribute to unstructured, informal workplace organizational designs. In turn, these relationships may be associated with the expression of high-risk behaviors, non-compliance, and the use of underage workers.

At a minimum, familial or other close relationships that occur within the occupational setting may undermine the motivation to conduct training in any form or to ensure that workers are complying with safety protocols. For example, Debarr, Ritzel, Wright, and Kittleson (1998) found that adolescents’ behavioral intent was influenced by their perceptions of the safety norms of their parents. In turn, these perceptions were associated with an increased likelihood of teenagers to resist compliance if they believed their parents viewed safety as unimportant. Debarr et al. identified the influence of familial relationships on compliance behaviors and attitudes in teenage workers. Essentially, familial ties may become strong barriers to safety within the workplace if all members do not internalize the value of a strong safety climate. There are few other instances in the workplace that reflect such strong conformity pressure or attitude convergence as that found in environments where individuals are related on the basis of familial or other close ties (i.e., friendships).

There have been relatively stronger research efforts to examine safety and health problems within small firms in general industries that may or may not consist of familial or close co-workers. For example, Champoux and Brun (2003) interviewed owners of 223 small firms (50 or fewer employees) in metal and manufacturing to identify formalized safety and health practices. Most of the owners reported they, and not their employees, were responsible for health and safety, indicating a lack of understanding of participatory safety cultures. The most frequent hazard prevention and control practices reported were site inspection of the premises and equipment maintenance. Prevention activities such as worker training and practice donning personal protective equipment were not conducted, because they were perceived to undermine productivity. Champoux and Brun identified 4 profiles across the small business owners who were interviewed: *Inactive, uniform firm, Inactive/traditional/unstructured firms, Active/participatory/unstructured firms, Active/participatory/structured/network firms.*

The majority of those interviewed reflected a profile associated with an ineffective safety climate. Similar studies by Eakin (1992) support the finding that occupational health and safety prevention and control efforts are not routinely practiced in small firms. Eakin found that owners perceived few opportunities to access health and safety intervention tools that would enhance their perceived control over negative outcomes such as accidents. For example, prevention efforts were believed to require large investments of time and resources, and were therefore perceived to be out of reach. Lingard and Holmes (2001) found a tendency among employees of small firms to believe that the best methods to prevent such hazards as falls or exposure to toxic substances were training and worker education. Very few employees understood that engineering controls such as designing out, guarding against, or other approaches such as using personal protective equipment were important prevention efforts. The tendency was to view safety and health prevention and control as emerging from the individual level only.

It is possible that these types of attitudes might lead workers to never achieve or to lose a sense of control over outcomes related to safety and health, which then leads to a failure to practice precautionary behaviors (Boyd and Wandersman, 1991; Harrell, 1996; Harrell, 1990). Similarly, the tendency to concede if the sole cause of accidents is believed to be related to the worker could lead to a fatalistic belief system, which is also linked to noncompliance. DeJoy (1994) explained patterns of resignation that occurred because of perceptions of minimal control over outcomes based upon health beliefs and models explaining patterns of self-protective behaviors.

Holmes, Lingard, Yesilyurt, and DeMurk (1999) found that workers in small construction firms did not see the importance of wearing personal protective equipment; thus workers reported a low motivation to wear PPE. Beyond a perceived ineffectiveness of PPE, workers reported that PPE was uncomfortable and that they were not given the opportunity to choose their own PPE. In this case, the value expectancy of wearing PPE was minimal and was associated with costs rather than benefits, which also undermined motivation. Another important finding from the Holmes et al. survey of small construction firms was similar to the Champoux and Brun study discussed previously. In general, both managers and employees had little to no knowledge of how to protect themselves from hazards on the job, or even the hazards themselves. For example, one of the transcriptions of the interview data reported by Holmes et al. (1999) was as follows:

I don't really know what's in the products we use so I really don't know...We aren't made aware of the dangers of what we are using. We just assume there isn't any danger (p. 254).

This statement reflects a lack of information to properly appraise the hazards, which, according to DeJoy's integrated theory, will undermine motivation to display protective behaviors. Research exists that highlights overall health and safety challenges faced by small construction companies and small companies in general. Some of the problems identified relate to lack of awareness and low perceived control over outcomes. In addition, barriers such as cost and resource demands were also identified. But, other factors are likely to be contributors to the increased accident occurrence within small companies. These factors are psychosocial in the traditional sense of relating to psychological issues introduced by the social context. Specifically, work and role conflicts in small construction firms are likely to undermine the ability of owners or employees to develop attitudes of joint responsibility for safety and health and to practice routine and formalized health and safety plans.

It is clear that the small size of informal construction work systems may contribute to accidents and the infrequent use of safety training. But beyond size, the higher prevalence of work systems consisting of individuals who are associated by kinship or friendship is also a factor

requiring further attention. Combined with an organizational environment that is informal or implicit, role confusions, role ambiguities, role conflicts and general reciprocal conflicts between work and family may occur. No other studies have examined this particular psychosocial variable in small construction companies with an emphasis on work and family conflict.

Gutek, Searle, and Klepa (1991) defined work-family conflict as involving conflicting demands that cross over into either domain – work or family – but are caused by the opposing domain. Work-family conflict involves the transfer of work conflicts to the family or home environment; family-work conflicts involve transfer of family conflicts into the work environment. Gignac, Kelloway, and Gottlieb (1962) and Frone, Russell, and Cooper (1992) conducted studies revealing that in cases where family demands occurred at work and conflicted with work demands, workers experienced more absenteeism and psychological distress. Bidirectional influence of work roles and family roles were considered by some to be negative, while other researchers concluded that positive outcomes resulted from involvement in familial work systems. Kepner (1983) suggested the very act of attempting to separate work from family in familial work systems could negatively impact *both* systems. For example, a father who owns a small construction firm who tries not to discuss difficult work matters when off-the-job with his son who is an employee may damage the relationship both at home and at work.

Further studies show difficulties among workers in family-owned businesses/familial work systems in coping with conflicts. Workers have difficulty separating family-derived lines of authority from work-related lines of authority (Goss, 1991). An interesting study by Rainnie (1989) indicated that managers/owners used family references that indicated role status to exert behavioral control when family members were in the workplace. For example, a manager or owner of a business exerted paternal control of workers who were his children, thereby allowing familial roles to control behavior in the work context (family-work conflict). Adult children, in turn, regressed to these same roles within the work context, allowing similar forms of domination occurring in the family system to occur in the work context without challenge. These same conflicting environments also lead to exposure incidents across family members who may be at or outside of the workplace. We refer to these incidents as “cross-over” exposures.

Another example of cross-over is revealed in a slightly different mechanism – involvement of children in the actual work context. For example, work-related injuries reported for teens less than 18 years of age indicate that many of these injuries occur when teens at “forbidden worksites” or were engaged in “forbidden tasks” at the time the injuries occurred (Parker, Carl, French, and Martin, 1994; Runyan and Zakocs, 2000). Runyan and Zakocs (2000) examined emergency department records and identified that injuries among teens doing hazardous work are grossly undercounted. About 15-45% of the injuries they identified led to permanent disability or work restrictions due to severity. Recommendations of Runyan and Zakocs included educating the public about fair labor and child labor laws and ensuring that teenagers are supervised appropriately on the work site. Developmentally appropriate health and safety training were also recommended. Additional research has identified several hazards associated with work-related accidents and fatalities among teenagers less than 19 years of age. These include motor vehicle crashes and industrial machinery (Castillo, Adekoya, and Myers, 1999; Cooper, Burau, Robison, Richardson, Schnitzer, and Fraser, 1999; Derstine, 1996). The problem of underage workers is so prevalent that it has warranted special programmatic attention by such organizations as NIOSH.

Work and family conflicts due to employment in informal work systems such as small construction firms that are family-owned are associated with psychological distress. In addition,

these environments also support the involvement of children and teenagers at a level that increases their risks of accidents. Finally, the cross-over of family roles and patterns into the work context may be associated with safety and health problems experienced by these workers and may also account for the lack of formalized safety programs.

Specific Aims

The following specific aims guided this research.

Specific Aim 1. Apply the Macroergonomic Analysis and Design Method method to analyze family-owned and self-employed work systems. There are two goals associated with this specific aim:

Goal 1: Identify the attributes of Informal Work Systems that increase the risk of accidents in construction work systems.

Goal 2: Identify the attributes of Informal Work Systems that reduce the likelihood of training or transfer of knowledge and skills relevant to injury prevention.

Specific Aim 2. Translate the results into design elements to produce training materials, organizational strategies, and other organizational tools that are customized to the needs of informal construction work systems. Two specific goals are also associated with specific aim 2:

Goal 1: Isolate user requirements for specialized training systems for informal work systems, including content, delivery media, and pedagogy.

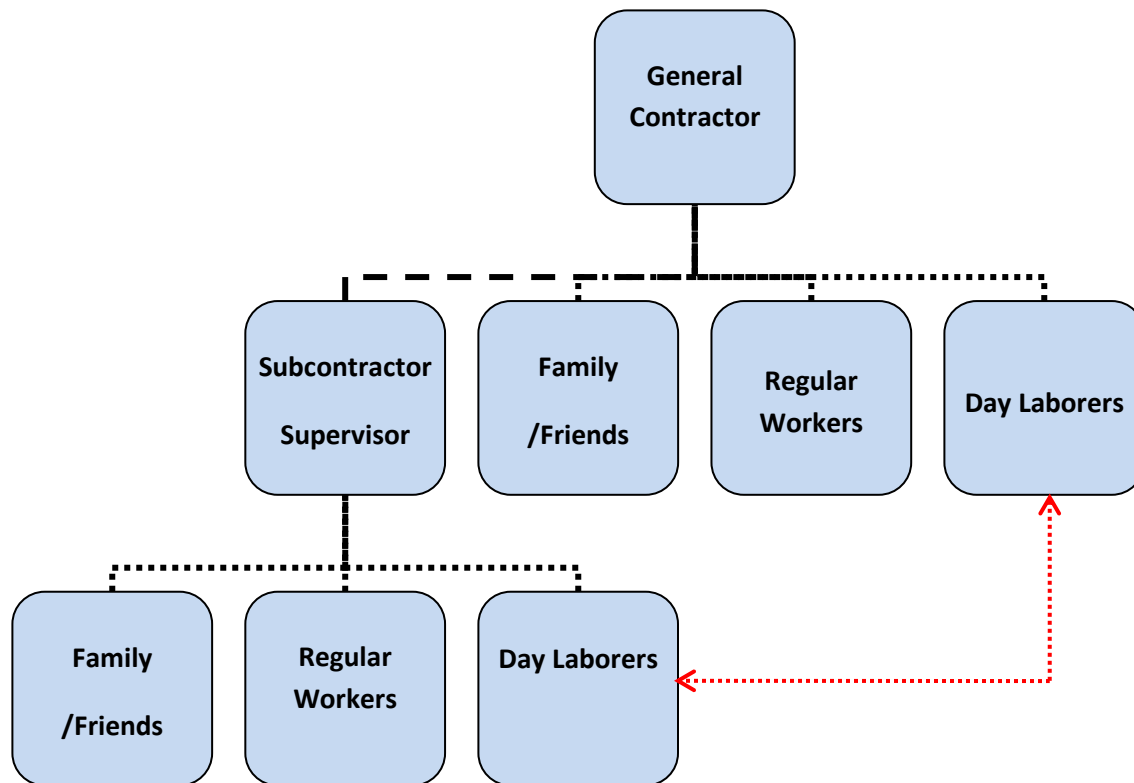
Goal 2: Design and disseminate preliminary training system, case studies, and recommendations.

Specific Aim 1A: MEAD Analysis. The MEAD analysis was conducted using an analytical review of the literature and scheduled discussions with internal advisory board members of the Center for Innovation in Construction Safety and Health. This portion of the study used the MEAD method. Environmental elements were identified that should be considered when determining how to conduct safety training within these work systems.

Table 1. Overview of Results from the MEAD Analysis

System Feedback (What System expects of Stakeholder)	Stakeholder	Stakeholders Expectations from System	Potential Interventions to Reduce Variance
Provide training program / best practices system, knowledge of safety issues	NIOSH / OSHA	Safer work practices	Make training available through 3 rd party system
Support, and small available projects	Community	Represent ideals and values of community	Community involvement
Provide land to develop on	Community	Economic development	Expedite building permit process
Research safety issues	Researchers	Information on preferred communication, best practices, transferring information	Project management
Development	Construction business, Owner	Job satisfaction, sense of community, job flexibility	Increased communication
Build relationship with workers	Construction business, Owner	Facilitate the means to a relationship	Team building skills
Cooperation, concern for each other's well being	Construction Workers	Pride in finished work, job satisfaction	Incentive programs
Provide funds and opportunity to work	Customer	Quality end product	Resource management
Cooperation	Customer	Satisfaction	N/A
Be involved in design process, create ease of daily coordination	Customer	Sense of trust and personal relationship	Increase communication of needs
Provide connection to work life	Family / Friends	Enjoyable work life and work environment	Alcohol/drug programs; other social programs
Provide a day's work	Day Laborers	Short term work, financial needs	Bilingual signs / instructions, safety expectations
Lower labor costs	Day Laborers	Informal treatment (i.e. no application or background)	None possible

The MEAD analysis supported the development of a conceptual organizational chart that characterized informal work systems in construction (Figure 1). The analysis revealed a number of informal lines of authority. In addition, in spite of the family and social acquaintance ties among small contractors, these businesses used day laborers frequently. Day laborers introduce an additional burden on safety climate due to their transient nature, which reduces the probability they will be trained.



Informal/Formal Line of Authority – For smaller projects typically the general contractor knows certain subcontractors and there is informal authority. Other times the General Contractor must hire unfamiliar subcontractors, creating a formal line of authority.

.....

Informal Line of Authority – For small construction firms the supervisors/owners have an informal line of authority with all their workers.

.....

The dotted red line represents a connection between workers. Day laborers have no attachment to any specific company and typically change places of work each day.

Specific Aim 1B: Interviews.

Methodology

We used a mixed-methods approach (Creswell, 1995) to address the aforementioned goals, using one sample of participants. The mixed-methods approach utilized three specific methods:

- A quantitative approach using Likert-type questionnaires and some of the interview responses to quantify factors that may be associated with risk of injury, safety climate, and other barriers or facilitators related;
- A qualitative approach using semi-structured interviews and consequent verbal responses to probe for specific work-family and other organizational factors that serve as barriers or facilitators of training or transfer of training.

Likert-type questionnaires and interviews were also used to address the research goals. These methods are described in the forthcoming section.

Participants

Ninety (90) participants from 69 different small construction companies were recruited using newspaper advertisements, word of mouth, and assistance from the External Advisory Board of the Center for Innovation in Construction Safety and Health, a NIOSH-sponsored research organization. Our efforts to recruit were primarily community-based and did not involve random sampling. We relied on convenience sampling and an approach that relied on data collection that was contextual and that relied on experiences as reported directly by respondents (Dooley, 1995; Monk, Nardi, Gilbert, Manteir, and McCarthy, 1993; Preece, Rogers, Sharp, Benyon, Holland, and Carey, 1994).

The following criteria were used as screening requirements for participation, and were included in the flyers and other advertisements:

- At least 18 years of age and currently employed in a family-owned construction business with at least 2 and no more than 20 employees.
- Company located in either Virginia or North Carolina (due to resource constraints on travel).
- Company operating continuously for a minimum of 5 years (many fail in less than 5 years).
- Related through kinship with the owner/manager or supervisor in a small construction business (or the actual owner/manager may be a participant, but must be related to at least one other employee) OR must self-define as a close friend or acquaintance of the owner/manager or supervisor.

Questionnaires and Semi-structured Interviews

Besides the demographic form, we administered two paper-based Likert-type questionnaires and one oral interview in either English or Spanish, based upon the first languages or preferences of participants. We modified the wording of the two Likert-type questionnaires associated with ratings to be more conducive to a 6th grade reading level. Participants were asked if they preferred to have items read to them and to provide oral responses or if they preferred to complete the questionnaire without involvement of the administrator. This approach has been used successfully and avoids embarrassing participants who may not be able to read or write or do so at very low levels (Boynton and Greenhalgh, 2004; Dumas and Rollock, 2004; Willis, Royston and Bercini, 1991).

A demographic questionnaire was administered to elicit the following information – age, gender, years of experience, relationship or kinship ties to owner or supervisor, ethnicity, level of

education, estimated number of employees at their company, and construction work type. Two additional single item ratings were added to the demographic form -- *Satisfaction* with current construction job and *Perceived likelihood of injury* on the job (1-10 rating). An open-ended question was also added to elicit the number of accidents the participant had experienced in the past year.

Questions were selected from different questionnaires to assess specific safety climate constructs. Selection of instruments and questionnaire development were influenced by the need to minimize the time requirements of participants and ensure information could be reported easily. Since most had 10 or fewer employees, the absence of an employee for an extended period of time or a lengthy interview even off site outside of the work hours was not feasible and would likely reduce the reliability and validity of the self-report data.

Table 1 summarizes the items and the sources for each. A Likert-type rating scale was used for the safety climate items but followed a 1 – 10 format from 1 (*strongly disagree*) to 10 (*strongly agree*).

Table 1. Safety Climate Questionnaire Items.

Construct	Item (s) and Source	
Safety Climate	1. My supervisor puts in a good work whenever he sees a job done according to the safety rules.	Zohar (1980)
	2. My supervisor talks to workers during work to discuss safety issues.	Tampere University of Technology
	3. My safety training helps me both at work and home.	Zohar (1980)
	4. Whenever a deadline is approaching, my supervisor wants us to work faster, rather than by the rules.	Zohar (1980)
	5. As long as there is no accident, my supervisor doesn't care how the work is done.	Zohar (1980)
	6. My supervisor only keeps track of major safety problems and overlooks common problems.	Zohar (1980)
	11. Workers who take safety-training courses are doing a better job than those who don't.	Zohar (1980)
	13. I do not receive enough safety training.	Tampere University of Technology
	14. The dangers of my job concern me.	Zohar (1980)
Level of participation and influence of relationship with supervisor	7. My relationship (relative, friend) to my boss interferes with my ability to work safely.	Hayes & Major (2003)
	8. I feel I can change the decisions of my boss on things that I am concerned about on my job.	Hayes & Major (2003)
	9. In my job, I am mainly responsible for safety.	Cohen, Smith, & Cohen (1975)
	10. In my job, my boss (foreman or supervisor) is mainly responsible for safety.	Cohen et al. (1975)
	12. I can make suggestions to improve the safety of my workplace.	Hayes & Major (2003)

Leonard, Hill, and Karnes' (1989) Risk Perception scale was used as the basis to develop a construction-specific risk perception scale. Based on Leonard et al.'s method, which uses

scenarios so workers could rate the degree of hazardousness, 7 items were developed and administered using a 0 (*not at all risky*) to 8 (*extremely risky*) scale format

- Not wearing ear plugs in a high-level noise environment.
- Not wearing steel toe safety shoes on the job.
- Not wearing a hard hat in construction areas where posted signs state they are required.
- Climbing from one ladder to another ladder at an elevated height.
- Walking on slippery surfaces while at work.
- Not wearing fall protection when working at elevated heights.
- Wearing damaged fall protection.

The order of administration of the two rating questionnaires (safety climate and risk perception) was alternated for each participant.

Semi-structured Interviews: A semi-structured interview script consisting of open-ended questions as well as structured questions with response alternatives was administered after the rating questionnaires were completed. All interviews were audio-taped for later translation and analysis of the transcripts. The interview script contained initial questions, and most of the questions were associated with a prompt (restatement and clarification of the question) and a probe (more detailed follow-up question). Table 2 lists the initial questions, prompts, and probes. Questions were designed using a “funnel” approach – from general to specific.

Table 2. Interview questions with associated prompts and probes.

Initial Interview Question	Prompt (if requested)	Probe
What is your opinion of the attitudes about safety at your construction company?	In other words, how do people think about safety where you work?	Could you explain or give an example?
Does your construction company believe that safety is everyone's job?	Does it seem like your company makes it the job of everyone to be safe and avoid accidents?	Yes: What makes you think this is the case? No: Why not?
What are some safety rules you are aware of?	In your job, could you give me some examples of the safety practices or rules you follow?	
Do you get safety training from your company?	Has your company trained you yet on safety and health in the area where you work?	Yes: Will you describe the types of training you have had? How did they train you? No: Why do you think you did not receive any safety training?
What problems do you see in your company that make it hard to do safety training? Please be specific.		

Initial Interview Question	Prompt (if requested)	Probe
Please give me an example of an incident that happened to you that you think relates to working with or for a relative or close friend (in this small construction company) and that might relate to safety issues.		
Do you think your relationship with family members or friends on this construction site will affect whether you get training in safety and health?	Does the fact that your work with or for people you are related to or people you are friends with affect the type of information you get about safety and health?	Yes: Please explain, in your opinion, why you think your relationships with the owner or coworkers will influence the information you get. No: Do you think the relationship you have with the owner or coworkers could make them assume that you know all you need to know about safety and health? (Yes: Please explain.)
What do you like and dislike about working in small construction companies with family members or people you are friends with?		Why?
Have you ever seen children under the age of 16 working at a construction site?		What is your opinion of underage children working in the construction field?
Can you think of any situations where your friendship or relationship with the owner or your co-worker got in the way of doing your work safely?	In other words, since you work with or for your ____, how has this influenced your ability to work safely?	Can you describe what it is like to work for someone you are related to or someone you are friends with (from the perspective of safety)? Does your relationship at home or outside of work ever get in the way of your work activities at the construction site?
What kind of safety training would you like to have?	What would you like to be trained in to avoid accidents and injuries?	Can you describe to me in more detail what you think you need to know to protect yourself from injuries?
Who does the safety training in your company?	Who trains people on safety and health at your workplace?	If no one formally does it, how do you get safety information?
If you could design your own training program, how would you like to have safety and health information given to you?		

Procedure

Questionnaires were administered at nearby locations to construction sites or in areas that were comfortable to participants, such as community centers. Our goal was to minimize the risk of any residual problems, such as reprisal or reprimand by supervisors or owners due to participation in this study.

Informed consent documents were presented orally and in writing. Participants were assured of confidentiality and were informed that the cassette tapes would be destroyed once transcripts were developed. After informed consent was acquired, the questionnaires and interview were administered. Participants were also asked at the end of the interview to discuss any additional issues they believed were relevant to health and safety problems or successes in their work settings. Sessions ranged from 30 minutes to one hour. At the completion of the session, participants were thanked and were compensated at the rate of \$10/hour.

Results

As stated previously, the goal of this research was to explore attributes that describe small family-owned construction companies to determine the needs, enablers, and barriers associated with training, risk of accidents, and injury prevention. The association between specific attributes and higher risk was qualitatively conceptualized as a function of the likelihood and the severity of an accident. Specific attributes or conditions within small companies in general can influence the probability or likelihood of an accident, as well as the severity (Glazner, Borgerding, Bondy, Mueller, and Kreiss, 1998; Greife, Lentz, and Wenzl, 2006).

Goal 1: Attributes of informal construction work systems

Demographic Attributes. Descriptive analyses of the demographic data were performed to provide a general profile of the construction workers (participants). The mean age of construction workers was 35.54 years ($SD = 13.94$, $range = 18 - 75$ years). The mean number of accidents while doing paid construction work before working in the current company was 1.20 ($SD = 2.18$, $range = 0 - 10$). The mean number of accidents experienced by participants in the current company was 1.28 ($SD = 2.62$, $range = 0 - 19$). Ninety-eight (98%) of the sample were males. Self-reported ethnicity of the participants was as follows:

- African-American (7%)
- Asian-American (1%)
- European-American/Caucasian (82%)
- Hispanic-American/Latino (7%)
- Other (3%)

Twelve percent (12%) of the participants did not complete high school, 42% had high school degrees, 36% had some education after college, and 10% had college degrees or advanced degrees. Forty percent (40%) were married and the remaining consisted of workers who were single, divorced, or separated.

Organizational Attributes. Thirty-three percent (33%) of the participants were “close friends or acquaintances” of the owner, while the majority were *related* to the owner (*parents, siblings, nephews, or cousins*). In most cases, the owner also served in the role of supervisor. Participants also reported their primary construction job duties and the size of the company, Figures 2 and 3 illustrate the organizational features of the informal construction work systems represented in this sample. Eleven of the 20 construction trade occupations recognized by the BLS (2006) were represented in the sample. Those not represented included boilermakers, construction and building inspectors, construction equipment operators, elevator installers/repairs, glaziers, hazardous materials removal workers, insulation workers, sheet metal workers, and structural/reinforcing iron and metal workers.

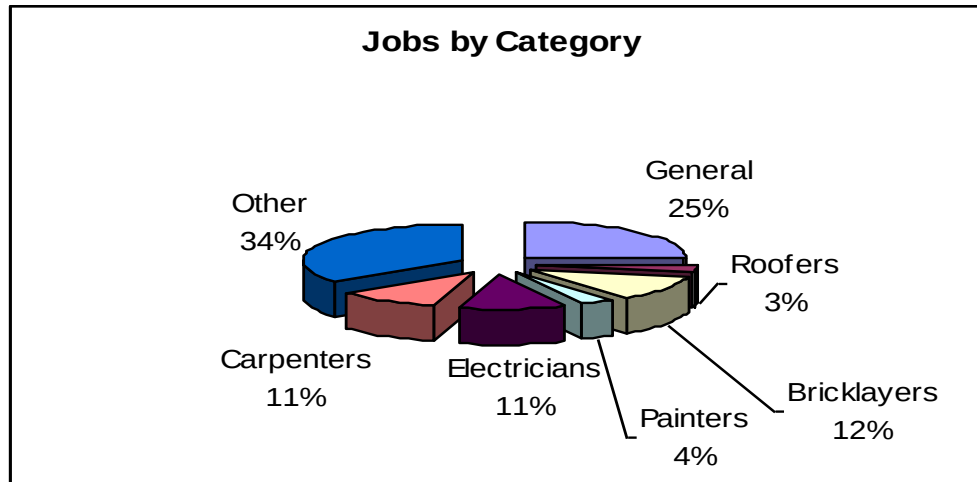


Figure 2. Job types by category. “Other” consisted of maintenance, landscaping, and mixing.

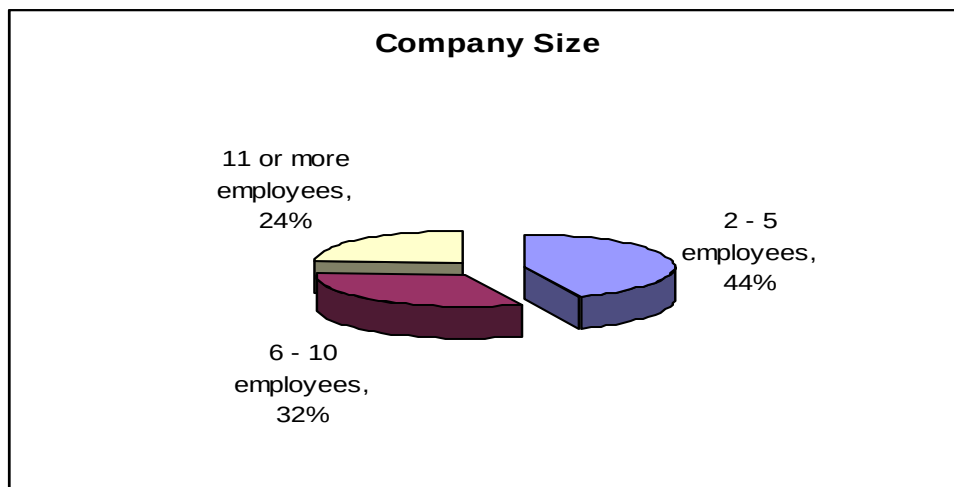


Figure 3. Company size as reported by participants.

Hazard Profiles and other Safety Indicators. In addition to the safety climate indicators on the ratings instrument (analyzed separately), additional questions were asked regarding the workers’ perceptions of safety and hazards in their workplace. Eighty-seven (87%) of workers reported that hazards were associated with their current jobs; and 37% reported experiencing an accident while involved in construction work. Table 3 is a summary of the hazard types described as frequencies reported by the sample of workers.

Table 3. Workers' Reports of Workplace Hazards

Hazard Type	Frequency Reported
Falls	29
Tool Hazards (saws, nail guns, pneumatic tools)	24
Construction Equipment/Heavy Machinery	19
Electric/Electrocution	14
Scaffolding and Ladders	11
Fumes, Solvents, Inhalants	7
Falling Objects	6
Fire, Explosives	3

Table 4. Descriptions of Construction Accidents and Comparisons to BLS National Data for Construction Occupations (2005; revised)

Category (Ranked by Frequency)	Description	Frequency reported*	BLS Rank (nonfatal by event or exposure)**	BLS Rank (fatal by event or exposure)**
Contact with objects	Cuts from tools, sharp metal, running into objects	8	Contact with objects	Falls from heights
Falls from heights	Falls from roofs, ceilings, ladders	6	Overexertion	Transportation Accidents
Struck by object	Shot with nail gun, walls or other objects falling on worker	5	Struck by object	Contact with objects
Falls from same level	Tripped over object	5	Falls (same level)	Exposure to Harmful Substances
Struck against object	Crushed or pinched by object such as	2	Assaults/violent Acts	Fires / Explosion
Overexertion	Due to lifting, pushing, pulling	2	Struck against object	Assaults/Violent Acts
		Total accidents = 28	Falls from heights	

*Frequency reported within the sample based on the time the worker had worked in the current company.

**Listed in order of frequency – most frequent (top cell) to least frequent (bottom cell).

Table 4 summarizes the accident descriptions that led to injuries, and provides BLS information regarding event or exposure ranks for 2005 statistics on fatal and nonfatal occupational injuries and illnesses in construction. Although the comparisons are not exactly equivalent (due to different reporting requirements for small companies), the table provides a general idea of the degree to which informal construction work systems compare to larger construction work systems using national data. The descriptions were categorized using the Bureau of Labor Statistics occupational injury and illness classification system. Categories are listed from highest to lowest frequency.

Further exploration of the potential relationship between attributes and risk was implemented by using quantitative approaches to determine the predictive validity of specific factors on job satisfaction (based on 1 – 10 rating), perceived likelihood of injury (based on 1 – 10

rating), and risk perception (based on Risk Perception Scale ratings of 0 - 8). Previous empirical studies have linked job satisfaction with accident involvement and injuries (Hayes, Perander, Smecko, and Trask, 1998; Michael, Guo, Wiedenbeck, and Ray, 2006; Nakata, Ikeda, Takahashi, Haratani, Hojou, Fujioka, Swanson, and Araki, 2006). Perceived likelihood of injury was used as an outcome measure to indirectly characterize workers' perceptions of workplace hazards and as a proxy for risk based upon workers' perceptions (Michalsen, 2003).

Risk perceptions that are incompatible with objective risk, specifically if they are comparatively lower, are associated with increased risk taking and decreased compliance with prevention or control practices (Ajzen and Fishbein, 1980; Boyd and Wandersman, 1991; Stewart-Taylor and Cherrie, 1998). Internal consistency reliability of the Risk Perception questionnaire was tested using Cronbach's alpha. The internal consistency was relatively strong, at $r_{\alpha} = .82$.

Predictor variables were developed using the questionnaires from the safety climate scales and demographic and organizational variables that were derived from responses elicited from the semi-structured interviews. This combination of predictors was isolated as the attributes that were common to the small construction companies represented in the sample.

Principal Components Analysis (PCA) using SASTM 9.1, was conducted to reduce the large set of individual predictor variables from the safety climate measures and to minimize any contributors to variance inflation. Varimax rotation was selected to isolate orthogonal factors, and the minimum criterion for eigenvalues was set at 1.00 (Kaiser, 1960). The results of the PCA isolated a factor structure supporting the retention of 5 factors that accounted for 89% of the variance. The factors and their loadings are shown in Table 5.

Table 5. Factor Structure of the Safety Climate Items (absolute values of factor load ranges are in parentheses)

Factor and Description	Item # (see Table 1)	Proportion of Variance
I General Safety Climate: overall perceptions of the commitment of the company to safety.	Items 1 – 3 and 11 (.59 - .78)	25%
II Perceived Safety Control: perceptions of ability to control their own safety practices without pressure from “boss” to work faster, etc.	Items 4, 5, 6, 13 (.63 - .79)	25%
III Worker Involvement in Safety: participation in training or safety-related decision-making.	Items 12, 14 (.64 - .76)	14%
IV Safety Responsibility: perception of who is responsible for safety (self, supervisor, or both)	Item 9, 10 (.68 - .75)	13%
V Relationship Interference: extent to which relationship with boss/supervisor interferes with safety.	Item 7 (.87)	12%

¹Some items were reverse coded. ²This item was reversed to establish a construct that reflected the degree of safety responsibility the worker assigned to themselves (which reflects a healthier safety climate). ³Factor values are rotated factor loadings.

As shown in Table 4, Item 8, *I feel I can change the decisions of my boss on things that I am concerned about on my job*, did not meet the minimal loading on any of the factors. Factor V consisted of only one item.

The summated item ratings for each of the five factors were used to derive a predictor score. Two additional variables derived from the semi-structured interviews were added to the

models as well – *time with the company* and *company size*. The linear combination of the predictors was regressed onto the outcome measures of *job satisfaction*, *perceived likelihood of injury*, and *risk perception* in three separate equations. The equation containing the 7 variables as predictors accounted for 28% of the variance in job satisfaction, $F(7, 86) = 6.03, p < .0001$. Beta weights (standardized) were reviewed and the predictor, *perceived safety control* with a coefficient of $-.43 (p < .0001)$, was significant. The same equation accounted for 15% of the variance in the *perceived likelihood of injury*, $F(7, 86) = 1.99, p = .07$, but the model did not achieve the accepted level of significance. *General safety climate* and *worker involvement* were significant predictors, with Beta weights of $-.28 (p < .05)$ and $.23 (p < .05)$ respectively. Twenty-two (23%) of the variance was accounted for by the 7 factors when regressed onto the *risk perception* score, $F(7, 86) = 2.87, p < .05$. *Worker involvement* and *relationship interference* were significant predictors at $.34 (p < .01)$ and $.27 (p < .05)$, respectively.

Goal 2, Training Barriers and Facilitators

Atlas.ti™ Knowledge Workbench Software was used to content analyze the verbal responses to the semi-structured interview questions shown in Table 2. Since responses were audiotaped, transcripts were produced and the subsequent files were imported into the content analysis software. Interviews conducted in Spanish were translated and checked for translational fidelity (Triandis, 1990). Three coders divided the transcripts roughly equally and used the same systematic coding process. A hybrid approach was developed that combined an underlying phenomenological philosophy of coding, which required coding of any meaningful statements regardless of the frequency of occurrence (Hein, 2001; van Manen, 1990) with a systematic process used by coders (to support reliability). The systematic process included five analysis steps based upon Krippendorff (1980) and Weber (1990):

The beginning and ending of a response to a question or probe was bounded as a coding unit within each transcript, so each transcript consisted of several coding units. A total of 10 *a priori* codes were established based upon the project goals and general topics within each question. All *a priori* codes were defined to be mutually exclusive. These codes were:

- *safety attitudes,*
- *previous safety knowledge,*
- *current method of training,*
- *desired method of training,*
- *relationship influences on safety,*
- *barriers to safety training,*
- *attitude toward informal work systems,*
- *training responsibility,*
- *safety areas of interest (desired topics of training),*
- *safety rules followed in the workplace.*

Coders used the list of *a priori* codes as the initial guide for analysis of transcripts.

Six (6) emergent code categories were isolated in the first 2 – 3 transcripts coded by each coder. The emergent codes were shared, defined, and agreed-upon by coders. Coders also agreed on the level of sensitivity of the analysis. Emergent codes were *inappropriate onsite behavior*, *attribution of causes for accidents*, *use of personal protective equipment (PPE)*, *safety precautions (practiced or not practiced)*, and *existence of under-age workers*.

The 16 total codes (some are shown in Table 6) comprised the master coding list (themes list), and sub-codes were organized under the master codes. A total of 110 sub-codes were identified, defined, and classified under the 16 master codes. Frequency counts were assigned to each of the 110 sub-codes yielding grand total frequencies for each of the 16 master codes. Only the most frequently occurring sub-codes are included in Table 6 and only those focused on the goal of identifying training needs and barriers. Some sub-codes were combined for the purpose of conciseness.

Table 6. Master Codes, Sub-codes, and Definitions (only some of the sub-codes are presented).

Master Code	Definition	Total Frequency*	
		Sub-codes	Frequencies
Attitude toward informal work system	Workers' reported attitudes about working with family or friends.	Positive (enjoy, increased job satisfaction)	79
		Positive (benefits, more trust, communication)	34
		Both positive & negative	22
		Negative (dislike, hurts the relationship)	14
		Negative (lack of formal procedures; equipment, accountability)	3
		Grand Total	152
Barriers to Safety Training	Workers' reasons for lack of or minimal safety training.	Sub-codes	Frequencies
		Supervisors feel safety training is not important.	34
		Already know all there is to know about safety due to experience or age	32
		Not enough time to conduct safety training	27
		Company too small, too few resources, cost prohibitive	26
		Workers feel safety training not important or a waste of time.	18
		Grand Total	137
Current Training Method	Method used to deliver safety training if practiced within company.	Sub-codes	Frequencies
		Training has never been done.	46
		Hands-on Training	21
		Meetings or classes	20
		OSHA-based training materials	4
		Grand Total	91

Table 6 continued. Master Codes, Sub-codes, and Definitions (only some of the sub-codes are presented).

Master Code	Definition	Total Frequency*	
		Sub-codes	Frequencies
Desired Training Method	Workers' preferred method of training.	Safety meetings or classes	41
		Hands-on Training/Demos	34
		Pamphlets, Manuals, Brochures, Posters	26
		Internet/Computer tutorials	10
		Grand Total	111
Previous Safety Knowledge	Workers' responses to the sources of their safety knowledge if gained from previous experience.	Sub-codes	Frequencies
		Previous jobs or training by previous company	49
		Acquired through "common sense"	7
		Grand Total	56
Relationship Influence on Safety	Workers responses to the manner in which their relationship with the owner or co-workers (as friends and/or family) influences safety on the work site.	Sub-codes	Frequencies
		Has no effect on safety	63
		Enhances communication, which prevents accidents	43
		Supports trust so workers will protect each other	20
		Causes personal or family conflicts or decreased communication because of conflicts, which cause safety problems	18
		Leads to discipline problems and unruly behavior	16
		Supports drug and alcohol abuse in the workplace	6
		Grand Total	166
Training Responsibility	Workers' perceptions of who is responsible for providing training.	Sub-codes	Frequencies
		Everyone is responsible.	49
		Supervisors/Owners	40
		Inspectors/Certified trainers	5
		Workers with more experience.	4
		No one is responsible	4
		Grand Total	102

*Frequency counts are based on the number of individuals reporting that sub-code. Single individuals may have reported experiences that relate to more than one sub-code.

Analysis of the emergent codes revealed information that would also characterize the safety climate of the workers interviewed. Codes with more than 10 individuals reporting were as follows (frequencies in parentheses):

- Inappropriate behavior: horseplay on the site, supervisors ignoring horseplay, family members arguing about work or family issues on site (18);
- Attributions assigned to accidents (accident causes as perceived by workers): Most were attributed to human error or safety attitudes (9); weather conditions (6); time pressure (4); and poorly maintained or lack of equipment (3);
- Safety precautions: Not routinely practiced in the workplace (18); routinely practiced in the workplace (15);
- Existence of underage persons (< 16 years of age) on site: Never occurs (24); children are on site as workers, “helpers”, or were visiting (13).

Both the quantitative and qualitative data were integrated to address the goals of the study. In addition, further analyses were conducted to acquire more information regarding typical practices of informal construction work systems (i.e., presence of children in the workplace). Additionally, the most frequently occurring qualitative codes were used to explore familial conflict issues in a subsequent study using forums consisting of family member and friends working within the same company. The interpretations and inferences reported here relate only to the results reported in this portion of the study.

Discussion

The first goal of this study was to identify the attributes of informal construction work systems that are associated with an increased risk of accidents. This study explored the goal by interviewing several participants from a number of small, informal construction work systems. Using questionnaires, a profile of sorts can be derived based on the descriptive and inferential analyses.

Seventy-six (76%) of the companies employed between 2 and 10 workers; and the majority of workers were related to the owner who acted as the work “supervisor” in most instances. Fifty-four percent (54%) of workers in informal construction work systems reported educational levels of high school or less. The age range was large, 18 – 75 years of age, indicating a variety of generational issues that could either facilitate or undermine the safety climate. The types of hazards reported in the workplace were similar to those reported in the larger construction industry (Table 3). Although many reported having no accidents in the company in which they were currently employed, the causes for those reporting accidents that led to injuries were somewhat similar to the 2005 BLS data reported for accident causes Table 4). The most frequent cause for nonfatal injuries based on the BLS data included contact with objects, being struck by an object, and same-level falls (slips and trips), and accidents within informal construction companies followed the same pattern. Workplace violence, although frequently occurring in the BLS data, was not an attribute of the informal construction work systems in this sample.

Workers’ attributes for the causes of accidents included poor safety attitudes and time pressure. Workers also reported the routine presence of individuals less than 16 years of age as being present on site. Other specific attributes were also identified using the questionnaire ratings. Unlike other researchers who found a predictive relationship between company size and specific outcome variables related to risk, this study did not find any significant relationship between company size and risk perception, job satisfaction, or likelihood of injury. Other studies examined the relationship between company size and injury severity odds ratios, safety performance, and fall injuries (see Kines & Mikkelsen, 2003; Lin & Mills, 2001) and found company size to be a strong predictor. This study focused on a narrow band within company size, due to a need to examine small construction work systems, so the restricted range may have impeded the discovery of a statistical connection.

Safety climate, risk perception, and other safety-related and organizational questionnaires did provide a unique characterization of small construction companies. The factors identified in the principal components analysis revealed a structure that differed somewhat from the initial structure of the questionnaires, many of which have only been used to assess larger companies (Table 5). The factors of general safety climate, perceived safety control, worker involvement in safety, beliefs about safety responsibility, and extent to which the relationship with the “boss” interfered with safety combined to account for 89% of the variance in the questionnaire ratings.

In turn, the dimensions of perceived safety control, worker involvement, and relationship interference predicted important outcome variables that are related to accident risk, namely job satisfaction and risk perception. The higher the perceptions of safety control, the higher the job satisfaction. Improving a workers’ perception of control over their safety or precautionary behavior at the worksite could be done with fairly minimal intervention. For example, supervisors can state or voice messages regarding the importance of safety, especially when working under time or resource constraints. Also, visual campaigns and short safety meetings or talks that are commonly practiced can also be utilized by smaller companies and should require minimal time and resource investment. A study by Lingard (2001) that examined the impact of generic first aid training on construction workers’ safety attitudes demonstrated a strong and positive impact on perceptions of safety climate. An intervention such as a first aid class requires little investment of time and energy, but might yield a substantial impact on safety climate, and ultimately, the risks associated with work within informal construction work systems.

Higher degrees of worker involvement were also associated with higher risk perception, which could reduce accident risks (extrapolating from the aforementioned literature). Likewise, workers who perceived their friendly or familial relationship with their boss to be a safety barrier tended to have higher perceptions of risk regarding their workplace. Although the models did not account for large amounts of variance (based on R-square values), a preliminary pattern is identified that can later be manipulated in further empirical studies. The predictive relationship between worker involvement and risk perception could justify the application of workplace practices that would allow workers to participate in decision-making regarding safety, especially if the work system driver placed value on logic of the relationship and its importance to decision-making. Involvement alone may enhance awareness of hazards and consequences, and in turn, increase the risk perception of workers who might otherwise fail to develop an awareness of hazards within the work system. Thus, modifications in workplace practice might lead to reduced risk in informal construction work systems, even in the absence of training.

The qualitative data also helped to structure a profile of small informal construction companies. For example, the predominant sub-code for the current training method was “training has never been done in the company.” This is not unlike the findings of Eakin (1992) and Champoux and Brun (2003) who found that small firms (across a variety of industries) did not routinely provide safety training. Combined with the lack of routine safety training practices, many workers did not perceive safety training to be of importance. This perception may also reflect a resignation or fatalistic belief system, especially if one combines the relatively high awareness of hazards in the workplace with a concomitant belief that safety training was not important. Similar findings have been discussed in research on small firms by Lingard & Holmes (2001).

Of those reporting that training had been conducted within their company, hands-on and meetings/classes were the most frequently used methods. Of interest were the methods that workers’ wished to have as part of safety training within their company. Safety meetings/classes were the most preferred, followed by hands-on training, and paper-based media (pamphlets, manuals, etc.). So, despite a predominant lack of training, workers’ were clear in articulating a desire for training and the type of training method that would be preferred. In addition, workers reported overwhelmingly that safety training was the responsibility of either everyone or the supervisors/owners.

Goal 2 focused on identifying specific factors that impede access to training in informal construction work systems. The qualitative data provided a more comprehensive understanding of the barriers to safety training within informal construction work systems, and also the impact of relationships on safety (as perceived by workers). First, the organizational impact of working with and for family members or friends was explored, and the respondents were generally positive. The family/friend relationship was perceived as adding benefits to the work systems such as increased job satisfaction or enhanced communication.

However, when specifically asked about interference with safety (later in the interview), relationships were also perceived as negative factors within the workplace and several reported that the work relationships led to conflict outside of the workplace, unruly behaviors, and an environment of informality (lack of procedures or safety practices). In addition, relationships were believed to support leniency in the context of such high-risk practices as use of alcohol and drugs in the workplace. Some of the negative factors are consistent with other industries, and the bidirectional pattern of work-family influence was evident in workers' reports of conflict due to their relationships in this particular sample of construction workers. Frone et al. (1992) identified work-family and family-work conflict as having strong associations with stressors that, in turn, could lead to pre-occupation, distraction, and fatigue. Several researchers prior to Frone et al. also identified these same negative impacts, but many of the studies did not focus solely on "blue collar" workers and none focused on small construction companies (Burke, 1988; Parasuraman, Greenhaus, Granrose, Rabinowitz, & Beutell, 1989). At least from a qualitative perspective, our study validates the existence of bidirectional indicators of work-family conflict in the context of construction safety. Accidents can result from any of these conflict states given the right conditions.

Other barriers identified from the reported experiences of workers included attitudes that safety training was not important or that workers held enough knowledge of safety and did not need training. In light of the awareness of hazards and reports of accidents from the quantitative data, predominant perceptions of the unimportance of safety training or a belief in having sufficient knowledge seems to be a contradiction. There were also frequent reports of constraints on safety training, namely cost, few resources, lack of access to qualified trainers, and lack of time. These are organizational constraints that are difficult to overcome for small companies, so the goal should be to design around the constraints.

DeJoy's (1994) motivational readiness theory is also relevant to the findings in terms of explaining the predominant belief that safety training was not important or that workers' already possessed adequate knowledge due to years of experience. The qualitative data revealed a general belief that working with family and friends provided protection, benefits, or a better environment to support safety. DeJoy's model also reveals the impact of time pressure on decision-making. Perceived safety control emerged as a statistical factor, which manifests the workers' belief that constraints such as time and resources control the extent to which precautionary behaviors can be practiced.

Impact on the Construction Industry

Thirty-five percent of Fortune 500 companies are controlled by families, and these companies account for 50% of the GDP for the U.S.; employing 60% of workers in the U.S. (Business Week, February 13, 2006). This study provides information that characterizes the attributes of informal construction work systems as well as the needs and barriers to training, which was found not to be routinely practiced. These smaller contractors are often not characterized in larger, national studies, yet accident rates within these companies are significant and reflect disparities that require more systematic and continued exploration.

Over sixty informal construction work systems were represented in the study, providing a relatively representative description. But, limitations of the study exist and were mainly driven by resource constraints. For example, the ethnicity of the sample was not diverse; the majority (82%)

of participants were European American/Caucasian. Additionally, our coding process for the interview transcripts did not use multiple coders for each coding unit, but relied on a systematic process to support reliability. Our need to maintain a short, practical interview and questionnaire administration in the field limited the number of quantitative and qualitative data points, yet the data gathered from the study provided a substantial amount of information.

Knowing the attributes of work systems can provide researchers, practitioners, and policy developers with a baseline understanding to ensure the approaches, practices, and policies are compatible with the strengths and constraints of informal construction work systems. From phone interviews of owners-managers of small size enterprises, Champoux and Brun (2003) found a lack of use of available safety training resources. Similar to other technologies, training systems that are available through OSHA and other venues may be underutilized by small construction firms because they are incompatible with the contexts and organizational cultures of the users within the construction companies.

Barriers such as cost, limited time, lack of recognition of the importance of safety training, beliefs that safety knowledge is really common sense can be translated to design requirements to support more usable and practical design features. For example, knowing the cost and time limitations, combined with workers' reported preference for hands-on learning suggest a possible successful application of real-time training based upon such programs as Dupont's STOPTM program, which supports peer observation and real-time intervention when necessary. The interventions when risky behaviors are observed can also include "teaching moments" or brief, hands-on or on-the-job training opportunities.

Within the United Kingdom (UK) several researchers have focused on informal training as the most compatible training approach for small and midsize companies. The informal training movement extends from informal learning, which gained prominence in the 1970s. Although there is no agreed-upon definition or approach, informal learning is effective only when it is situated, void of hierarchy (egalitarian), and influenced by social constructions that can be formed by the learner (Kolb, 1984; Lave and Wenger, 1984). In workplace environments, Kitching (2007) highlighted the benefits of informal training and argues that the theoretical benefits of informal learning are also applicable to informal training. Some benefits include the advantage of being able to situate learning within a small company by using "teachable" moments and the ongoing opportunities for new types of learning, since every construction contract will introduce unique contexts. Other researchers have recommended the use of informal training as the primary mechanism for small firms (Anderson and Boocock, 2002; Johnson and Gubbins, 1992).

The existence of conflicts due to relationships with the supervisor or owner is important to consider when designing training programs for this particular kind of work system. How can relational dynamics be used to develop usable and compatible training? No research has been done in this area. From the results of this study, it is clear that family dynamics will influence the manner in which a company is managed by the owner, and the manner in which the work activities are supervised. If, for example, companies are challenged by time limitations, resource limitations, and family demands that interfere with the workplace, safety training practices that impose further demands or that conflict with the current relational dynamics will not be implemented. It may be more feasible to allow external field trainers to provide no-cost safety training of supervisors/owners who can then implement and more manageable real-time hands-on safety training practice.

Based on the findings, some preliminary considerations for the design of safety training systems are provided:

1. Family dynamics will impact the effectiveness of safety training, so "train the trainer" programs offered to owners should include components related to conflict resolution in the context of training delivery.

2. Informal construction work systems are challenged by time and resource limitations. Training programs must be integrated during day-to-day work practices and should consist of short, concrete “lessons”.
3. Informal training systems should be framed to allow owners of small firms to enhance their training skills using the theories of informal training. Although this type of training is referred to as “informal”, it does not imply that the structure is haphazard or unintentional. The intentionality and flexible structure of informal training systems can be made more concrete and additional train the trainer programs can be developed for business owners.
4. The use of set-aside training opportunities such as classes or meetings should only be done if they can be incorporated into scheduled breaks (i.e., lunch, for example).
5. Individual training, rather than group training, is more compatible with the constraints of informal construction work systems.
6. The use of such labels as “training” and “trainer” may need to be eliminated due to conflicts with power dynamics associated with familial and social relationships.
7. Beliefs that informal work systems based on family or social ties have positive attributes such as enhanced communication, more benefits, increased job satisfaction, and more trust could be used as motivators for training systems. For example, persuasion techniques that highlight the positive features of a current system can be used to gain entry or buy-in that will encourage adoption of a new system.

We followed the interviews with family forums, or focus groups that included employees of the same company who were related or close friends. A total of 4 focus groups were conducted. The data revealed three main issues that influenced safety in the workplace. The most predominant was the problem of family life interfering with work life. Participants reported that arguments or conflicts within the family would influence how they communicated or did not communicate in the workplace. In addition, difficulties with childcare led to the presence of children on work sites. In spite of the challenges, workers reported that it was an advantage to work in an environment where workers were familiar with each other. Some reported the closeness led to a more protective attitude among workers for each other.

Specific Aim 1B: Critical Incident Reporting. The goal of this study was to use critical incident reporting to acquire context specific work-family conflicts from participants in small construction firms that are family owned, and that are believed to be directly or indirectly related to workplace safety and health or safety climate. The critical incident technique was developed by Flanagan (1954) to identify problems that are important to design. A critical incident is any event that is believed to be a significant indication of a system problem, in this case, a safety or health-related problem. Critical incidents are commonly used in human factors engineering, especially in process safety, aviation, and human-computer interaction. The critical incident reporting is considered ethnographic in the sense that the reports will reflect actual incidents that occurred in the work domain and will be reported by participants who were involved in the incidents.

Participants

Our goal was to recruit 30 participants for this study, but due to the time frame in which we recruited participants (late winter and early spring), we did not achieve that number. Instead, 14 participants were recruited. Participants recorded incidents for 4 weeks. We used the following selection criteria:

1. Worked in a family-owned construction business with at least 5 and no more than 20 employees.
2. At least 18 years of age.
3. Reachable using a residential phone number.
4. Able to read and write (self-selection will occur, since the advertisements will highlight the requirement of keeping a log).
5. Had at least 1 year of work experience with the family-owned construction business.
6. Located in either Virginia or North Carolina.
7. Business must have operated continuously for a minimum of 5 years.
8. Had to be related to the owner/manager or supervisor in a small construction business (or the actual owner/manager may be a participant, but must be related to at least one other employee).
9. Had to be willing to attend a training session held in a nearby location.
10. Had to be willing to participate in the study for one full month.
11. Had to commit to maintaining confidentiality of the study for the full length of the logging session (28-30 days).

Procedure

We developed structured incident reporting logs to help participants report the information in a manner that assisted the data collection goals. Four logs were given to each participant, and a participant number was recorded on each log. The logs were mailed in the return, self-addressed stamped packet provided to each participant. Logs were mailed at the end of each 7-8 day period. The schedules for mailing were different for each participant based upon their beginning date. A mailing schedule was provided. The reporting structure contained the following items to guide the content reported by the participant:

- Date of critical incident
- Type of construction work associated with the incident (describe task)
- Description of the critical incident (what happened, where, when?)
- Roles or descriptors of persons involved
- Safety and health problems you believe are a result of the critical incident
- Other factors you think may have caused the critical incident
- Suggestion of solutions or organizational practices to prevent a similar incident in the future

The reporting logs were designed to hold up to 70 critical incidents, of about ½ page each.

Informed consent was acquired by first mailing forms to participants who volunteered for the study, and then following up with a phone call to review the informed consent document. Once the signed document was mailed by the participant and received by the research team, the participant was contacted to schedule an orientation session. The critical incident reporting logs were mailed to the participant immediately upon receipt of the signed informed consent.

Participants were asked to log critical incidents as soon as possible after they occurred AND only after they had completed the workday or had sufficient privacy to record an event in a private setting (e.g., during a lunch break while eating in their truck). Participants were asked to return one critical incident log every 7-8 days, until all 4 logs have been returned. Follow-up phone

calls were made each week to both remind participants to record critical incidents and to remind them to mail in the reporting log for a specific week.

Critical incidents were typed into a text document as they arrived. Content analysis of the qualitative data was conducted on the critical incident data (using Atlas.ti). Each participant Incidents were then merged such that all themes were combined for the entire data set.

Results

As stated, a total of 14 construction workers who were either related to or closely acquainted with the owners of the companies for whom they worked were recruited for the study. A total of 678 critical incidents were collected from the participants.

Of the incidents or close calls that were believed to be associated with the presence of another person, only 14 out of 80 involved family members or friends. The remaining involved “others” such as visitors to the site or day laborers. The higher number of incidents occurred equally between the hours of 9 to 11 am and 2 – 4 pm. Factors reported as being related to the incidents are listed in descending order of frequency as follows:

1. Lack of personal protective technology.
2. Poor awareness of surroundings or poor concentration.
3. Weather conditions and having to work in poor weather conditions.
4. Clutter on the work site.
5. Time constraints or time pressure.

Additional analyses will be continued on these data to specify more factors that are embedded in the critical incident logs.

Discussion

Requirements from this study are similar to the prior studies. It is evident that small construction firms are in need of resources to purchase and use personal protective technology. In addition, training that addresses issues of situation awareness and work site clean-up and maintenance will be more effective and more relevant to these work systems. Another issue that is revealed in the high-level results is that the limited resources require continued work during poor weather conditions and in context of cluttered work sites. With the time and resource constraints characteristic of this work system, the work conditions are usually not conducive to ideal safety conditions and there are few opportunities to stop the work to eliminate clutter or higher additional laborers to clean the site. Training on work safety practices could assist in providing recommendations to use work procedures that prevent the accumulation of clutter.

Specific Aim 2. A portion of this research was designated to translating the requirements identified into design recommendations for the development of training systems. The results indicated a need for informal training as the most compatible training for these types of work systems. By definition, informal training is not designed, but recommendations for implementation can be identified. We did not continue the translation work due to the time constraints, but were able to work with small construction company owners to develop guidelines to persuade other contractors to use informal training practices such as peer-assisted training or just-in-time, unstructured training. These guidelines are as follows and are based on Rogers 1995 technology adoption principles, and the guidelines assume that comparisons can be made on the basis of pre-intervention data collected by small contractors:

1. **Demonstrate Relative advantage** – Contractors must be able to see the specific gain when using informal training above and beyond what they have done before.
 - a. **Guideline: Investigate costs, benefits and risks associated with the adoption of technology.** Managers, supervisors, or safety personnel, investigate costs, benefits and risks associated with the adoption of informal training practices. Relative advantage will be distinguished once benefits are greater than pay-offs.
 - b. **Additional guideline (for small contractors): Estimate benefits and costs associated with the adoption of technology.**

With regard to benefits, small contractors need to see a reduction of work completion time, improvement of production as well as income to know practical advantage gained after the adoption of informal training practices. Small contractors should also estimate whether the introduction of informal training practices resolves work-family conflicts and improves current methods of training.

2. **Compatibility** - A contractor must be able to see the new technology as consistent with their work values, beliefs, experiences, world views, and physical environment.
 - a. **Guideline: Conduct a questionnaire on technology acceptance.** Managers, supervisors, or safety personnel, conduct a questionnaire on technology acceptance if the technology is consistent with employees' beliefs and experiences.
 - b. **Additional guideline: Enquire/survey employees about their acceptability of technology.**

Small contractors should ask employees whether the new training interferes with their work with family & friends and their work in the workplace. In addition, small contractors also should determine if the technology is perceived as practical, (neither too simple nor complex) to be applied to their workplaces.

3. **Complexity** - A contractor must be able to see the level of difficulty to learn or use the new technology.
 - a. **Guideline: Evaluate learnability and ease of use of technology.** Managers, supervisors, or safety personnel, evaluate learnability and ease of use of technology. Typical usability evaluation methods could be used.
 - b. **Additional guidelines (for small contractors): Observe the use of technology between employees.** Due to limited resources, small contractors could directly observe how employees interact with or use the training. Employees will not have problems with the training if they comprehend it.

4. **Trialability** - A contractor must be able to easily try out the new training before committing to its use.
 - a. **Guideline 1: Test & examine training effectiveness across time periods.** Managers, supervisors, or safety personnel, can try out and examine the effects of the training to determine if the effects are consistent and reliable across time periods. The performance of training requires a valid way to measure whether there was a reduction of safety problems.
 - b. **Guideline 2: Test & examine risks and penalty of technology adoption.** Managers, supervisors, or safety personnel, should examine risks and dangers after the adoption of the training practices.

5. **Observability** - A contractor must be able to see the results after adopting the new training practices.

- a. **Guideline 1: Observe workers' working behavior.** Managers, supervisors, or safety personnel, observe workers' working behavior after the adoption of certain training practices. Workers' safe working behavior is expected to increase after the adoption of the training practices.
- b. **Guideline 2: Monitor safety records.** Managers, supervisors, or safety personnel, monitor the injury rate and safety problems after the adoption of certain training practices. Safety problems are expected to be reduced.
- c. **Additional guidelines: Recruit "volunteers" to observe workers' safe working behavior and safety records.**
Small contractors recruit volunteers to observe the improvements of current methods of safety training, work-family conflicts, workers' safe working behavior as well as company's safety records after the adoption of technology. Volunteers could be people from their insurance companies and neighborhood communities, or be nearby university and college students. Workers' safe working behavior is expected to see after the adoption of technology. Safety problems are expected to reduce after the adoption of technology.

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- Kleiner, B.M., Smith-Jackson, T.L., Baldev, D., Artis, S., and Price, C. (2007). Influence of familial relationships on safety and health in informal construction work systems. *Proceedings of the 2007 Industrial Engineering Research Conference*, G. Bayraksan, W. Lin, Y. Son, and R. Wysk, eds., 1725-1730.
- Terry, T., Burneo, P., Riofrio, J., Martinez, C., and Smith-Jackson, T. (2008). Construction safety and informal training: A two-part study. *Proceedings of the Human Factors and Ergonomics 52nd Annual Meeting*; (in-press).

Inclusion of Gender and Minority Study Subjects

Study Title: Center for Innovation in Construction Safety and Health

Total Enrollment: 144

Protocol Number: 04-418

Grant Number: 5 U19 OH008308-02

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative)				
by Ethnicity and Race				
Ethnic Category	Sex/Gender			
	Females	Males	Unknown or Not Reported	Total
Hispanic or Latino	0	8		8 **
Not Hispanic or Latino	7	126		133
Unknown (Individuals not reporting ethnicity)	0	3		3
Ethnic Category: Total of All Subjects*	7	123		144 *
Racial Categories				
American Indian/Alaska Native	0	0	0	0
Asian	0	1	0	1
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	1	24	0	25
White	3	112	0	115
More than one race	0	0	0	0
Unknown or not reported	0	3	0	3
Racial Categories: Total of All Subjects*	4	115	0	144
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	Females	Males	Unknown or Not Reported	Total
American Indian or Alaska Native				
Asian				

Native Hawaiian or Other Pacific Islander				
Black or African American				
White				
More Than One Race				
Unknown or not reported				
Racial Categories: Total of Hispanics or Latinos**				**

* These totals must agree. ** These totals must agree.

Inclusion of Children

N/A

Materials Available for Other Investigators

N/A

2. QUANTIFICATION OF AND SOLUTIONS TO THE IMPEDIMENTS TO SPEECH COMMUNICATION AND SIGNAL DETECTION IN THE CONSTRUCTION INDUSTRY

(Casali) Start Date: 9/15/04 - End Date: 08/31/07

ABSTRACT

An empirical evaluation of noise in the construction environment was conducted, with particular emphasis on road construction which utilizes a variety of heavy excavation vehicles and paving equipment. The primary objective was to determine the impediments to workers' hearing of common auditory warning signals and speech communication in construction noise, and to conduct experiments to assess both technology-based (e.g., hearing protection) and work operations-based (e.g., ground worker-vehicle separation distances) countermeasures to improve safety. First, a task-analytic approach was adopted to determine those auditory signals that construction workers needed to hear to maintain safety. Although certain vehicle-specific, nonverbal auditory signals were found (e.g., crane boom signals, in-cab signals of vehicle systems status), by far the most common signal was the ubiquitous backup (i.e., reverse) alarm that is found on nearly all construction vehicles. Therefore, this warning signal was subsequently used in three human factors experiments during the research project. The task analysis also demonstrated that inter-worker communications were seldom accomplished via the uttered voice when in high levels of noise, and that the typical distances between ground workers and equipment (e.g., crane) operators necessitated radio communications or simple hand signals. Learning this, it was deemed most appropriate for the experiments to concentrate on the hearing of auditory alarms and not speech.

Task analysis was followed by a comprehensive noise sampling of the noise emissions of approximately 50 construction vehicles and a few powered hand tools that were obtained while these devices were performing work. Average measurements (Leq in dBA, 3 dB exchange rate), maximum levels, and minimum levels were recorded and are tabulated in the report. Maximum levels (in dBA, rms) for a few types of paving equipment, e.g., milling machines, regularly exceeded 100 dBA. Dosimetry on 14 operators of various types of paving equipment yielded time-weighted average (TWA) exposures exceeding 85 dBA for all but one worker, with most workers' exposures exceeding the 90 dBA TWA OSHA "criterion" level. Daily noise doses from road paving equipment ranged up to 570% dose in the sample, with pavers, milling machines, and excavators being particularly severe. Observations of the ground workers and vehicle operators in these environments, a sample of over 500 employees, revealed that despite the aforementioned severe noise exposures, very few workers were using hearing protection. When interviewed as to why not, a common answer was that they were fearful that they could not hear backup alarms and traffic noise while wearing hearing protection. This again confirmed the acute need for effective hearing protectors that also provide for pass-through of important auditory information, especially warning signals. A series of spectral signal-in-noise calculations were made based on the equipment and ambient noise measurements and backup alarm signals, using ISO 7731-2003. These analytical predictions showed that in most all construction site noise around road paving and earthmoving operations, backup alarm detection would not be considered as reliable, and that the alarm itself needed improvement. Pre- and post-workday audiometry was performed on 9 earth-moving

vehicle operators, and evidence of temporary threshold shifts (TTS), from about 2 to 8 dB, depending upon frequency, was found in all but one operator. Operators of enclosed-cab vehicles tended to exhibit less TTS than those of open vehicles, though the sample size was small and a definitive conclusion could not be made regarding that noise control intervention. Permanent threshold shifts (PTS) were exhibited by several older workers, though the etiology could not be definitively ascribed to construction work, due to the workers' reported mixes of other non-occupational exposures.

Backup alarms were obtained and measured in the anechoic room of the Auditory Systems Laboratory. From these, and based on discussions with heavy construction equipment manufacturers, a 97 dBA alarm (per SAE J994b Type C) was selected for use in three signal detection/localization experiments, as this backup alarm output level was reported by manufacturers to be the most "typical" standard alarm for this category of equipment. Also in preparation for these human factors experiments, a broad investigation was made into commercially-available hearing protection devices (HPDs) of the conventional passive type, and of both passive amplitude-sensitive and active sound transmission devices, the latter two categories having been "advertised" to facilitate workers' hearing in noise.

First, a laboratory-based acoustical manikin test was made on electronic sound transmission hearing protectors. The aim was not to ascertain their noise attenuation characteristics, but to measure their passband and amplification gain for signals external to the earcups. Five such devices were measured in pink noise of 80 and 85 dBA. While there were substantial differences in frequency response linearity among the 5 devices, the passbands were found to generally range from about 500 Hz to 6000 Hz. Broadband gain at maximum settings ranged from about 12 dB to 20 dB, depending on device, so it was expected that the hearing of backup alarm signals (for which the dominant frequencies do fall in the passband of most of these sound transmission HPDs) could potentially be improved by these HPDs, at least in moderate levels of noise below about 85 dBA. But the ensuing experiments did not bear this out. The first human factors experiment was in-field, and aimed at determining the linear distances at which normal hearing listeners who wore a high attenuation earmuff (having attenuation of the approximate protective level needed around a milling/paving operation) could detect a 97 dBA backup alarm in a free-field over a grassy plane. The average detection distance was determined to be 725 feet, and this distance was then combined with other variables, including worker's recognition/decision and evasive movement time, to develop a predictive equation of the minimum "safe" distance required for workers to maintain away from construction equipment, to afford them time to escape the equipment's path. Using estimates of the reversing speeds of various equipment, this model can be used to establish needed safe working envelopes between workers and machines at a construction site.

The second human factors experiment investigated the *detectability* of a standard backup alarm (i.e., per SAE J994b; and having 1250 Hz dominant and 2500 Hz harmonic frequencies) in 75, 85, 95, and 105 dBA pink noise and milling machine noise. Normal and hearing-impaired subjects participated, and each wore 4 different hearing protection devices in the tests: two electronic sound transmission earmuffs, and two conventional passive earmuffs which were identical design counterparts to the electronic muffs. Masked threshold for the backup alarm served as the dependent measure. The results showed that hearing-impaired subjects required about 10 dB more backup alarm level than normal-hearing subjects to detect the alarm under all conditions. For normal hearers, the electronic earmuffs exhibited no difference in detection as

compared to conventional earmuffs at any noise level, and one electronic earmuff was associated with poorer detection than the passive device at 75 dBA. For the hearing-impaired, the results were worse for the electronic earmuffs, which were associated with poorer detection than conventional muffs at most sound levels, except at 105 dBA, where there were no differences. Pink noise and milling machine noise did not differ in their effects on backup alarm detection. Overall, the results of this experiment did not support the use of either of the two electronic sound-transmission earmuffs under study, and these two were believed to be among the better-designed and most popular for industrial use. Yet they do not provide benefit in the construction environment for detecting backup alarms, at least in the noise conditions mentioned above.

The third human factors experiment was a comprehensive factorial investigation of backup alarm *localization* by normal hearers in 360-degrees azimuth in a free-field over a reflecting plane, in both 60 and 90 dBA pink noise. A standard 97 dBA backup alarm was compared with a modified backup alarm which was developed by the Research Team to exploit the benefits of interaural phase and intensity cues, so this alarm included a 400 Hz and a 4000 Hz component in addition to the standard backup alarm frequencies. The hearing protection device variable consisted of 1) an open ear condition, 2) Moldex #6604 foam earplug (Spark Plug_), 3) E-A-R Ultrafit_ premolded earplug, 4) E-A-R HI-FI_ earplug (a “flat” attenuation device), 5) E-A-R Arc_ earplug (a passive, ported device), 6) Bilsom Lightning_ L3HV passive earmuff, 7), a custom-modified Bilsom Impact sound transmission earmuff that was converted to a diotic design (one microphone fed both earphones), and 8) a Bilsom Impact_ dichotic sound transmission earmuff (separate microphones fed each earphone for binaural hearing). Measures of localization performance included: 1) the number of accurate (i.e., correct) localization responses, 2) the number of left/right localization errors, 3) the number of front/rear localization errors, and 4) the absolute deviation in degrees from the source of sound. The results from this study are very complex, but in general, it was found that backup alarm localization was very adversely impacted at the higher (90 dBA) noise level. There were few differences among hearing protection devices as to their effects on localization; however, all results consistently showed that the diotic electronic earmuff produced the poorest localization and thus it should not be used in dynamic construction environments. There was no particular advantage of the dichotic electronic earmuff over the passive devices either. In some conditions and measures, the deep-insertion, high attenuation foam earplug produced significantly poorer attenuation than the premolded earplugs, but those effects were relatively isolated. Also, on the measures of right-left and front-rear localization errors, all protectors, with the exception of the diotic earmuff, did not differ from the open-ear in performance. Ported, amplitude-sensitive earplugs and flat attenuation earplugs yielded no localization advantages over a standard passive premolded earplug.

Another important result of the third human factors experiment was that there were statistically-significant, but relatively small magnitude, improvements in several metrics of localization performance for listeners when using the Research Team’s modified backup alarm as compared to the standard backup alarm. Thus, there are distinct localization benefits for construction workers through the use of an improved backup alarm that incorporates the additional frequencies of 400 Hz and 4000 Hz. This points to the need for SAE and other Standards organizations to review and amend the current backup alarm standards, particularly with respect to alarm frequency content to foster localization.

Section 1: Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry

Highlights/Significant Findings

Road construction workers in the sample obtained within this research were exposed to high noise exposures in some jobs and around certain vehicles; these exposures are often above OSHA-prescribed safe limits.

- Road construction workers were rarely seen wearing any kind of hearing protection across over 30 construction sites visited.
- Predictions (using ISO 7731-2003) of masked threshold for backup alarms on construction vehicles operating in ambient construction noise indicate that workers cannot reliably detect backup alarms.
- Laboratory evaluations of selected electronic, sound transmission hearing protection devices indicate some, albeit limited, potential for improving construction workers' hearing in the bandwidth that encompasses most current critical speech and warning signal frequencies (i.e., 1000-4000 Hz). Maximum amplification (gain) of such devices ranged from about 12 to 20 dB.
- Field-based backup alarm detection experimentation resulted in a formula that predicts at what distance normal-hearing workers wearing a hearing protection device should be kept away from a reversing construction vehicle (of various backing speeds) to allow time to remove themselves from the vehicle's path.
- Laboratory experimentation indicated that sound-transmission technology in currently available hearing protection devices (HPDs) does not offer advantage over conventional passive HPDs with respect to the detection of a backup alarm signal within various levels and types of noise.
- Laboratory experimentation indicated that sound-transmission technology in hearing protection devices result in a disadvantage for some hearing-impaired listeners when compared to counterpart, passive devices.
- Laboratory experimentation indicated that an earmuff incorporating diotic (one microphone feeding both earphones) technology resulted in the poorest backup alarm localization ability of all passive or active, dichotic (two microphones, one feeding each earphone) HPDs tested.
- Laboratory experimentation indicated that certain passive premolded earplugs afforded backup alarm detection that was equivalent to the open ear in some noisy conditions, and better than detection afforded by deeply-inserted foam earplugs.
- Laboratory experimentation indicated that, as background noise levels increased, listeners experienced much greater difficulty in localizing a backup alarm signal, as evidenced by poorer localization scores.
- Laboratory-based experimentation indicated that statistically-significant (though relatively small in magnitude) improvements in backup alarm localization could be realized when using a modified (i.e., with additional low [400 Hz] and high [4000 Hz] frequencies) backup alarm signal when compared to the standard backup alarm that has dominant frequencies at about 1250 and 2500 Hz.

Translation of Findings

Governing Standards bodies should consider the adoption of a revised backup alarm standard that includes additional frequencies, such as 400 Hz and 4000 Hz or thereabouts, to the current backup alarm's primary frequencies of 1250 Hz and 2500 Hz, in that the research herein indicated that significant improvements in right-left and front-rear localization of the backup alarm could be realized with the additional frequencies. Along with these design changes, new Standards are needed to govern the design, manufacture, and placement of alarms on vehicles.

Due to the intense noise exposures measured at various construction sites in this research, coupled with the dirty environment, it is suggested that construction workers be issued premolded earplugs which, while providing moderate-to-high levels of attenuation (depending upon the device and the prevailing hazard risk), afford the listener with backup alarm localization ability on a par, or at least near to that afforded by the unoccluded (open) ear, as evidenced in this research for normal hearers.

At least at this stage of hearing protector development, workers should not assume that electronic, sound transmission hearing protectors either: 1) improve their abilities in detecting backup alarms, or 2) improve their ability to localize, and therefore avoid, a backup alarm-sounding vehicle. These devices, which are intended to provide more acute hearing in the workplace environment as well as protection, do not manifest improvements in the hearing of signals, especially when the ambient noise has significant spectral energy in the passband of the hearing protector.

Construction site safety managers should closely monitor the hearing abilities of construction workers, and take steps to ensure that an appropriate hearing conservation program is in place due to the very high noise exposures that occur around certain types of equipment in road construction and excavation operations.

Based on the various work envelopes at a given construction site (with respect to dynamic equipment operations in relation to workers on the ground working around that equipment), safety managers can utilize the data herein to assess whether construction workers will have sufficient time to remove themselves from the path of reversing equipment which has a sounding backup alarm. The data and formulae presented herein can assist in determining the proper separation distances.

Much more work is needed in the development of new technology, and exploitation of existing technology, in signal processing and sound transmission devices, to improve the hearing of auditory warning signals in the construction environment. Due to the prevailing noises of construction work, any such new devices will need to provide hearing protection benefit as well as enhanced signal detection and overall hearing acuity.

Outcomes/Relevance Impact

In addition to the impacts stated above, this research report provides valuable data with respect to not only the noise endemic to various construction operations, but moreover its impact on the construction workers themselves from both a hearing hazard risk as well as a signal detection/localization standpoint. The noise levels, spectra, and dose for road construction operations add to the existing knowledge base of equipment sound levels and their effect on construction workers. Both the field- and laboratory-based experimentation outlined below

provide data that indicate that certain types of HPDs are more appropriate to the construction environment than others, in that some products are better suited to help construction workers to not only protect their hearing, but also avoid potential incidents with respect to reversing vehicle accidents. The data outlining the localization performance improvement that was realized through the use of a modified backup alarm could also lead to a revised backup alarm Standard for industry, requiring a broader spectrum of tonal content, which could reduce the incidence of construction vehicle runovers of on-ground workers.

Section 2: Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry

SCIENTIFIC REPORT

Background: Noise in Construction

Excessive noise is recognized as a serious problem in the construction industry (Schneider, 1993; Suter, 2002). It has been estimated that more than 750,000 of the 5+ million construction workers in the United States are exposed to noise levels exceeding 85 dBA (Hattis, 1998), with the most noise-exposed individuals being employed in road construction, carpentry, and concrete work. Noise levels measured for specific pieces of construction equipment and tools appear in Table 1. Similar levels are reported by Nipko and Shields (2003) for a wide variety of construction equipment and related tools. Clearly, construction sites are noisy places and the potential for adverse effects is tremendous.

TABLE 1. 1-minute Leq noise levels of selected construction equipment/tools. (from Suter, 2002).

Tool Name	Tool Drive Type	Minutes	Median dBA	SD dBA	Range dBA
Air compressor	Pneumatic	255	96	11.2	70–114
Backhoe	Gasoline	1908	86	6.0	70–108
Bulldozer	Gasoline	494	89	8.2	70–104
Chipping gun	Pneumatic	1151	93	13.1	70–120
Chop saw	Electric	631	80	8.6	70–106
Crane	Electric	3059	78	7.7	70–110
Forklift	Gasoline	3727	85	5.8	62–125
Hand hammer	Mechanical	4443	85	8.0	56–110
Jackhammer	Pneumatic	267	104	11.4	70–112
Lejeune gun	Pneumatic	390	89	8.4	70–120
Truck	Gasoline	970	78	8.0	70–123
Welding torch	Other	1923	84	8.9	70–118

In any situation in which people are exposed to noise levels sufficient to cause noise-induced hearing loss (NIHL), such as some of those presented in Table 1 above, it is always best to eliminate or reduce the noise through engineering controls. This can be accomplished either through the design and manufacture of quiet machinery, installation of sound absorptive materials or barriers at the worksite, or completely isolating the worker from the source of the noise, as in a vehicle cab. However, although such solutions are always preferable from an ergonomic or health and safety perspective, they are not always feasible, practical, or economically viable. Furthermore, even when such controls are possible, they cannot always

be implemented in a timely manner. While the ultimate solution to reducing construction workers' long-term noise exposure and concomitant NIHL may, and should be the implementation of engineering controls to reduce or eliminate the noise problem at the source, effective short-term solutions must also be investigated. Finally, there are many types of machines for which, even with the best engineering efforts, noise levels may be never be reduced to the point where workers and machine operators can work in the vicinity without using hearing protection devices (HPDs). Examples of such machines include jack hammers, pile drivers, rock drills, explosive devices, and rock crushers, to name a few.

Hearing Loss and Hearing Protection Devices

The most obvious result of excessive noise exposure is hearing loss. It has been estimated (Ohlin, 1999) that the percentage of individuals in selected construction-related occupations suffering a hearing loss of 25 dB or more ranges from 19 to 33 percent. While much of this hearing loss could be prevented by the use of appropriate hearing protection devices (HPDs), their use has traditionally been resisted based on the (at least in part incorrect) belief that HPDs interfere with the wearer's ability to hear speech and other auditory warning and indicator sounds (Casali and Horylev, 1987; Kerivan, 1979; Suter, 1989; Suter, 2002; Wilkins and Acton, 1982; Wilkins and Martin, 1978). However, this is not necessarily true. Hearing protection devices work by physically blocking the air-conduction pathway to the user's inner ear. The intended purpose of hearing protectors is to reduce the noise level reaching the ear so as to minimize the potential for damage to the user's hearing. Although workers often cite the inability to hear speech and other auditory signals as one reason they do not like to wear HPDs in noisy work environments, the preponderance of research in this area suggests that with normal hearing individuals in at least some situations, HPDs may, in fact, not compromise the hearing of these stimuli.

Studies have shown that at noise levels of 85 dBA and higher, individuals with normal hearing are able to detect auditory signals just as well as, if not better than, they could if they did not wear hearing protection (Casali, Dabney, Robinson, and Gauger, 2000; Suter, 1989; Wilkins and Martin, 1978). The reason for this is that although the HPD attenuates both the signal and the noise equally, it reduces their levels to the point where the cochlear distortion present at high noise levels is reduced or eliminated, enabling the listener to distinguish the signal from the noise (Suter, 1989). This effect, however, is HPD-specific in that the attenuation of the device must be sufficient to adequately reduce the distortion present in the cochlea. This situation is analogous to the way sunglasses reduce visual glare, enabling the wearer to distinguish visual details not otherwise visible. Cochlear distortion may be thought of as the acoustic analog of visual glare; in fact, cochlear distortion is sometimes referred to as acoustic glare. Wilkins and Acton (1982) suggest that one reason for the continued belief that HPDs interfere with auditory perception is the mistaken assumption on the part of the user that since HPDs reduce the audibility of signals when worn in quiet, they must do the same in noise. HPD attenuation can, however, interact with a preexisting hearing loss in such a way as to prevent the wearer from hearing a desirable acoustic signal or speech. This is why it is extremely important to carefully match any HPD to both the user and the environment in which it will be used. In fact, NIOSH (1998a) has specifically identified the need for new or augmented HPD designs intended to improve "speech intelligibility and audibility of warning signals" (NIOSH, 1998a; page 71) as a

priority area needing further research. The issue of both conventional and augmented HPD effects on the audibility of signals in the construction workplace was the primary focus of the research described herein.

Hearing Loss and Construction Safety

Existing hearing loss among the population of construction workers, in combination with the preponderance of noise at construction sites can also contribute to the occurrence of accidents that can result personal injury and death. While there are presently no statistics relating specifically to the number of accidents, injuries, or deaths in which noise was a factor, there is data to support the above statement. Construction ranks third in terms of workplace fatalities and injuries (Sweeney, Fosbroke, Goldenhar, et al., 2001). Construction workers are twice as likely to be killed by a motor vehicle than workers in other occupations, with 40% of these deaths being pedestrians. Between 1980 and 1992, nearly one-third of the 2000 reported machine-related deaths in construction involved an individual being hit by a moving machine. While it is not possible to attribute these deaths specifically to the victims' inability to hear the vehicle or machine hitting them, it is likely that at least some of these deaths could have been avoided if the vehicles had been audible to the victims. (Anecdotally, the authors are also well-apprised of the prevalence of civil court actions that surround the inaudibility, or lack of heeding, of reverse alarms on construction equipment.) Finally, over a period of 15 years, Laroche et al., (1993) were able to attribute 22 fatalities at construction sites in Quebec Province to faulty backup alarms. They concluded that hearing loss, high background noise levels and inattention (in addition to poor design and placement of the alarms) were leading factors in these accidents. Based upon the available evidence, it is clear that there is a safety-related need to examine the impediments to construction workers' hearing of auditory signals within construction workplace, with particular emphasis on the masking noises and the warning signals themselves, coupled with various types of hearing protection.

Research Goals and Objectives

The overall project goal was to improve the safety of construction workers, and this goal has been supported through the following specific aims related to the acoustic environments of construction: 1) determinations of what impediments exist to the hearing of auditory signals (e.g., backup alarms on construction vehicles) in the construction industry (including a general assessment of workers' noise exposures, 2) quantification of the magnitude of the problems, 3) determination/development of appropriate interventions aimed at mitigating or removing the impediments, and 4) evaluation of the interventions to empirically determine their effectiveness. This report provides a comprehensive discussion of the research activities conducted toward each specific aim, and will provide recommendations with respect to: 1) warning signal design (specifically, backup alarms), 2) hearing protection device (HPD) selection, 3) the use of 'augmented hearing protectors' advertised for improving hearing, and 4) guidance for establishing 'safe working envelopes to help accommodate the hearing needs of construction workers. A systematic human factors methodology was implemented to first characterize and then quantify representative construction environments in which the ability to hear auditory signals is important. This was accomplished through the use of task- and job-analysis techniques to characterize all aspects of the communications and listening tasks.

It is important to recognize that the significance of this research is borne out by NIOSH's "Construction Program Draft Strategic and Intermediate Goals and Performance Measures," dated 11/21/05, which emanated from the National Occupational Research Agenda (NORA) meetings (NIOSH, 1996). In that draft, two strategic goals directly related to the aims of this research project were as follows: 1) Strategic Goal 2: Reduce fatal and serious injuries caused by roadway construction workers being run over by vehicles and equipment. This project was directed specifically toward the improvement of the hearing of signals, primarily backup alarms and horns, which are intended to warn construction workers of approaching vehicles and equipment; 2) Strategic Goal 5: Reduce noise-induced hearing loss (NIHL) among construction workers. This project has assessed the noise exposures of construction workers, and has identified and tested a large number of hearing protection devices that provide adequate protection against NIHL, some of which may provide some enhanced hearing capability in construction noise over conventional passive protectors.

In the discussions that follow, the research goals are presented and briefly described by Phase/Element rather than by year. This is done since the four Phases of the project, while they began and ended at different times during the three-year period, were for the most part conducted in parallel. This will become apparent as each Phase is described in more detail within the Research Results section.

Phase I - Determining Impediments to Communications and the Ability to Hear Auditory Signals on the Jobsite

Phase I was predominately Exploratory in nature and comprised most of the first year's effort. It did, however, continue through the second year and into year 3. After the end of the first year's effort, the percentage of the total effort represented by Phase 1 was gradually reduced until it ended very early in year 3. Data were made available to other researchers in the Center as needed and were published and presented at appropriate conferences whenever such opportunities occurred.

Element 1: Job/Task Analysis

Task analysis is a formalized method of examining the performance demands on the human elements of a complex system (Drury, Paramore, Van Cott, Grey, and Corlett, 1987). The fundamental advantages of task analysis are its flexibility and adaptability. It can be used to analyze just about any system involving human interaction and can be carried to any level of detail necessary to accomplish the desired objectives. With the proper application of the task analytic paradigm, it can be assured that all of the hearing-related functions and tasks of interest are identified and described.

Element 2: Acoustical Measurements

The second part of the Phase I effort concerned the characterization, quantification, and digital recording of the various background noises as well as auditory signals. In addition to performing these measurements at the cooperating construction sites, some measurements (i.e., for samples of noise produced by specific tools or equipment) were also performed off-site or after hours when possible/necessary so as to minimize contamination of the measurements and samples by extraneous unwanted noises.

Phase II - Quantifying the Magnitude of the Problems/Impediments

Based on the noise and signal measurements performed as part of Phase I, masked threshold predictions for the various noise environments, signals, and stimuli was performed using available, standardized methodologies. These calculations served to quantify the problems, provide an indication as to how severe the problems are, how much improvement is necessary, and, to some extent, what type of countermeasure might be most appropriate. Phase II began shortly after Phase I started and paralleled Phase I, ending shortly after Phase I ended. While Phase II was essentially Exploratory in nature, it did have a Prevention/Intervention component in that it served to quantify the problems being investigated and provided direction to the effort to develop suitable interventions.

Phase III - Determining/Developing Appropriate Interventions to Mitigate or Eliminate the Impediments

Unlike Phases I and II, Phase III was predominately Prevention/ Intervention-oriented since it was directly associated with developing interventions that were identified in Phase I and which were quantified in Phase

II. Phase III began shortly after the initiation of the Phase II effort, and continued throughout the project, and ended near the end of the third year of the research effort.

Phase IV - Evaluating Interventions to Empirically Determine Effectiveness

The Phase IV effort was entirely Prevention/Intervention in nature in that it was concerned with evaluating the effectiveness of the interventions developed in Phase III. The results of various laboratory- and field-based experiments are presented and discussed.

Research Results

Phase I - Determining Impediments to Speech Communication and the Ability to Hear Auditory Signals on the Jobsite

Element 1: Job/Task Analysis

The first step of this process was to determine what trades/crafts/labor categories (carpenters, electricians, plumbers, laborers, crane operators, dozer operators, etc.) are represented at a wide range of construction sites (including small single-unit residential sites, large industrial sites, road construction, and commercial construction) by conducting a task analysis. Each trade/labor category was analyzed to determine communications needs, signals listened for/exposed to, and any other related information.

As mentioned previously, the task analysis presented herein followed the methodology described by Drury et al. (1987), which includes four phases:

- 1 System description and analysis
- 2 Task description task list
- 3 Descriptive data collection
- 4 Activity analysis

System Description and Analysis. The system of interest is the construction worker and the tool/machine; specifically, that part of the operator interface and/or construction worker duties that may require the use of hearing and/or communication. There are, of course, other elements of construction worker duties that require the use of the other senses: vision, touch, smell, and perhaps taste—but these are outside of the research focus. Hearing, or audition, is a perceptual sense, and the human auditory system is ‘always on,’ in that it is ready, at any time, to receive input—except in cases of deafness, a masking noise, or when using hearing protection devices. From the observations made in this research project, it became apparent that noise is a constant presence at a construction site; thus, the ability to detect, recognize, and accurately respond to an aural stimulus is degraded due to masking effects.

In identifying those construction worker tasks that require the use of hearing or audition, the focus was upon how signals may or may not be affected by the presence of noise, which itself is often unpredictable in time, thereby precluding the use of a timeline-based task-analytic approach. Although most construction operations are continual in nature, no two segments of operations are exactly alike, unlike (for example) an industrial assembly line, wherein the same operations are repeated. The presence of other construction workers, other construction equipment, adverse weather, ambient noise (e.g., traffic), and even clothing (e.g., headbands in cold weather that cover the ears) ensures that construction tasks are rarely uniform. Such constraints dictate the need for the task analysis to take the form of a task list, which itself is not constrained temporally, but rather is broken down into functional categories. Construction worker hearing tasks can thus be placed into the following functional categories:

- 1 Communication
- 2 Detection of mechanical problems
- 3 Detection of internal warning signals
- 4 Detection of external warning signals

These functional categories were utilized for the task analysis. The next step was to develop a task description task list. To comprehensively do so, the third phase of task analysis (descriptive data collection) was initiated, which included three elements (in order): 1) subject-matter expert (SME) interviews, 2) questionnaire dissemination, and 3) job observations. Each element is discussed and results presented below.

Subject Matter Expert Interviews. Descriptive data collection was accomplished by interviewing site supervisors, engineers, foremen, shift supervisors, academics, and of course, the construction workers themselves (through questionnaire dissemination, discussed below). Collectively, these individuals are referred to as SMEs. Most of these interviews were conducted one-on-one (e.g., with a Safety Supervisor from a regional construction entity, a Construction Professor in the Department of Civil Engineering), but group interviews (focus groups) with six to ten individuals at a time were also completed (e.g., contractors for the Virginia Department of Transportation). For each job identified by the SMEs, the hearing requirements were determined first in general terms that can be described as speech (e.g., directional statements from ground crew to a vehicle operator), intentional non-speech auditory displays (i.e., vehicular backup alarm), or incidental sounds (e.g., traffic noise). After classifying

the hearing requirements in this fashion, the specific sounds being listened for were determined (e.g., face-to-face speech communication or via a radio, the specific class of backup alarm on a front-end loader). General impressions from the SME interviews are listed below:

- Noise is “not much of an issue” in residential construction.
- Direct talking/communication does occur in commercial and industrial settings—typically simple instructions using walkie-talkies (e.g., “come here, do this”).
- In infrastructure operations, communication does occur between foremen and equipment operators, but it is seldom direct: usually, the operator steps down from the cab to talk due to noise.
- Crane operations have important communication issues related to the efficiency of hand signals.
- There is an “eye contact ethic:” one makes direct eye contact with an operator before walking through a work area.
- Most industrial and infrastructure jobs do not involve workers standing on their feet; all or most are seated in machines.
- The research focus should be on infrastructure operations, which are the noisiest and are the most prone to accidents due to the inability to hear signals.

The Hearing in Construction Questionnaire. Extensive background and foundational work was completed with respect to the interviews and follow-ups with SMEs that led to the development of a comprehensive questionnaire (see Appendix A) that was given to construction workers (e.g., laborers, foremen, equipment operators, and superintendents) to help complete the descriptive data collection. The questionnaire and the interviews with the SMEs provided insight into 1) worksite activities, worksite signals (as identified by the workers themselves in most cases), open-ended responses regarding worker hearing and its relation to work tasks, and identification/use of existing hearing protection devices on the worksites (if applicable); 2) establishment of construction-type focus as suggested by the SME interviews as well as the identification of contractors and organizations that are currently involved in that area; and 3) contacting and meeting with identified contractors to gain their cooperation in the research effort.

The researchers identified and contacted numerous local and Virginia state (e.g., Virginia Department of Transportation) contractors to gain the necessary permissions and rules for access to various worksites throughout the research effort. Successful relationships were established that allowed for access to commercial and industrial building construction sites for data collection. Once the researchers were confident that they had identified all of the hearing-critical tasks for the different construction sites, SMEs were again consulted to ensure that no jobs were left out of the listing. Job lists specific to each type of construction site were then compiled and distributed to workers who were asked to rate the jobs using a Likert-type scale in terms of how critical hearing is to each specific job and rate the importance of the event associated with each signal.

Approximately 75 questionnaires and informed consent forms (see Appendix B) were distributed to industrial/commercial construction workers, encompassing tasks that ranged from sheet metal working to forklift operations, as part of the initial background data collection effort. Participants who returned the questionnaire ($n = 13$) ranged in age from

33-62, were 70% male, worked an average of 46 hours per week (with a maximum average of 65 hours per week), and had a lifetime work experience average of 13.8 years.

From the questionnaires received back from workers and from the naturalistic observations made, much was learned with respect to the various types of construction that exist, the types of equipment that are used, and what kinds of speech and signal detection issues typically occur within construction operations. This information led to further identification and verification of those construction jobs and tasks that were 'hearing-critical.' Figure 1 diagrams the types of equipment used by construction workers.

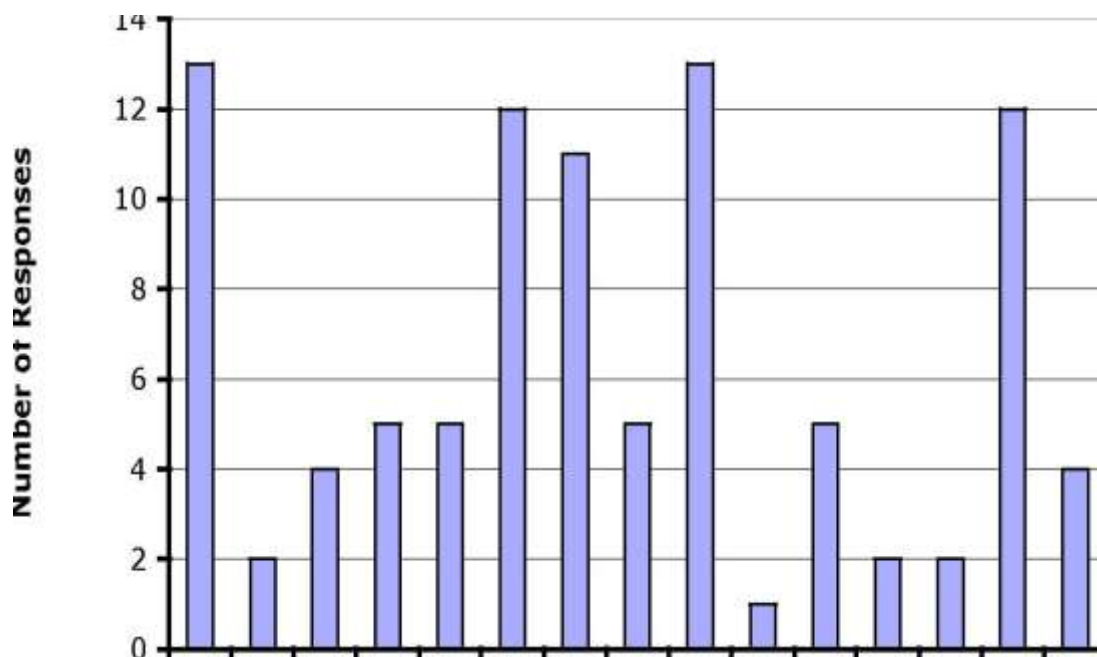


Figure 1. Equipment used by construction workers from the construction worker sample questionnaire data.

As can be seen in Figure 1, most construction workers within the infrastructure sub-category use or have used graders, dozers, excavators, backhoes, and trucks. Each of these equipment types has variations that can either enhance or reduce the capacity for NIHL (e.g., enclosed versus open cabs), and/or have an effect on signal detection (e.g., muffler placement and its effect on alarm detection). One of the difficulties in attempting to make a connection between construction worksite noise and associated hearing loss is that one cannot reasonably conclude that the latter is caused by the former. Construction workers reported a myriad of outside-of-work activities that potentially could contribute to a loss of hearing (see Figure 2). Hunting, automobile and other vehicle racing, and equipment used in yard work and other chores are known to produce exposure levels that can contribute to and exacerbate NIHL (e.g., NIH, 1990). Other contributions to hearing loss may have come from previous employment. Many workers related that they had worked in other 'noisy' industries or jobs before their current construction position, including the military, machine shops, lumber/furniture industry, and automobile/truck repair.

Workers indicated that communication by voice and hearing was conducted for the purposes of “letting other employees know what to do” and for general “directions on the day’s work.” A majority of the respondents indicated that they either experience difficulty in hearing or being heard during these communications. When asked to explain why there was difficulty, the workers largely indicated that this was due to the noise produced from equipment and other tools. Respondents indicated that when worksite problems occur (e.g., emergency help, assistance, when other vehicles are dangerously close), they are first detected through the hearing sense, with the visual sense a close second. For other problems, such as load shifting or mechanical/hydraulic failure, workers relied on their sense of touch or smell.

Questionnaire respondents were also asked to relate any anecdotes of ‘critical incidents’ experienced over their work life, most of which alluded to the sense of hearing. One worker stated, “In 1979, while working on Eagle Rock Bridge, a runaway truck blowing its horn alerted us to stop traffic, possibly avoiding any accident.” Another worker related, “While operating a trackhoe with trucks backing into the work area, the backup alarm on the truck forewarned me and I was able to get out of the machine before being hit.”

Section II of the questionnaire elicited responses related to construction workers’ hearing. Almost twice as many workers answered ‘no’ to the question, “Are you concerned about your noise exposure at work,” while equal numbers answered yes or no to the question, “Are you concerned about your ability to hear warning signals at work?” Interestingly, all workers who responded agreed with the questions, “Do you feel that hearing is important to your job?” “If you feel that it is important, do you feel that it is also necessary?” and “Do you feel that your worksite is loud?” However, most workers answered “no” to the question, “After a workday, do you sometimes have difficulty hearing others talk or find it difficult to hear things (e.g., radio/TV)?” A majority of respondents indicated that they did not have any known hearing loss, while the responses were split when they were asked if they had had a hearing test. Of those who indicated that they did have a hearing loss, all responded that the loss was either “mild” or “moderate.” None of the respondents indicated that they wore a hearing aid. Finally, workers were asked about any hearing protection that they currently wore. A majority of respondents indicated that they did wear hearing protection when exposed to noise at work, but half indicated that they did so while engaging in leisure activities. Of those who did wear hearing protection, a majority indicated that they were in the form of earplugs as opposed to earmuffs.

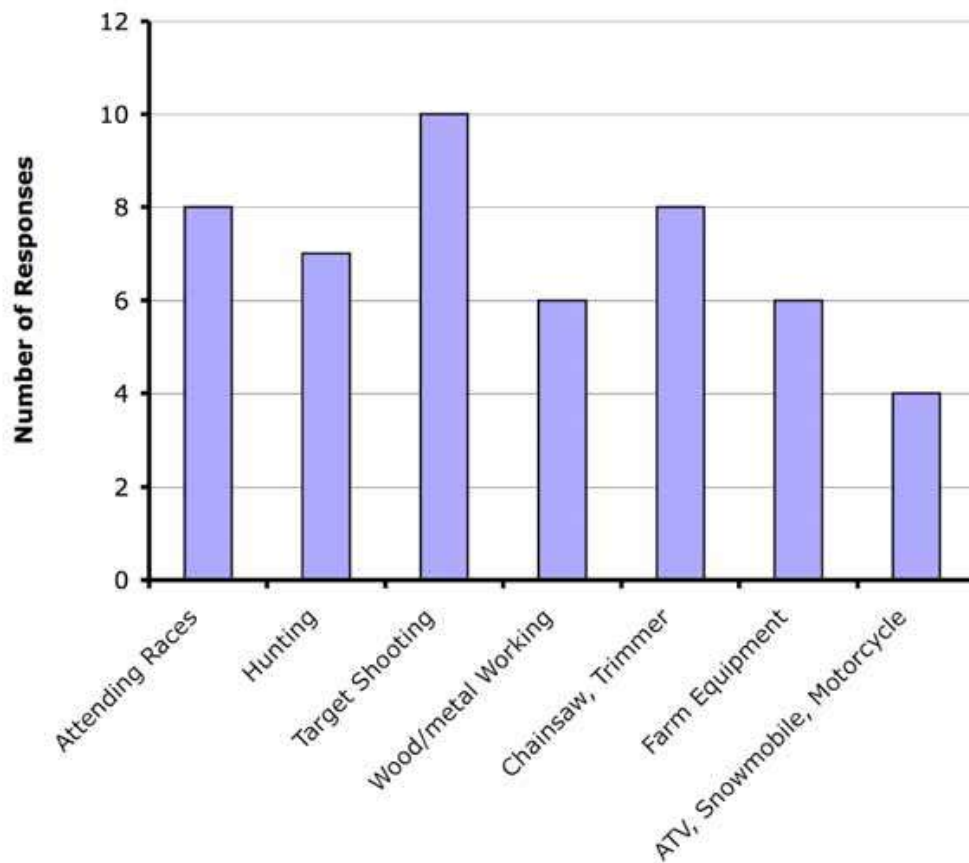


Figure 2. Outside-of-work activities as listed by construction workers from the questionnaire sample (Total of 13 respondents out of 75 questionnaires).

Based on the results from the received questionnaires, and from the aforementioned interviews with SMEs, it was determined that the research investigation should be concentrated within infrastructure operations (i.e., road construction) and, to a lesser extent, within commercial and industrial construction operations (e.g., stadium building, airport runway construction). These determinations were made because noise and signal detection issues have been related to be most prominent within these site types when compared to, for example, residential construction, which has (comparatively) few noise and/or signal issues that exist as impediments to communication or warnings which are hearing-critical. Finally, it was observed that noise and signal detection issues are most prominent within said infrastructure operations, where the injury and catastrophic potential is higher.

The questionnaire and SME interview data (descriptive data collection) helped to produce a task description task listing of various construction equipment whose operation includes a hearing-critical and/or safety component (see Table 2). The various equipment types and the operations conducted with them have specific alarms and/or signals that are integral to safety, and helped to determine the focus of subsequent site visits with respect to sound/signal and worker measurements (i.e., individual dosimetry for ground operators, signal measurement of specific equipment and their alarms, pre- and post-workday audiometry on volunteer workers)

at those sites. Due to the prevalence of backup alarms on most machines (as compared to other alarms which were much more isolated in application, as shown in Table 2), and the importance of backup alarms to construction site safety for the workers on the ground, the backup alarm was focused upon in the latter experimental stages of this research. The successful relationships that were established and maintained with various contractors were valuable to the research effort, as many of these organizations conducted operations throughout the state of Virginia.

These entities also gave the research team all of the necessary permission and rules for site access, thereby ensuring breadth and depth with respect to inclusion of the many types of infrastructure construction work as well as the environments in which they occur. The research team also underwent the necessary safety training for entering and working in road construction sites that were under the purview of VDOT. The research team continued to seek site access for all construction types, especially variations of infrastructure (emphasizing road milling/paving) operations, throughout the project. Thus, distribution of questionnaires to all construction workers at each identified site, and analysis and interpretation thereof, continued until this phase of the project was completed.

TABLE 2. Types of construction equipment that have signals and/or alarms.

Equipment Type/Operation	Signal or Alarm	Purpose of Signal or Alarm
Motor Grader	Alarm	Backup
Air Compressor	Alarm	Low Pressure Warning
Milling Machine	Alarm	Backup
Crane	Alarm	Overload, Backup, Load Lowering
Crawler Loader	Alarm	Backup
Dozer	Alarm	Backup
Excavator	Both	Backup, Movement, Off-balance
Forklift	Alarm	Backup, Load Lowering
Loader Backhoe (Wheeled)	Both	Backup, Horn, Movement
Scraper	Alarm	Backup
Skid Steer Compact Loader ('Bobcat')	Both	Backup, Off-balance
Trencher/Boring Machine/Cable Plow	Alarm	Backup
Dump Truck	Both	Backup, Horn, Turning
Water Pump Equipment	Alarm	Pressure Irregularity
Wheel Loader	Both	Backup, Turning, Brake Engage
Roller	Alarm	Backup

Activity Analysis

The final step of the task analysis was to verify that the task descriptive data collected within the previous steps did indeed represent actual worksite conditions, and that they were comprehensive with respect to the identification of jobs and tasks. This verification was

accomplished through two means: 1) SME review of the task descriptive data, and 2) visiting various construction sites to conduct naturalistic observations of their operations. Since tasks were identified that were both safety-critical and required the use of hearing, then the research team could be confident that subsequent interventions could be evaluated in later Phases based on whether or not they improved or supplemented human audition toward ensuring signal detection. Both the SME reviewers and the research team's site observations resulted in the judgment that the final job and task listing was complete and appropriate.

Element 2: Acoustical Measurements

As the information was gathered in Element 1 regarding noisy jobs, the noise environments in which these jobs are performed were characterized and quantified, as were the noise exposures (dose) of the affected workers. Full and/or 1/3 octave-band (OB) analyses (using a portable Larson-Davis real-time spectrum analyzer) were conducted to characterize the background and environmental noise levels and spectra. For example, vehicle backup alarm spectra were compared with both ambient (i.e., general construction site) noise and equipment-specific noise spectra to determine the signal-to-noise ratio (S/N) for current conditions, which is useful for assessing the influence of the noise environment towards worker detection and recognition of signals and alarms, and for suggesting possible interventions to improve detection and recognition ability.

Portable dosimeters (Quest Q-300) worn by workers during their daily work activities were used to quantify individual noise exposures. Dosimeters were also placed in noisy areas and in the vicinity of noisy machinery to determine the dose for any individual who must work near the machine for an entire work shift. In addition, information as to the brand and model of the hearing protectors currently worn by individuals in each of the jobs analyzed were obtained (there were very few protectors observed in use). Signal recording of signals and noise for laboratory reproduction (e.g., equipment engine noise, in-cab and external signals) onto digital audiotape (DAT) was also conducted. Finally, pre- and post-shift audiometry was performed using portable audiometers (Beltone 119 MicroLab portable audiometer). These data provided an indication if exposures were sufficient to cause a temporary threshold shift which, in turn, could indicate the potential for permanent NIHL. Each of these data sets are presented and discussed in turn.

Equipment, Machine, and Background Noise Spectra and Levels. In addition to characterizing the background noise and individual noise exposures, the non-verbal signals identified in Element 1 were also characterized in terms of their levels and spectra using 1/3 OB (or narrow-band) analysis. For intentional non-verbal auditory displays (primarily alarms, as opposed to incidental sounds), the device manufacturer's information (alarm type, manufacturer, model number, part number, etc.) was obtained whenever possible. Doing so allowed the research team to obtain more detailed information about the design of the alarm from the device manufacturer. Specific backup alarms (Preco 370, 6003, 6011, and SAS215) were provided by the manufacturer to enable more accurate measurements to be obtained in a laboratory environment, and to conduct the subsequent assessment and intervention studies in later Phases. As mentioned, as the various background noises and non-auditory sounds were characterized, they were also recorded. This allowed the sounds to be reproduced in later portions of the research effort dealing with masked threshold determinations.

Over 300 noise measurements were taken (i.e., min, max, Leq with 3 dB exchange rate,

spectra) for approximately 50 different types of equipment (e.g., milling machines, dozers, cranes, trucks, chainsaws, drills, augers) and background noises (e.g., traffic noise, airport runway noise) for this study, see Figure 3 and Table 3. The Research Team measured and catalogued many noises surrounding workers at road and other construction sites, and nearly all were significant in terms of sound level and projected duration. What is immediately notable in Figure 3 is that many of the short-term average (i.e., Leq) noise levels would approach or exceed OSHA general industry exposure “action” levels (i.e., 85 dBA TWA if projected over an 8-hour day, even using the arguably more conservative 3 dB exchange rate as taken in this instance, as opposed to OSHA’s 5 dB exchange rate), and several of them would exceed OSHA’s general industry exposure “criterion” level of 90 dBA TWA. (It should also be noted that the 1971 OSHA construction regulation [OSHA, 1971] consists only of the 90 dBA TWA “criterion” level, and unfortunately OSHA has never adopted an “action” level toward implementation of a full hearing conservation program for construction workers in the same vein as it did in 1983 for general industry [OSHA, 1983].) It is also of significant concern that the maximum sound level values reached during a particular measurement period (i.e., ‘max’ setting) averaged over 100 dBA across all measured equipment shown in Figure 3.

Road milling operations were measured and found to consistently produce maximum sound pressure levels in excess of 100 dBA (e.g., 103 dBA for a paving machine, 105 dBA for a high-frequency roller), and some non-road operations have produced similar levels (e.g., 101 dBA for a hydraulic excavator, 103 dBA for a bulldozer involved in earth-moving work), and Leq values in the mid-90 dBA range. Workers on and around milling machines (and the equipment that supports its operations, such as Broche Brooms) were not observed to wear any hearing protection at any of the 14 infrastructure construction sites that were visited, which covers a sample of over 500 workers. Some interviewed workers provided anecdotes regarding their individual noise concerns—and in one instance, a worker managed to persuade his employer to purchase an enclosed cab to reduce noise and dust exposure. Measurements on other operations indicated very intense noise levels as well, including earth moving, drilling, and crane work, all documented in Figure 3 and Table 3.

The aforementioned sound level measurements provided the research team with the information needed to determine which jobs/tasks and operations required further data collection with respect to worker noise dose, time-weighted average (TWA) values, and to target possible threshold shifts of exposed workers through pre- and post-workday audiograms.

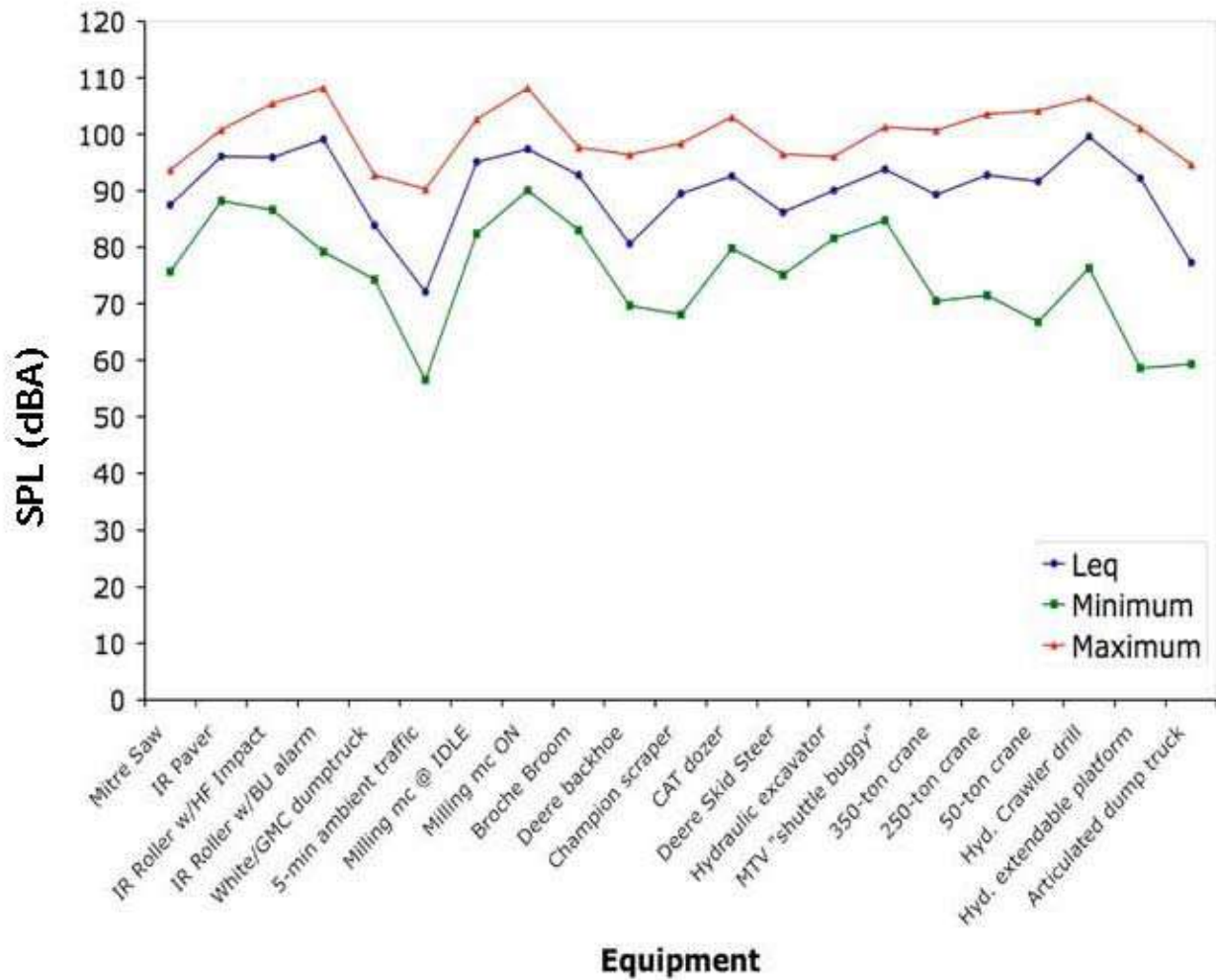


Figure 3. Construction equipment and ambient (background) noise levels as measured at various construction sites by the research team.

TABLE 3. Construction equipment and ambient (background) noise levels (dB) as measured at various construction sites; Leq obtained with 3 dB exchange rate and measurement time given in first row.

Device	Mitre Saw	IR Paver	IR Roller w/HF Impact	IR Roller w/BU alarm	White/GMC dumptruck
Measure Time (sec)	10.0	33.3	21.8	12.8	10.4
Leq	87.5	96.1	95.9	99.1	83.9
Min	75.7	88.2	86.6	79.2	74.3
Max	93.7	100.8	105.5	108.2	92.8

Device	5-min ambient traffic	Milling mc @ IDLE	Milling mc ON	Broche Broom	Deere backhoe
Measure Time (sec)	300.0	31.1	125.3	28.8	89.2
Leq	72.1	95.1	97.4	92.8	80.6
Min	56.5	82.4	90.1	83.0	69.7
Max	90.3	102.7	108.2	97.7	96.4

Device	Champion scraper	CAT dozer	Deere Skid Steer	Hydraulic excavator	MTV "Shuttle Buggy"	350-ton crane
Measure Time (sec)	21.6	30.7	31.4	31.1	48.1	89.7
Leq	89.5	92.6	86.2	90.1	93.8	89.3
Min	68.1	79.8	75.1	81.6	84.8	70.5
Max	98.4	103.1	96.5	96.1	101.3	100.7

Device	250-ton crane	50-ton crane	Hyd. Crawler drill	Hyd. extendable platform	Articulated dump truck
Measure Time (sec)	217.3	379.8	76.4	224.3	504.2
Leq	92.8	91.7	99.6	92.2	77.3
Min	71.5	66.8	76.3	58.6	59.3
Max	103.6	104.2	106.5	101.1	94.6

Dosimetry. Personal dosimetry data, in concert with pre- and post-workday audiograms of workers, were collected using Quest Q-300 dosimeters to assess exposures and to identify threshold shifts. Dosimeter data collection on individual workers and near noisy areas was conducted (n = 14), as were noise dose data on specific equipment and in ambient conditions. Workers for whom dosimetry data were captured also participated in pre- and post-workday audiograms which, when evaluated with the noise spectra and levels for the equipment operated on that day by those workers, provided a complete ‘noise picture’ with which to ascertain the impediments to speech and signal detection for particular operations utilizing particular equipment, and to help determine appropriate interventions to support signal detection.

Dosimetry data showed noise exposures (8-hour TWA, 5 dB exchange rate) that exceeded the OSHA industry exposure “action” level for all but one measured worker, with most TWA measures over the OSHA “criterion” level of (Figure 4). Workers operating these pieces of equipment have often been exposed to OSHA noise doses of well over 250% (where 100% is the maximum allowable).

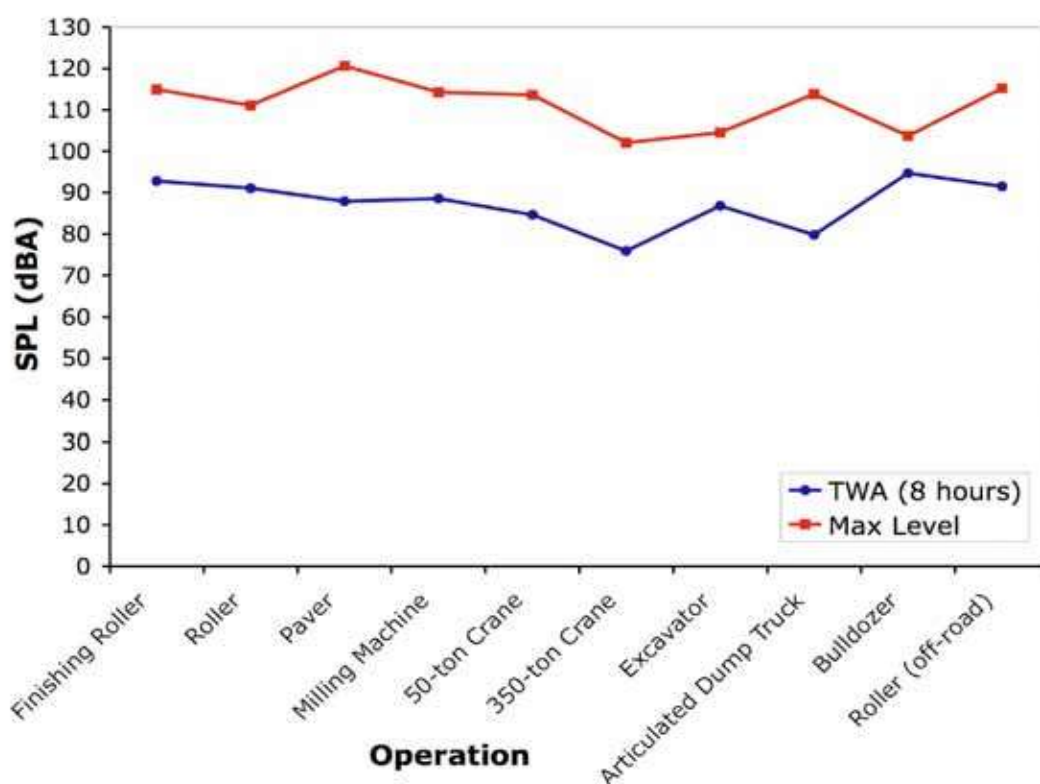


Figure 4. Time-weighted average exposure and maximum sound pressure levels for various construction equipment operators.

Pre- and post-workday audiograms indicated temporary threshold shifts (TTS) for all workers with the exception of one, who was noted to routinely wear earplugs (n = 10, see Figure 5). This worker, compared with another who operated the same equipment (chainsaw) for an entire shift and who did not wear earplugs, did not experience a threshold shift as compared to

the unprotected worker. The particular earth-moving operations site at which these data were collected was the only site at which HPDs were found to be offered to workers. The threshold shift between the protected and unprotected worker is quite dramatic, especially in the mid-frequencies (i.e., 1000-4000 Hz). As earth-moving and infrastructure activities often have various equipment (e.g., dozers, articulated dump trucks) conducting operations nearby a given operator, such a hearing shift in this frequency region can be expected to degrade the detection and recognition of the vehicular backup alarms, which present most of their energy at or around 1250 Hz, with a significant harmonic at 2500 Hz (see Figure 6).

Figure 7 displays the mean TTS for nine earth-moving vehicle operators whose pre- and post-workday audiograms were collected. The amount of TTS ranges from about 2 to 8 dB, depending upon frequency.

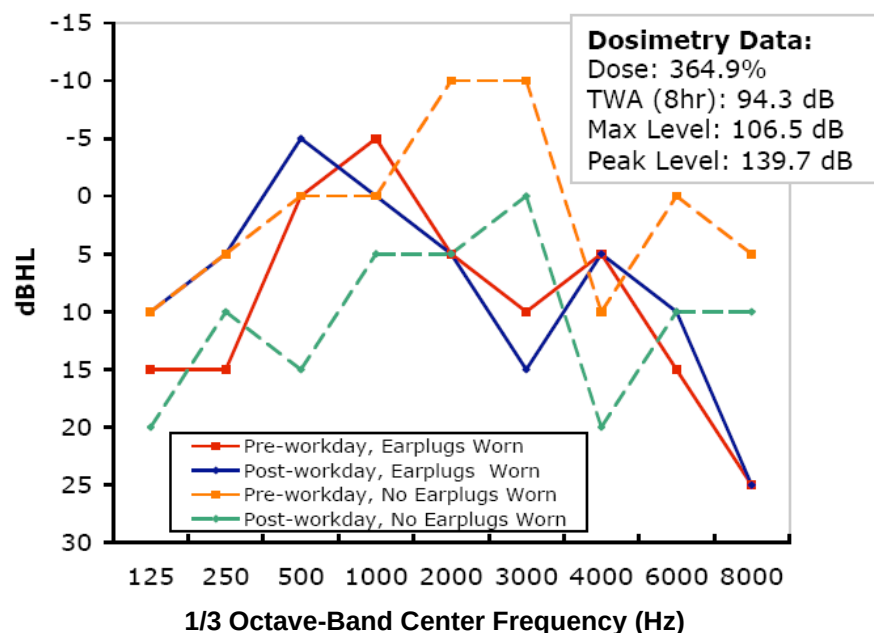


Figure 5. Worse-ear pre-post workday hearing thresholds and exposures for two workers who operated a chainsaw. One worker wore earplugs during the operations, and the other did not. (Lower on Y-axis represents better hearing.)

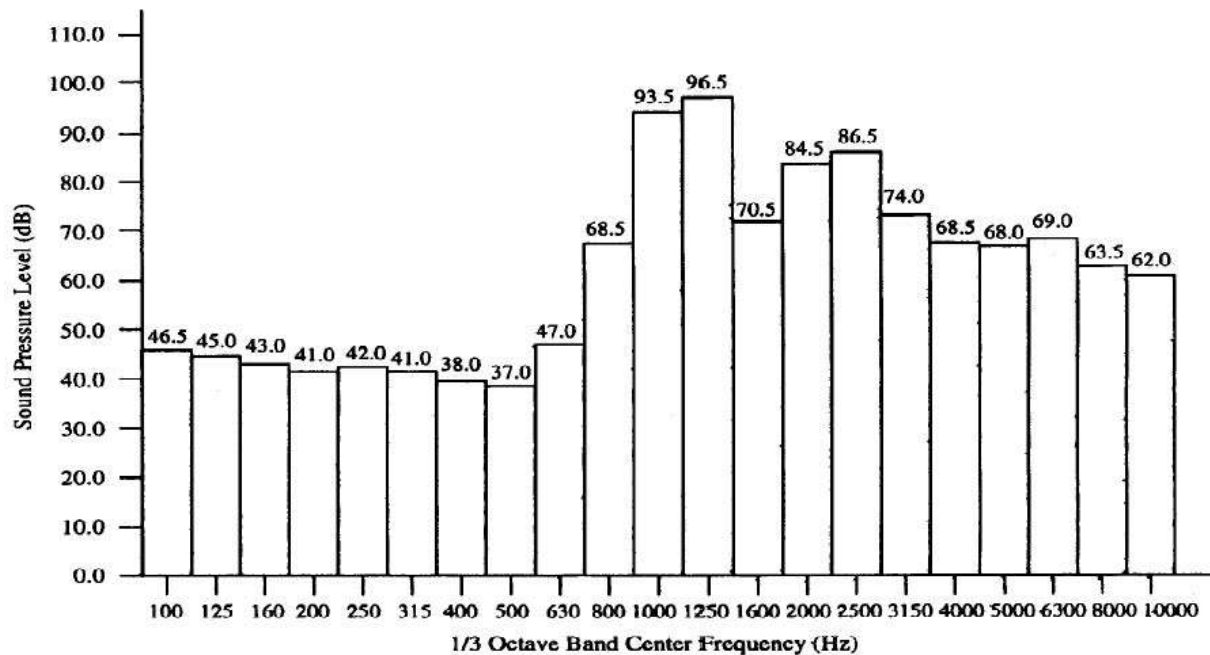


Figure 6. Backup alarm spectrum. Note the peak energy at 1250 Hz, which is the backup alarm primary frequency (Adapted from Casali, Dabney, Robinson, and Gauger, 2004).

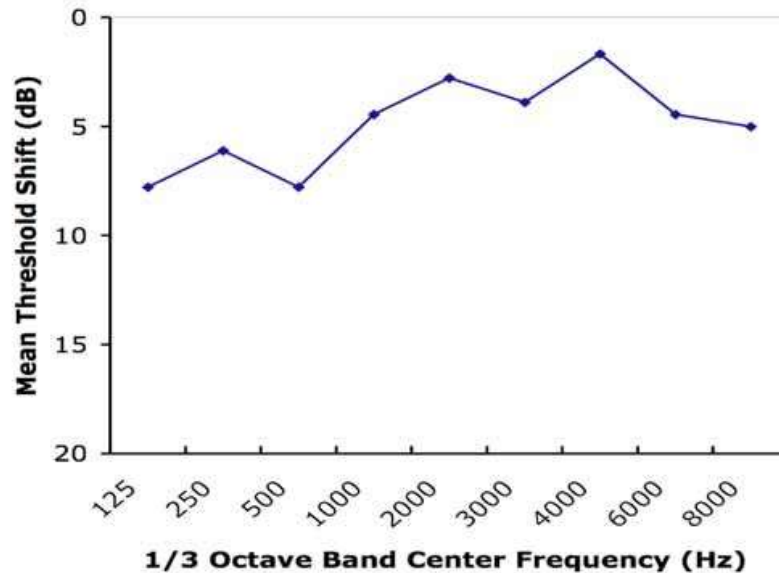


Figure 7. Mean worse-ear temporary threshold shift (TTS) for ten earth moving equipment operators after an 8-10 hour workday.

An enclosed cab can help to mitigate or remove noise exposure for the operator. While these engineering controls in the form of cab enclosures are becoming more commonplace, there still exists a large number of 'legacy' vehicles that do not have them and, as a result, the operators of such equipment are exposed to increased intensities of noise when compared to

equipment types that do have them—noise largely from the equipment itself, although some noise may emanate from the ambient environment, and from other machines operating nearby. Many equipment operators ‘specialize’ in their work—that is, a worker may operate a bulldozer each and every day, while others are capable of operating a variety of different equipment. The effect of an enclosed cab versus an open one on noise exposure and its accompanying effects can be seen in Figures 8 and 9. Figure 8 displays the exposure data and TTS of a bulldozer operator whose equipment did not have an enclosure. While the TTS is notable, the pre-workday audiogram may have resulted from years of exposure operating this particular machine, without an enclosed cab, leading to a permanent threshold shift (PTS), although as noted earlier, one cannot be entirely sure whether or not the shift was due strictly to work activities, or if it was due to a previous job or leisure exposures. The TTS, noise dose, TWA, etc. paint quite a negative picture of noise exposure for this individual.

Both pieces of equipment, while different in operation, produced similar average (Leq) noise levels (i.e., 92.6 dBA for the dozer and 90.1 dBA for the excavator), yet it is quite clear the effect that an enclosed cab had on noise dose (i.e., 253% for the dozer, and 64.2% for the excavator).

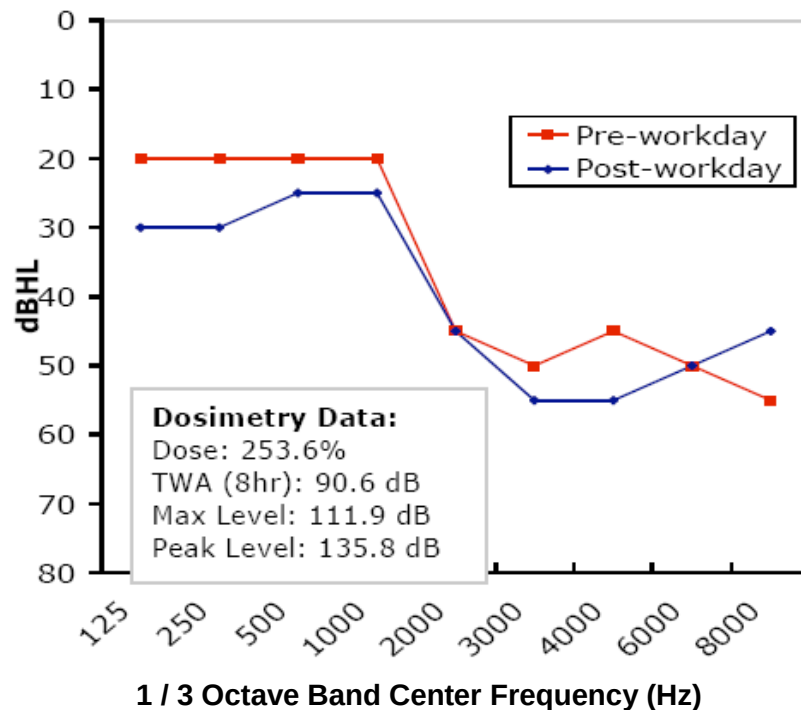


Figure 8. Worse-ear TTS and exposure data for an operator of an open-cab bulldozer.

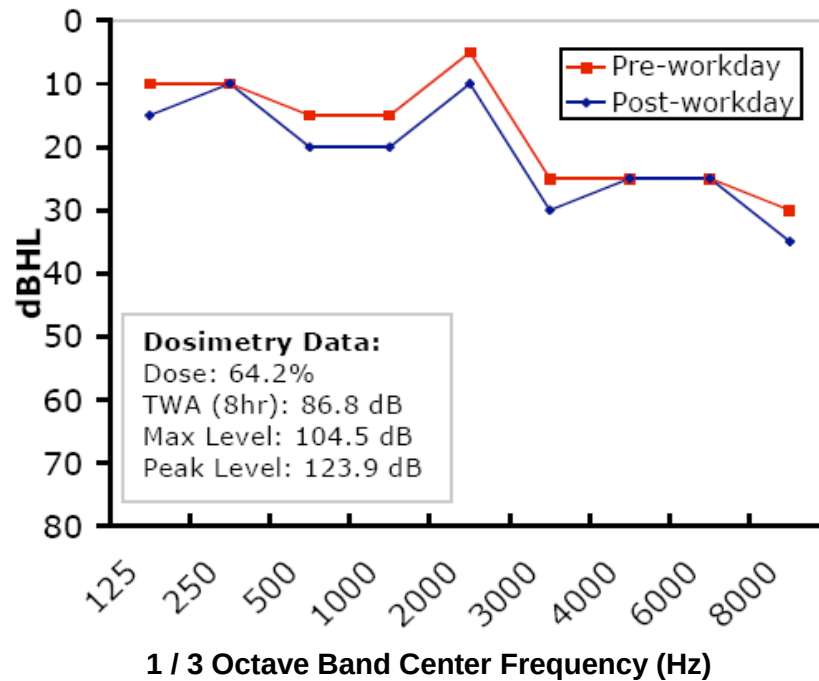


Figure 9. Worse-ear TTS and exposure data for an operator of an enclosed-cab hydraulic excavator.

Exposure data also indicated a substantial noise dose for the operators of several different types/kinds of construction equipment (see Figure 10). The noise dose for a paving machine operator was measured to be 570%, a value that exceeds the maximum allowable 100% dose quite dramatically. As can be seen in Figure 10, most operations that produced TWA levels of 90 dBA and above resulted in much higher noise doses. Conversely, for those operations that either approached a TWA of 90 dBA but did not exceed it, or were below the OSHA action level of 85 dBA (i.e., 50% noise dose), while not quite reaching a 100% noise dose, certainly approached it (e.g., 350-ton crane operator [96% noise dose], scraper operator [89% noise dose]). Again, at only one construction site, across all sites visited, was a worker (and only one at that) seen to be wearing hearing protection. One 73-year old dozer operator who indicated that he had worked in construction since he was 16 represented a compelling example of the effects of continued, unprotected noise exposure (see Figure 11). This worker's pre- and post-workday audiogram barely changed (perhaps due to the already large hearing loss), but significant PTS is obviously apparent in the audiograms. Anecdotes from this individual described a difficult home life, at which his wife was "getting tired of me saying 'what?' all of the time." Speaking with this operator, it was interesting to note that he had apparently resorted to lip-reading when conversing with others, as he simply could not hear normal speech. This condition is not too surprising when his audiogram is considered—most of the frequencies containing human speech (i.e., 1000-4000 Hz) were considerably elevated, and likely went beyond the audiogram limit of 70 dBHL (the research team did not present pure tones above that hearing level). This worker indicated that he rarely, if ever, wore hearing protection, even though his exposure (239 % noise dose, 96.3 dB TWA) most certainly warranted it.

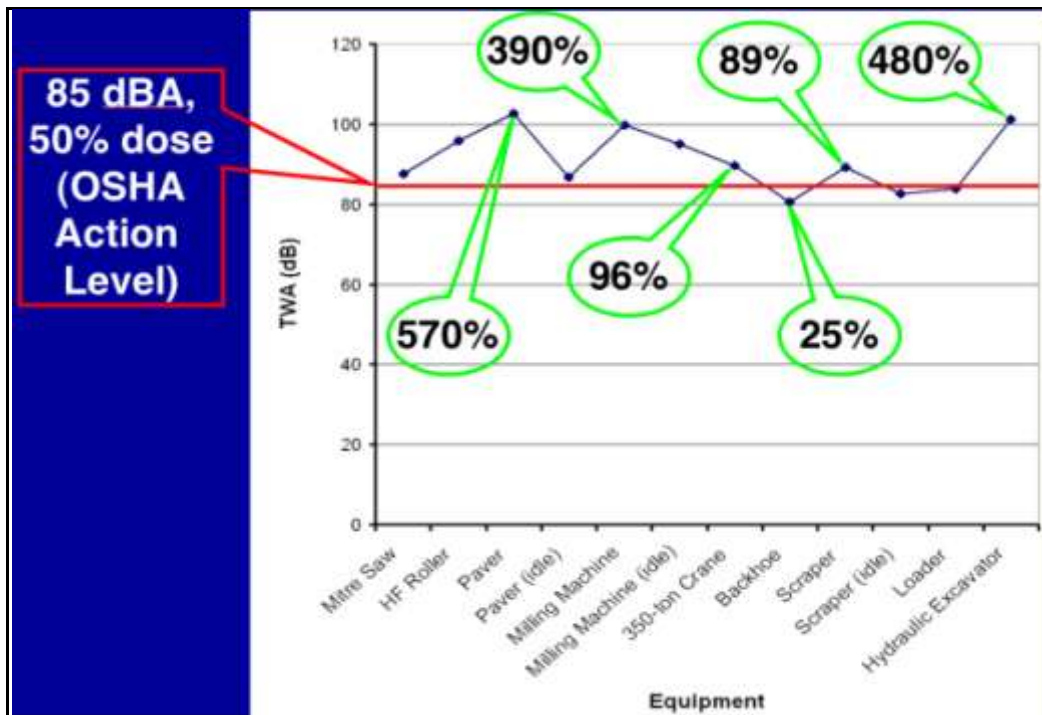


Figure 10. TWA and noise dose for various construction equipment operators, with the OSHA ‘action’ level depicted for reference.

Other operations with respect to road construction were measured to produce TWA values and noise doses that clearly exceeded OSHA action (i.e., 85 dBA TWA) and criterion (i.e., 90 dBA TWA) levels, as well as maximum levels and true peak values that exceeded OSHA limits on those metrics (see Table 4). Roller and paver operators are exposed to noise levels that far exceed OSHA allowable levels. Just on the maximum level alone (i.e., the maximum RMS [root mean square] sound level with a time constant [slow] applied), and without even taking into account the TWA and noise dose values, the paver operator was exposed to levels that were above the OSHA ‘never exceed’ maximum limit of 115 dBA (the finishing roller operator was also essentially at that limit at 114.9 dBA).

Clearly, the noise levels and exposures for operators in road and earth-moving construction operations often meet and exceed safe limits. Continued exposure appears to lead to TTS, which may ultimately progress into PTS, which itself leads to NIHL. While the workers’ off-the-job exposures may also contribute to their NIHL, there is no question that the on-the-job construction exposures are, in many cases, hazardous to hearing. Furthermore, these noise conditions have a direct impact on construction workers’ ability to detect and recognize operational signals such as backup alarms because of their masking effects. It is these conditions for which the evaluations and interventions conducted within the next two research Phases sought to address.

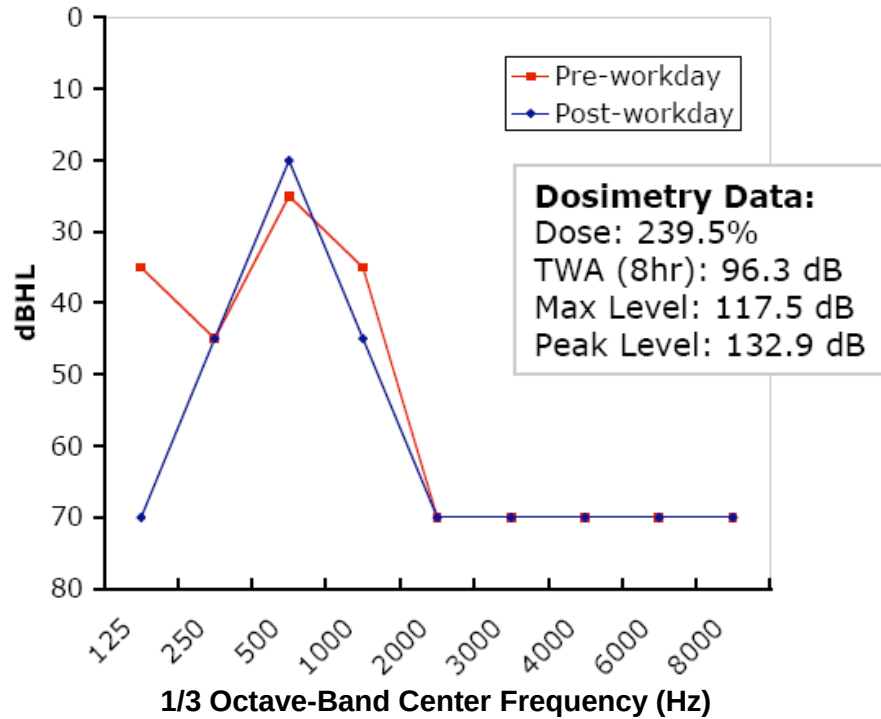


Figure 11. Pre- and post-workday audiogram, noise dose, TWA, maximum and peak level data for a 73 year-old dozer operator, who had been working in construction for 57 years, reportedly without wearing any hearing protection throughout that time.

TABLE 4. Operator TWA, noise dose, maximum and peak levels for various infrastructure construction equipment operators.

Operation	Equipment	TWA	8 hour Dose	Max Level	Peak Level
Finishing Roller Operator	Ingersoll-Rand DD110-HF	92.8 dB	609.6%	114.9 dB	142.7 dB
Roller Operator	Ingersoll-Rand DD90-HF	91.1 dB	407.1%	111.1 dB	132.4 dB
Paver Operator	Ingersoll-Rand PF-4410	88.3 dB	156.5%	118.6 dB	140.4 dB

Phase II - Quantifying the Magnitude of the Problems/Impediments

With the copious amount of data collected across various construction sites with respect to their noise levels, spectra, noise dose, TWA values, and maximum and peak levels across various equipment, the research team was then able to ascertain (quantify) the magnitude of the problems for construction workers in detecting the operational signals that they need to hear, with an eye toward increased operational safety.

The masking of essential signals by background noise is a source of concern in any environment that relies on the use of auditory signals. Various studies (e.g., Suter, 1989; Casali et al., 2004) have revealed that, in noisy environments, an unoccluded ear (i.e., one without an HPD) has difficulty in perceiving speech or other auditory cues. This difficulty arises mainly because of the distortion that results in the cochlea (i.e., ‘cochlear distortion’) at high sound levels. The use of HPDs tends to reduce this distortion, making it easier, in some situations with some HPDs, for normal-hearing listeners to perceive speech and other essential operational cues. Research has also shown that hearing is the primary warning sense, in that a sound that is loud enough in contrast to the background noise will be heard, and there is nothing that one can do in terms of completely blocking out the sound. Contrary to that contention, in the sense of vision, one needs to be looking at the correct place at the right time (using foveal vision), and as such one can easily ignore or miss visual stimuli. However, many of the situations wherein auditory warnings are necessary and in fact, critical, are pervaded by intense noise levels, such as in the construction environment.

In noisy environments such as in construction, an auditory signal has to be presented at a higher sound pressure level (SPL) than in a quiet environment for that signal to be heard by the workers in the vicinity. This is because the condition of one sound (in the case of construction, ambient and equipment operational noise combined) reduces the sensitivity of the ear to the other sound (the auditory signal; e.g., a backup alarm). This reduction in sensitivity is due to a phenomenon called masking, which can be defined as the dB amount by which the absolute threshold of a sound (masked sound) is raised in the presence of another sound (masking sound). An operational definition from signal detection theory is that masked threshold is the signal level in dB required for 75% correct detection of a signal when presented to the listener in a two-interval task, wherein the listener reports which one of the two listening intervals randomly contains the signal (both intervals contain the same noise). In psychophysics, this would be 50% correct for the listening interval.

There are three basic principles, or types, of masking that can occur. The first is pure tone masking, a condition wherein a tonal signal (i.e., a single frequency) is masked by another tonal noise (the masking tone). The phenomenon of upward spread of masking often occurs, wherein high intensity, low frequency sounds reduce one's ability to hear higher signal frequencies; however, the reverse (downward spread) does not happen, at least not as readily. Another type of masking is masking of a tonal signal by narrow bands of noise. Narrow bands of noise are more efficient maskers than are pure tones, and result in upward spread of masking as well, but the masking is not as complicated as with pure tones. The third type of masking is that by broadband noise (i.e., many different frequencies). Broadband noise is sometimes referred to as 'white' noise (equal energy across all frequencies), or 'pink' noise (equal energy across octaves), although these are just two common types. Since broadband noise contains all pure tones, all pure tone signals (such as the backup alarm primary frequency and its harmonics) are masked with considerable efficiency. Further, there is a linear increase of masked threshold with increase of masking noise level. Among the different types of masking noted here, masking by broadband noise is the primary issue at construction sites, wherein many different types of equipment and the ambient environment combine to produce a cacophony of broad-spectrum noise that can mask the detection of operational signals, such as the backup alarms that are overwhelmingly prevalent at construction sites (see Table 2).

There are several techniques with which to predict masked threshold, including Detectsound (Laroche, Quoc, Hetu, and McDuff, 1991), critical band theory, and through the ISO 7731-2003 standard: Ergonomics—danger signals for public and work areas—auditory danger signals. Detectsound is a computerized model that can predict the capability of workers to detect auditory warning signals in noise. Critical band theory represents the narrow range of frequencies above and below a particular frequency that represents a 'sphere of influence' of that sound (i.e., the critical band). However, at SPLs above about 50 dB, the critical band concept is of limited value for predicting the masked threshold of a particular tone because sounds outside of that band influence the threshold, whether or not the masker is lower or higher in frequency, although the amount of masking is greater for frequencies near to the masked signal, called direct masking.

ISO 7731-2003 is the appropriate applicable standard for the prediction of masked threshold for operational signals in the high-noise construction environment. This international standard specifies the physical principles of design, ergonomic requirements and the corresponding test methods for danger signals for public and work areas in the signal reception area, and provides guidelines for the design of these signals. The ISO 7731 standard states that any danger signal must be clearly audible, and the effective masked threshold must be distinctly exceeded, and includes masked threshold calculations between 500-2500 Hz specific to measurements taken in any one of three methods:

- 1) **Method A:** for measurements of the A-weighted SPL, the difference between the two A-weighted SPLs of the signal and the ambient noise shall be greater than 15 dB ($L_{S,A} - L_{N,A} > 15 \text{ dB}$).
- 2) **Method B:** for measurements of the octave-band SPL, the SPL of the signal in one or more octave-bands shall exceed the effective masked threshold by at least 10 dB in the octave-band under consideration ($L_{Si,oct} - L_{Ti,oct} > 10 \text{ dB}$).

3)**Method C:** for measurements of the 1/3-octave band SPL, the SPL of the signal in one or more 1/3-octave bands shall exceed the effective masked threshold by 13 dB in the 1/3-octave band under consideration ($L_{Si,1/3oct} - L_{Ti,1/3oct} > 13 \text{ dB}$).

All of the measurements taken in Element 2 were in 1/3-octave bands; therefore, Method C is appropriate. For method C, the calculations are made thus:

Step 1: In the lowest 1/3-octave band, $i=1$

$$L_{Ti} = L_{Ni}$$

Where: L_{Ni} is the noise level measured in 1/3-octave band i .

Step 2: For each subsequent 1/3-octave band, i , the masked threshold (L_{Ti}), is the greater value of the either the noise level in that band or the masked threshold value in the immediately previous band ($i - 1$). (The previous band computation accounts for upward spread of masking.)

$$L_{Ti} = \max(L_{Ni}, L_{T(i-1)} - C)$$

Where $C = 2.5 \text{ dB}$ for 1/3-octave band data.

Repeat step i for $i=2 \dots$ up to the highest 1/3-octave band.

Unless operational signals automatically adjust to accommodate any ambient noise (e.g., as with an automatic gain control), the threshold of a signal is elevated within that noise, and this elevated threshold (the masked threshold) must be exceeded by the signal for detection. The construction equipment and worksite ambient measures presented previously indicate intense noise levels; thus, signal masking is the major issue confronting construction workers' detection of operational signals such as backup alarms.

With respect to signal detection, one has to take into account any ambient noise that may elevate a listener's threshold for signal detection. In an example of this, an ambient airport runway noise spectrum has been plotted along with the noise spectrum of a dump truck that had its backup alarm in operation (i.e., the 'signal,' measured at approximately 10 feet from the dump truck). Construction activities at this particular site involved earth moving operations and the paving of a new runway at an airport (akin to highway paving). To calculate the 1/3-octave band masked threshold of the dump truck's backup alarm and how it relates to the ambient noise, one needs to consider the noise energy in the critical bands that contain the center frequencies of interest (in this case, the 1250 backup alarm frequency and the 2500 Hz backup alarm frequency harmonic). Application of ISO 7731 to this particular signal detection issue indicates that the dump truck's backup alarm frequency (and its harmonic) could not be reliably audible in the noise conditions. At 1250 Hz, the backup alarm signal would need to be presented (at the listener's position) at 95.1 dB for it to be reliably detected (and at 87.6 dB for its 2500 Hz harmonic) by a worker. The actual measured level of 84.5 dB at 1250 Hz (and 61 dB at 2500 Hz) is simply not at a sufficient intensity for reliable detection (see Table 5 and Figure 12).

TABLE 5. Masked threshold of a dump truck backup alarm within airport runway construction noise, per ISO 7731-2003.

1/3 OB Center, Hz	Ambient Noise, dB	Masked Threshold, dB	Masked Threshold +13 dB	Signaling Device Level, dB
500	77.2	77.2	90.2	65.7
630	83.7	83.7	96.7	66.4
800	87.1	87.1	100.1	67.7
1000	79.8	84.6	97.6	68.1
<i>1250</i>	<i>77.0</i>	<i>82.1</i>	<i>95.1</i>	<i>84.5</i>
1600	75.2	79.6	92.6	62.6
2000	72.5	77.1	90.1	63.1
<i>2500</i>	<i>70.2</i>	<i>74.6</i>	<i>87.6</i>	<i>61.0</i>

Note: Bold values indicate a masked threshold level higher than the corresponding band level, and italic values represent the frequencies of interest in the backup alarm.

Table 5 is but one example of how construction noise interferes with the audibility of operational safety signals. Similar calculations have been made for the detection of signals within the noise produced from various other equipment within background noise, with the same result: the conditions are too noisy to allow reliable alarm and signal detection. Application of ISO 7731 to the signal detection issue of a backup-alarm annunciating Roller vehicle indicates that its backup alarm frequency (and its harmonic) also would not be reliably audible at the closest ground worker position in road construction noise conditions. At 1250 Hz, the backup alarm signal would need to be presented (at the listener's position) at 88.5 dB for it to be reliably detected (and at 84.8 dB for its 2500 Hz harmonic) by a worker. The current level of 75.0 dB at 1250 Hz (and 70.2 dB at 2500 Hz) is simply not at a sufficient intensity for reliable detection (see Table 6 and Figure 13).

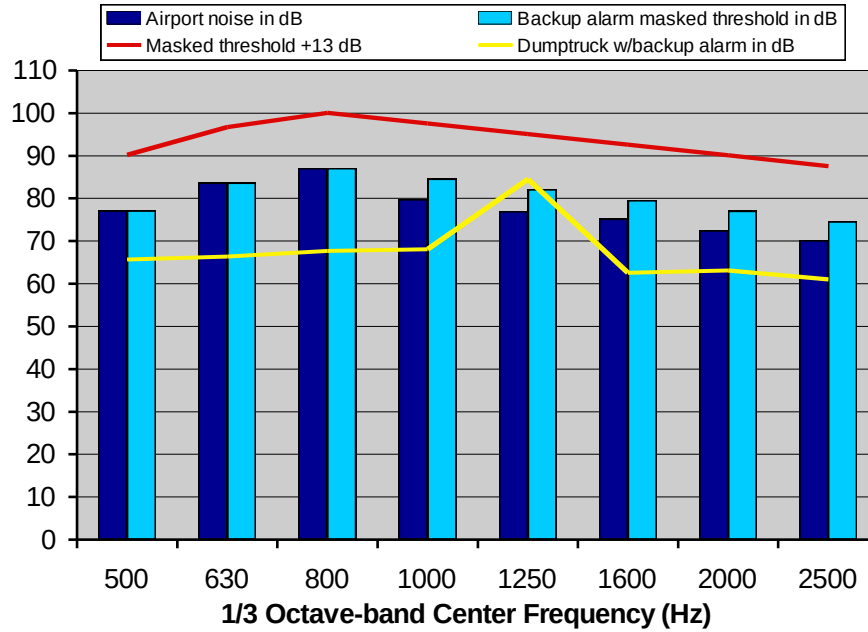


Figure 12. Plot of Mack dump truck noise (with actuating backup alarm), ambient airport runway construction noise spectra, backup alarm masked threshold, and masked threshold +13 dB, calculated per ISO 7731-2003. Note how the backup alarm primary frequency (84.5 dB @ 1250 Hz) is partially masked by the airport noise at that frequency (77 dB @ 1250 Hz).

Applying the standard again to the signal detection issue of a backup-alarm-annunciating Road Milling machine indicates that its backup alarm frequency (and its harmonic) could not be reliably audible in the ambient traffic noise conditions of a road construction site. At 1000 Hz, the backup alarm signal would need to be presented (at the listener's position) at 98.6 dB for it to be reliably detected (and at 92.8 dB for its 2000 Hz harmonic) by a worker. The current level of 92.5 dB at 1000 Hz (and 81.1 dB at 2000 Hz) is simply not at a sufficient intensity for reliable detection (see Table 7 and Figure 14).

TABLE 6. Masked threshold of a Roller's backup alarm within road construction noise.

1/3 OB Center, Hz	Ambient Noise, dB	Masked Threshold, dB	Masked Threshold +13 dB	Signaling Device Level, dB
500	75.5	75.5	88.5	87.6
630	78.8	78.8	91.8	74.4
800	78.6	78.6	91.6	74.6
1000	78.0	78.0	91.0	73.1
1250	74.5	75.5	88.5	75.0
1600	73.9	73.9	86.9	71.4
2000	71.0	71.4	84.4	70.8
2500	71.8	71.8	84.8	70.2

Note: Bold values indicate a masked threshold level higher than the corresponding band level, and italic values represent the frequencies of interest in the backup alarm.

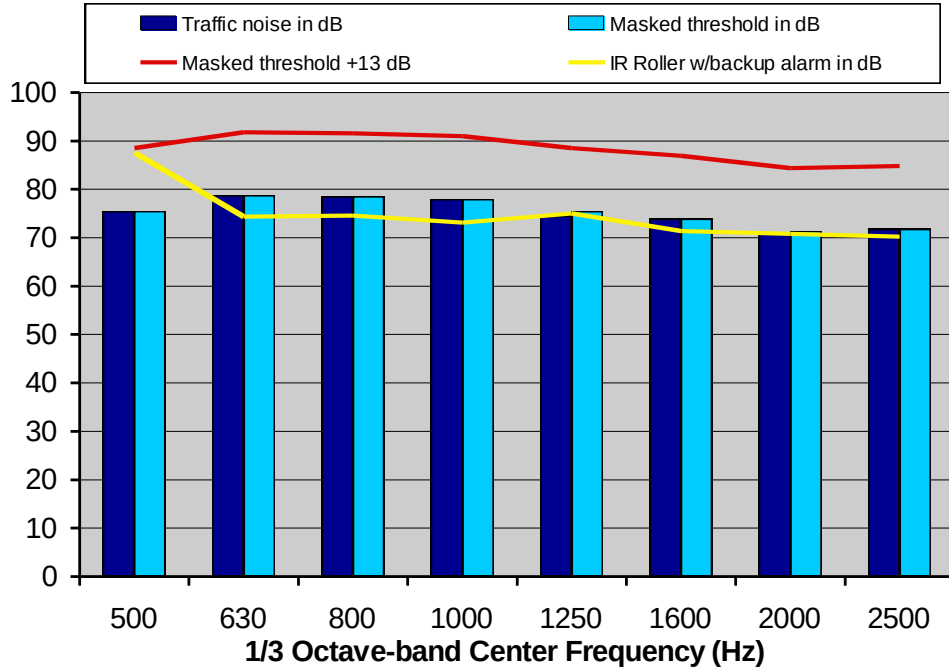


Figure 13. Plot of Ingersoll-Rand Roller noise (with actuating backup alarm), ambient road construction traffic noise spectra, backup alarm masked threshold, and masked threshold +13 dB, calculated per ISO 7731-2003. Note how the backup alarm primary frequency (75.0 dB @ 1250 Hz) is partially masked by the traffic noise at that frequency (74.5 dB @ 1250 Hz).

TABLE 7. Masked threshold of a Road Milling Machine's backup alarm within ambient road construction traffic noise.

1/3 OB Center, Hz	Ambient Noise, dB	Masked Threshold, dB	Masked Threshold +13 dB	Signaling Device Level, dB
500	89.3	89.3	102.3	79.5
630	89.2	89.2	102.2	80.7
800	87.1	87.1	100.1	78.7
<i>1000</i>	<i>85.6</i>	<i>85.6</i>	<i>98.6</i>	<i>92.5</i>
1250	84.6	84.6	97.6	81.7
1600	82.1	82.1	95.1	77.7
<i>2000</i>	<i>79.8</i>	<i>79.8</i>	<i>92.8</i>	<i>81.1</i>
2500	79.2	79.2	92.2	77.9

Note: Italic values represent the frequencies of interest in the backup alarm.

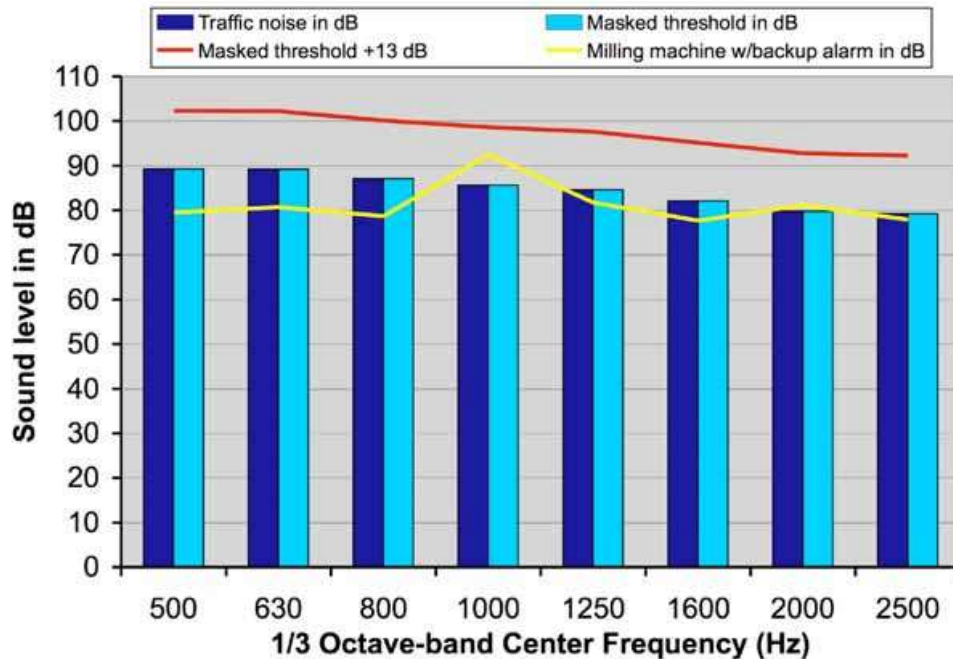


Figure 14. Plot of Road Milling Machine noise (with actuating backup alarm), ambient road construction traffic noise spectra, backup alarm masked threshold, and masked threshold +13 dB, calculated per ISO 7731-2003. Although the traffic noise does not appear to mask the Milling Machine's backup alarm, the alarm cannot be reliably detected according to the ISO standard.

The masked threshold calculations presented above suggest that construction workers cannot be expected to reliably detect operational backup alarm signals across a range of measured noise environments. As a result, interventions are warranted that increase the signal-to-noise ratio (S/N) between the warning signal and the ambient noise, while providing concomitant hearing protection, such that workers can more reliably detect backup alarms (and other warning signals). Phase III below outlines efforts that were made to address this need.

Phase III - Determining/Developing Appropriate Interventions to Mitigate or Eliminate the Impediments

With the prevailing high noise exposure levels that construction workers face, various forms of interventions may be applied to help reduce these exposure levels. As a way to alleviate such exposures, different prevention strategies can be used, which are generally within one of the following three categories:

- 1 Engineering controls
- 2 Administrative controls
- 3 Personal protective equipment (PPE)

Engineering controls are considered one of the most effective and best long-term solutions of controlling noise hazards. This is because engineering controls reduce the

hazardous noise levels right at the source and/or in its path—in other words, before the exposure reaches the construction worker. The most common types of engineering controls include isolating the machine, or redesigning the machine (e.g., muffler placement). However, these controls are not always feasible, and are often limited (Casali, 2006).

The second form of control is administrative, which does not necessarily reduce the noise levels, but focuses on reducing exposure time, which may reduce hearing hazard risk but does nothing for signal detectability. Some of the strategies used for this form of control are rotating construction workers between noisy and quiet jobs, and taking appropriate breaks. Particularly in a construction work environment where certain jobs are rather specialized, there is an obvious disadvantage of reduced productivity and efficiency with administrative controls. However, on other jobs, such as those of the general laborer in a paving operation, use of administrative controls may be beneficial.

The last form of reducing exposure levels is through use of personal protective equipment (PPE). Although this form might be the least effective means to reduce exposure and is viewed by OSHA (1983) as an interim measure only (at least for general industry), it is the most widely used countermeasure in both industrial and construction settings—likely because most of the devices are cheap and easy to implement, especially when compared to some engineering controls (Casali, 2006). A major difference between a construction setting and a regular industrial setting is that in the former the workers frequently work in rapidly changing work sites with exposure to noise from varying equipment and from the environment, while the latter environment is generally more static with respect to noise and its variability. In addition, construction workers have relatively little control over their environment. Therefore, noise exposure on construction sites may not be as amenable to engineering controls as in the manufacturing sector. However, one can see the positive effect of engineering controls on the worksite in the form of TTS (or lack thereof) through the institution of an enclosed cab (see Figures 8 and 9). But there are many instances, particularly for the worker on the ground, wherein engineering controls are not feasible or effective; in such situations, there is a strong need hearing protectors that cannot only protect workers' hearing, but which also provides some capacity to detect operational safety signals.

Amplitude-Sensitive, Sound-Transmission Hearing Protection Devices

Amplitude-sensitive (or assistive-listening) sound-transmission devices contain active electronic circuitry that has the ability to amplify signals in a specified passband, such as speech and warning signals, helping to differentiate them from other harmful background noises, as long as the noise does not also fall in that passband (Casali and Gerges, 2006). These systems pass through signals by providing increased passband amplification to an at-ear loudspeaker when in low ambient noise levels, and automatically reduce amplification at high noise levels, progressing toward a pure passive attenuator. Amplitude-sensitive devices incorporate a microphone on the outside of an earmuff or earplug, and an amplifier and loudspeaker on the inside, for the purposes of transmitting low-intensity external sounds to the user's ears but, when high noise levels are present (e.g., continuous construction noise, impact noise, impulsive noise), the amplification abilities of these devices decreases rapidly and ultimately shuts off at a predetermined incident noise level, and the user is protected from exposure purely by means of the device's passive qualities.

Signals may be filtered to only pass a narrow band of frequencies (such the critical speech and typical warning signal bandwidth of about 1000–4000 Hz). The limiting amplifier typically maintains a predetermined (in some cases, user-adjustable) gain, often limiting the under-the-HPD output to 82-85 dBA (in keeping with the OSHA action level), until the ambient noise reaches a predetermined cutoff level wherein the amplifier ceases to function (as illustrated in Figure 15), at which point the HPD maintains similar behavior to a conventional HPD (Casali, 2005). Auditory perception and noise levels under these devices may depend upon factors such as: cutoff sound level (and the sharpness of attenuation transition at that level), system response delay, frequency response and passband bandwidth, distortion and residual electronic noise, signal/noise ratio at sound levels below the cutoff, and sensitivity to wind effects (Casali, 2005).

The microphone design for these electronic amplitude-sensitive HPDs maybe diotic, in which a single microphone in one ear cup feeds both earphones, or dichotic, in which each earcup has a separate microphone feeding a different signal to each ear. The dichotic design should provide for better localization abilities in cases where sound localization is important, and this aspect was tested under this research project (as discussed later in this report). Since earplugs are not so amenable to construction activities (i.e., dirt and other detritus possibly entering the ear canal when inserting or adjusting), it was determined that earmuff-type amplitude sensitive devices provided the most promise for improving operational signal detection in the construction environment.

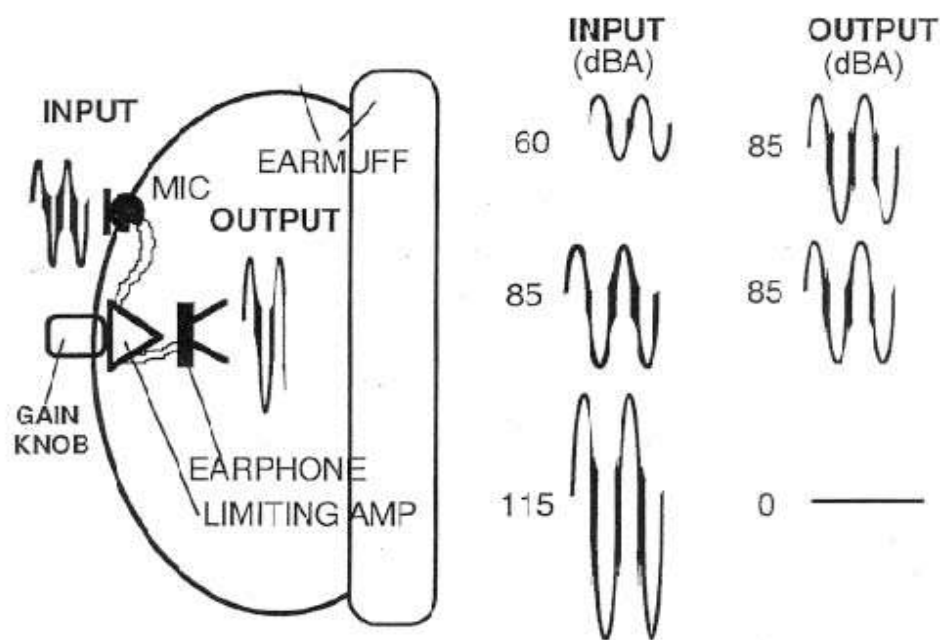


Figure 15. Functional characteristics of electronic amplitude-sensitive, sound-transmission HPDs (Adapted from Casali, 2005).

Laboratory Experiment Using an Acoustical Test Fixture (ATF)

The commercially-available “communications-augmented” hearing protectors and headsets of all major HPD manufacturers were reviewed by the Research Team, and those devices which

appeared to have the most promise for improving speech and signal detection in construction were procured for laboratory analysis. The electronic sound transmission devices were subjected to laboratory-based experimentation to determine their potential for improving workers' hearing in the bandwidth that encompasses critical speech and warning signal frequencies (i.e., 1000-4000 Hz).

The experiment provided data, via microphone techniques (per ANSI S12.42-1995), to reflect the acoustical performance of several new designs of hearing protectors that provide sound transmission through the protector via the previously described microphone-amplifier-earphone circuit with a passband intended to span that of critical speech frequencies as well as most warning signals.

Various electronic sound-transmission HPDs from Bilsom, Howard Leight, Deben, and Peltor were evaluated with an acoustical test fixture (ATF, per ANSI S12.42-1995, see Figure 16) within various levels of pink noise (75, 80, 85, 90 dBA) to ascertain how well or how poorly they can be expected (again, based on microphone, not listener, measurements) to foster improved alarm and signal detection, and also, whether or not their amplification (if applicable) leads to increased noise exposure above incident noise levels of about 85 dBA (the OSHA TWA action level). The reason for including passive designs in the evaluations was to determine how advanced electronic technologies may help to foster signal detection when compared to their passive counterparts (i.e., counterparts in terms of their similar construction and labeled noise reduction rating [NRR]). Pink noise, which provides a flat spectrum across octaves, was used as the test stimulus from which to determine the intensity changes at each frequency and within each noise level achieved under each HPD at the following electronic sound transmission circuit amplifier settings: off (passive), half-gain, and full-gain (i.e., on with volume turned to maximum). For headsets that maintained a dial for power/gain, the half-gain amplifier setting was determined through the use of a string and protractor to determine the 'halfway point' between 'full-off' (passive) and 'full-on' (full-gain). For headsets that maintained buttons for power/gain, the number of button presses needed to realize full-gain was determined, and the half-gain setting was realized by halving that number.



Figure 16. Acoustical test fixture (ATF) used to evaluate potential HPDs (electronic amplitude-sensitive, sound-transmission earmuffs) to support signal detection (protocol per ANSI S12.42—1995).

Hearing protector type. Five circumaural, amplitude-sensitive earmuffs were evaluated in the ATF experiment. These included the Bilsom Impact™, the Bilsom Electro™, the Peltor Tactical Pro™, the Peltor Push-to-Listen (PTL™), and the Deben Slim Electronic earmuff. These devices represented the latest technology available at the date of the experiment.

Bilsom Impact™. The dichotic Bilsom Impact (NRR = 23) uses electronic noise filtering that was designed to protect the wearer from harmful background noises, and to amplify sounds one may want to hear, such as verbal communication and warning signals (Figure 17). As prior discussed, when the electronics are turned off, the sound transmission device attenuates the noise as a passive HPD. When the electronics are turned on, however, the amplifiers amplify external signals (such as a backup alarm) as long as they reside in its passband, while at the same time attenuating any excessive, unwanted noise (e.g., ambient background noise), as long (as it is not in its passband). According to the manufacturer, the actual limiting level of amplification for this HPD is a 'safe' 82 dBA.



Figure 17. The Bilsom Impact™ amplitude-sensitive earmuff, NRR = 23.

The ATF results for the Bilsom Impact™ were mixed. In 75 dBA pink noise, the under-the-headset SPLs (in dBA) were 59.2, 66.8, and 76.0 within passive, 1/2-gain, and full-gain conditions, respectively (see Figure 18a). The intensity of the peak backup alarm frequency (1250 Hz) was measured to produce an under-the-headset level of 69.2 dBA at full gain at this noise intensity. However, as the pink noise increased to 90 dBA, the under-the-headset SPLs (in dBA) were measured at 62.4, 74.2, and 79.6 within passive, 1/2-gain, and full-gain conditions, respectively (see Figure 18b). The intensity of the peak backup alarm frequency was measured at 72.7 dBA at full gain at this noise intensity. See Appendix C for the ATF results (for all tested headsets) at pink noise intensities of 80 and 85 dBA.

Bilsom Electro™. The dichotic Bilsom Electro™ was identical to the Bilsom Impact™ except for the inclusion of a built-in AM/FM radio capability. The 'sound level limitation' as listed on its accompanying literature also stated, as did the Bilsom Impact™, that "all sounds above the limit of 82 dBA are excluded, while harmless sounds below the limit are amplified (Package insert A, 2006, see Figure 19). It was determined that the sound-amplification circuit operated on the same circuit as did the radio feature, suggesting that additional amplification may occur as a result (i.e., turning on the circuit for radio listening may affect under-the-headset sound levels over and above a headset that did not have AM/FM radio capability).

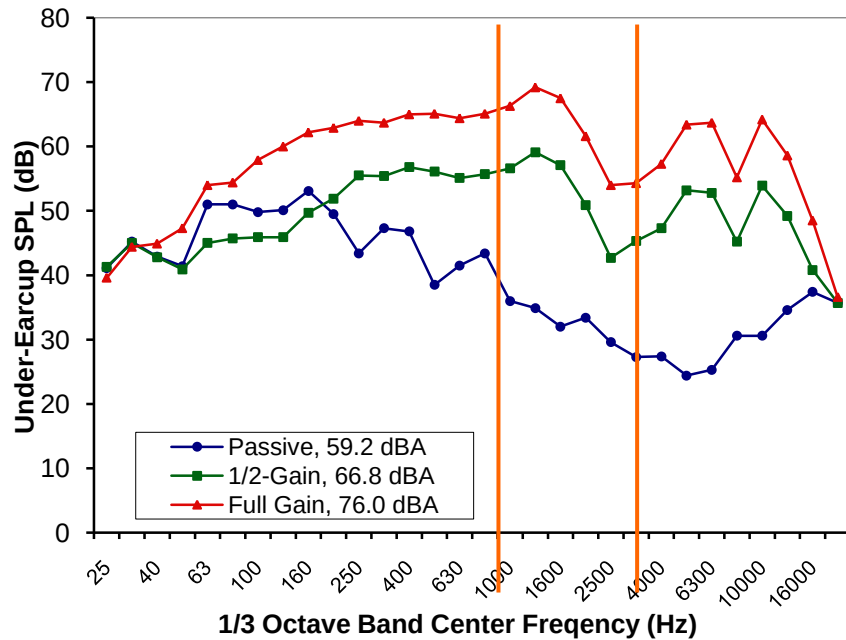


Figure 18a. Under-the-earcup spectra and noise levels for the Bilsom Impact™ amplitude-sensitive earmuff within 75 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

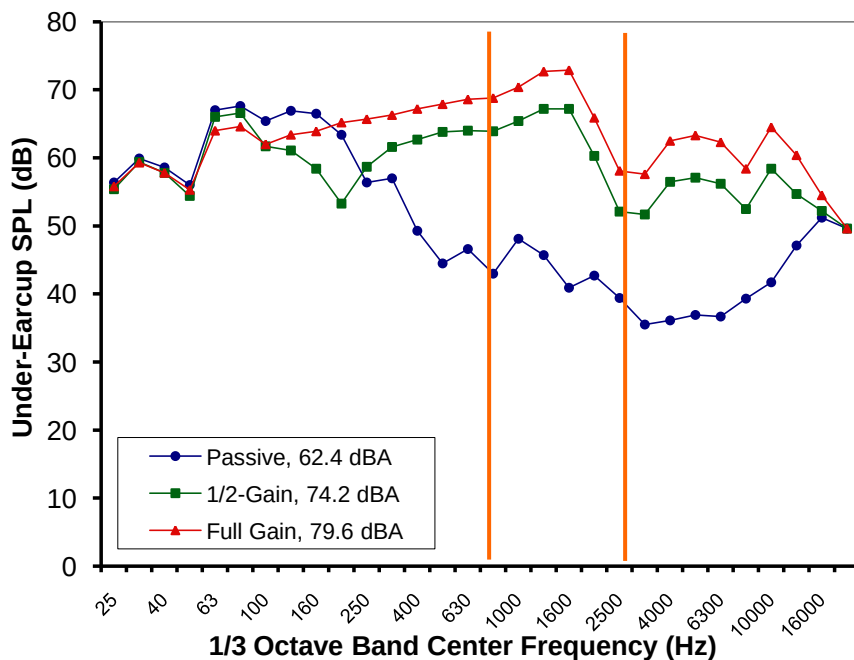


Figure 18b. Under-the-earcup spectra and noise levels for the Bilsom Impact™ amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

Further, evaluation of the Bilsom Electro™ HPD was considered important due to the fact that construction workers have been observed to use personal radios while on worksites, suggesting that if circumaural interventions were offered, workers may opt for a device that includes AM/FM radio capability.



Figure 19. The Bilsom Electro™ amplitude-sensitive earmuff, NRR = 23.

The ATF results for the Bilsom Electro™ indicated that, in 75 dBA pink noise, the under-the-headset SPLs (in dBA) were 59.8, 59.9, and 79.1 within passive, 1/2-gain, and full-gain conditions, respectively (see Figure 20a). The intensity of the peak backup alarm frequency (1250 Hz) was measured to produce an under-the-headset level of 72.3 dBA at full gain at this noise intensity. However, as the pink noise increased to 90 dBA, the under-the-headset SPLs (in dBA) were 66.2, 69.5, and 80.8 in passive, 1/2-gain, and full-gain conditions, respectively (see Figure 20b).

The intensity of the peak backup alarm frequency was measured at 74.1 dBA at full gain at this noise intensity. These results indicate that the radio circuit's operating on the same circuit as the amplifying circuit resulted in higher under-the-headset levels when compared to the same device that did not maintain a radio feature (i.e., the Bilsom Impact™).

The fact that the measured levels at the highest intensity (90 dBA), and at full-gain were 80.8 and 79.6 for the Bilsom Electro™ and Bilsom Impact™, respectively, may be an indication that users may be exposed to slightly increased noise levels when wearing a radio-equipped amplitude-sensitive earmuff when compared to one of similar design that is not so equipped.

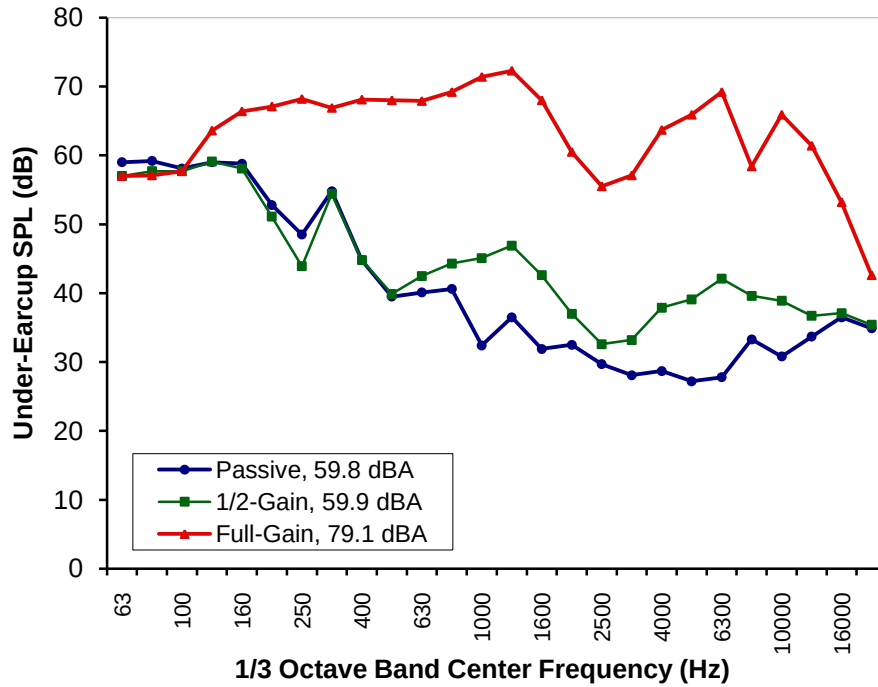


Figure 20a. Under-the-earcup spectra and noise levels for the Bilsom Electro™ amplitude-sensitive earmuff within 75 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

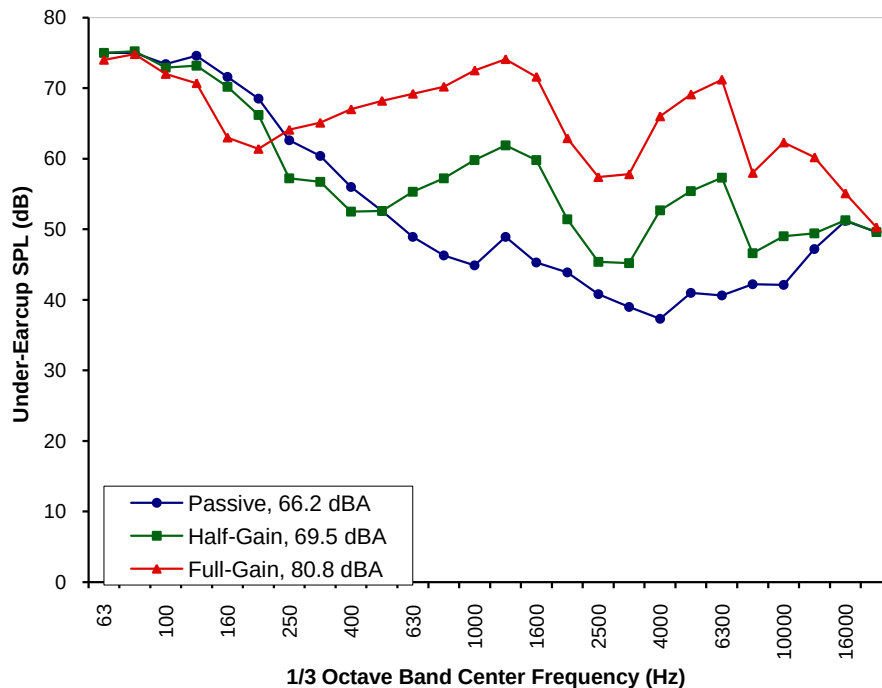


Figure 20b. Under-the-earcup spectra and noise levels for the Bilsom Electro™ amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

Peltor Tactical Pro™. According to the manufacturer, the dichotic Peltor Tactical Pro is an active hearing protector that allows “comfortable contact with the surroundings, while effectively protecting the user from harmful noise” (Package insert 2006, see Figure 21 below). Primarily targeted to hunters and sportsmen as a ‘shooters earmuff,’ the overall design and large earcup volume suggested that this device may be useful as a possible HPD for construction workers.



Figure 21. The Peltor Tactical Pro™ amplitude-sensitive circumaural earmuff, NRR = 26.

The ATF results for the Peltor Tactical Pro™ were improved when compared to the two Bilsom products noted above. In 75 dBA pink noise, the under-the-headset SPLs (in dBA) were 59.3, 59.4, and 72.1 within passive, 1/2-gain, and full-gain conditions, respectively (see Figure 22a). The intensity of the peak backup alarm frequency (1250 Hz) was measured to produce an under-the-headset level of 50.1 at full gain at this noise intensity. However, as the pink noise increased to 90 dBA, the under-the headset SPLs (in dBA) were 61.1, 74.7, and 74.6 within passive, 1/2-gain, and full-gain conditions, respectively (see Figure 22b). The intensity of the peak backup alarm frequency was measured at 53.6 dBA at full gain at the 90 dBA pink noise level.

These results suggest that the passive attenuation qualities of the Peltor Tactical Pro™ (e.g., earcup design, seal material) resulted in decreased under-the-headset levels at all noise intensities when compared to either of the Bilsom offerings. Further, these same qualities produced a markedly decreased under-the-headset intensity of the primary backup alarm frequency when compared to the Bilsom products (i.e., 53.6 dBA [Peltor Tactical Pro™], 72.7 dBA [Bilsom Impact™], and 74.1 dBA [Bilsom Electro™]) in 90 dBA noise; this decrease could be a disadvantage to signal detectability.

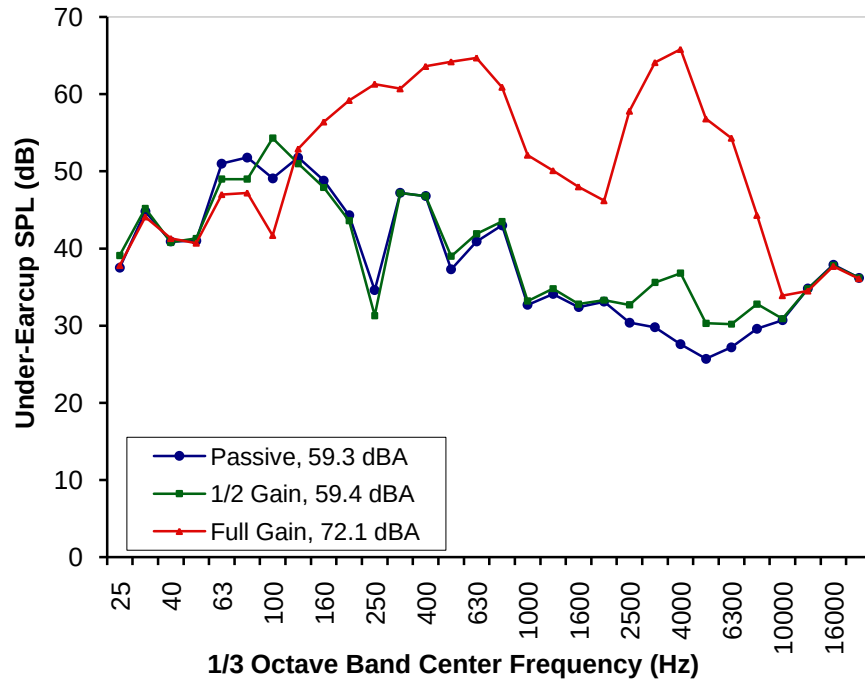


Figure 22a. Under-the-earcup spectra and noise levels for the Peltor Tactical Pro™ amplitude-sensitive earmuff within 75 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

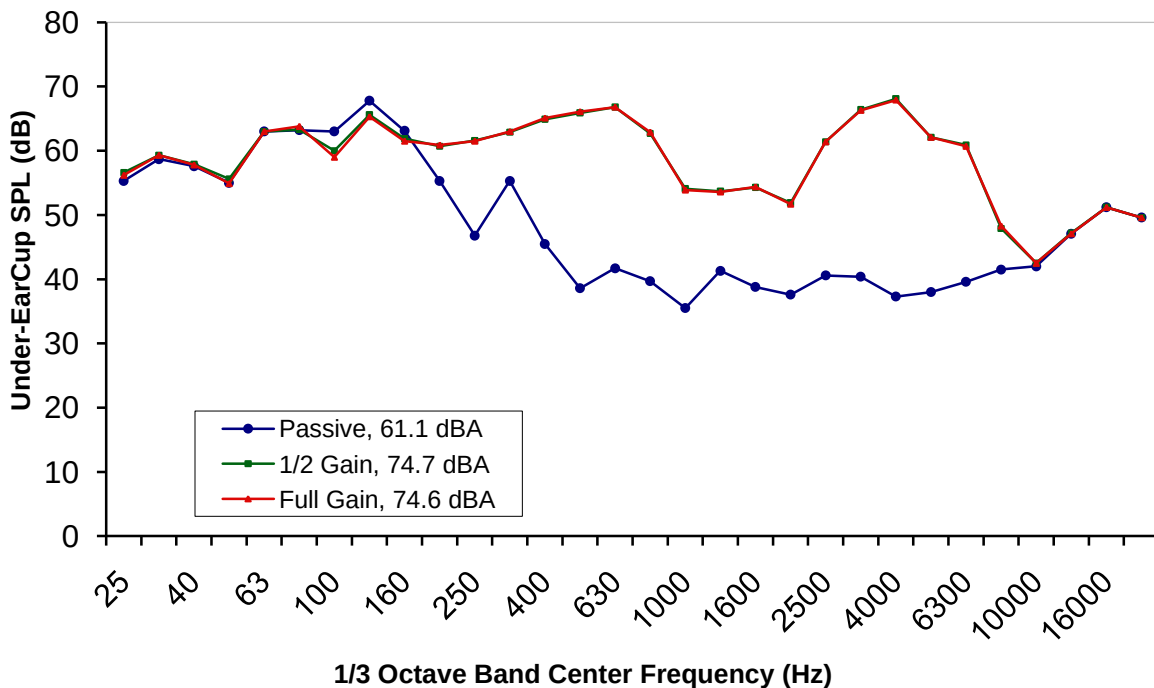


Figure 22b. Under-the-earcup spectra and noise levels for the Peltor Tactical Pro™ amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

Finally, the broadband under-the-headset sound level of the Peltor Tactical Pro at the highest noise level (90 dBA) was at least 5 dBA below that of the Bilsom products, suggesting the this device has a comparatively improved ability to protect the worker's hearing (the Peltor Tactical Pro's NRR is 26, compared to the Bilsom's 23), while presenting operational signals at levels that are perceived as much lower (i.e., 5 dB lower). But with the improved passive noise attenuation qualities of the Tactical Pro headset, the detection of the backup alarm, even at its lower under-HPD intensity, may indeed be facilitated from a S/N ratio standpoint.

Peltor Push-to-Listen (PTL™). The Peltor PTL was the only monaural amplitude-sensitive earmuff tested (see Figure 23). The PTL is monaural in that only one of the two earcups maintains an amplification feature—the other earcup remains passive. The idea behind the PTL is that it functions as a passive hearing protector but when the wearer wants to communicate with another worker or wants to hear a signal, he/she presses a button located on one of the two earcups (there is no labeled left or right earcup but there is a forward-backward orientation of the microphone port), which activates the amplification feature in that earcup (which stays 'on' for about 30 seconds), thereby fostering communication and signal detection without the need to remove the earmuff to do so. If at any point during that 30-second amplification an impulsive/harmful intensity noise is detected, the amplification feature is claimed to immediately shut off, and the device functions as a passive hearing protector. Quite obviously, this device has no 'always on' amplification ability, requiring the user to actuate the amplification feature, so it is not an "automatic" response to signals in the vicinity. This issue represents a significant disadvantage in most, if not all, construction jobs, where workers often do not have the time nor the ability to discern when amplification is suddenly needed to auditorially attend to a warning signal -- they simply need to hear the signal itself.



Figure 23. The Peltor Push-to-Listen (PTL™) amplitude sensitive circumaural, monaural earmuff, NRR = 26.

Since the Peltor PTL™ does not have a volume/intensity setting (it is either 'on' or 'off'), there was no ability to measure how various gain settings (e.g., 1/2-gain, full-gain) affected under-the-headset levels. As such, the device was tested in 'passive mode' and in 'active mode.' The ATF results for the Peltor PTL™ indicated that, in 75 dBA pink noise, the under-the-headset SPLs (in dBA) were 59.3 and 71.2 within the 'passive mode' and 'active mode' conditions, respectively (see Figure 24a). The intensity of the peak backup alarm frequency (1250 Hz) was measured to produce an under-the-headset level of 62.7 dBA when in 'active mode' at this noise intensity. However, as the pink noise increased to 90 dBA, the under-the-

headset SPLs (in dBA) were 61.2 and 79.8 within the ‘passive mode’ and ‘active mode’ conditions, respectively (see Figure 24b). The level of the peak backup alarm frequency was measured at 66.5 dBA when in ‘active mode’ at this noise intensity.

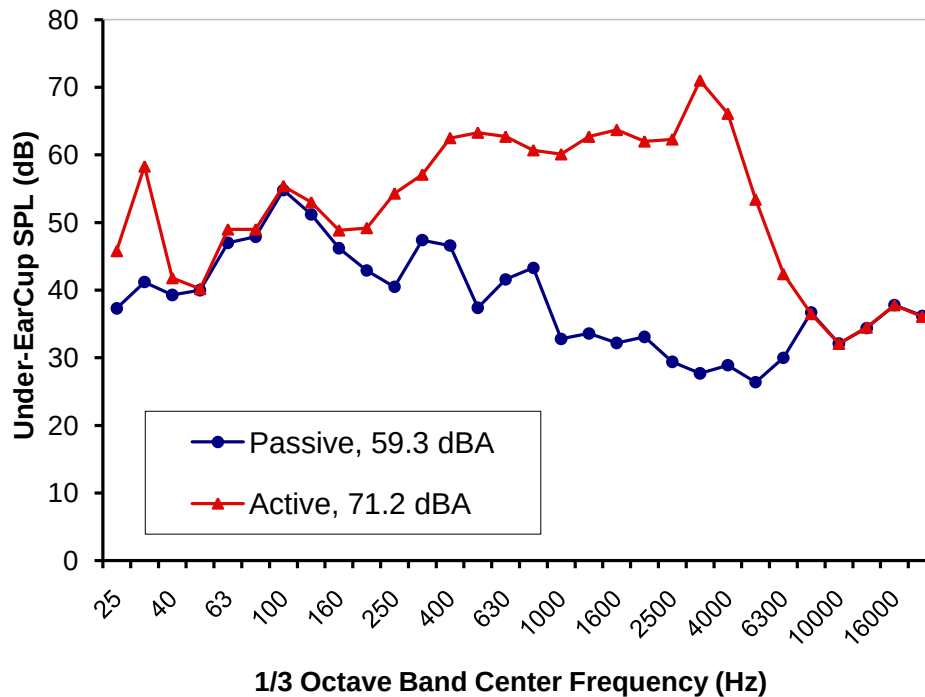


Figure 24a. Under-the-earcup spectra and noise levels for the Peltor PTL™ amplitude-sensitive earmuff within 75 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

Deben Slim Electronic. The dichotic Deben Slim Electronic, similar to the Peltor Tactical Pro™, was developed primarily for the shooter. Its design is quite ‘slim’ compared to the other amplitude-sensitive devices tested, but this is considered a ‘feature’ by the manufacturer: (the Deben was) “designed to be one of the slimmest folding products available,” yet provides “an impressive 23 dB NRR protection and stainless steel headband” (Package insert, 2006; see Figure 25). Due to its comparatively slim design, the Deben device may be attractive for construction workers who wear fabric caps or hardhats, in that it may be easier to fit. However, the slim design results in a lower earcup volume when compared to the other devices, which may reduce its passive protection abilities.

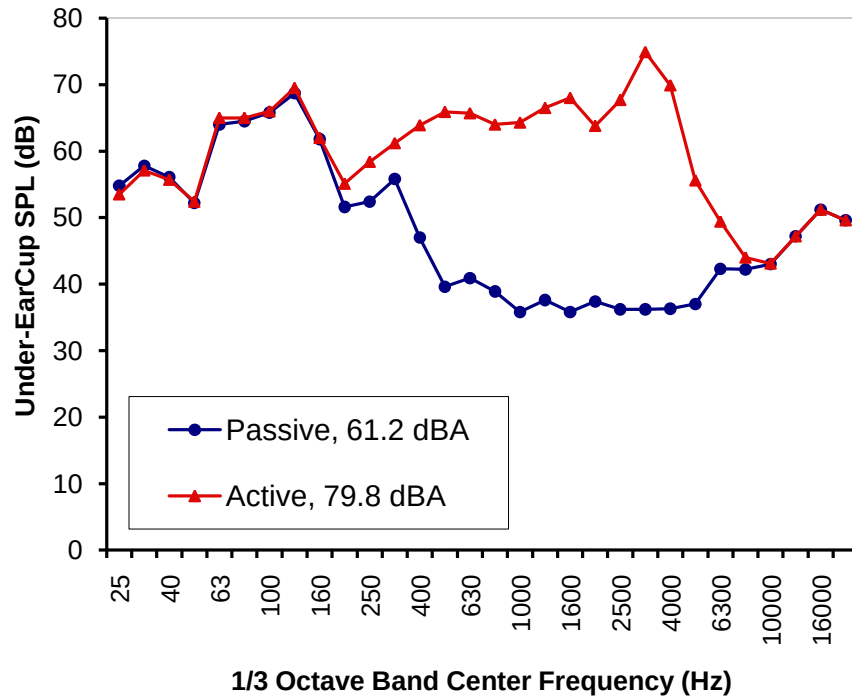


Figure 24b. Under-the-earcup spectra and noise levels for the Peltor PTL™ amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.



Figure 25. The Deben Slim Electronic circumaural amplitude-sensitive earmuff, NRR = 23.

The ATF results for the Deben Slim Electronic were as expected—the slim design, while possibly affording comfort due to its decreased earcup volume, resulted in comparatively increased levels under-the-headset. In 75 dBA pink noise, the under-the-headset SPLs (in dBA) were 60.5, 71.4, and 79.0 within passive, 1/2-gain, and full-gain conditions, respectively (see Figure 26a). The intensity of the peak backup alarm frequency (1250 Hz) was measured to produce an under-the-headset level of 73.0 dBA at full gain at this noise intensity. However, as the pink noise increased to 90 dBA, the under-the-headset SPLs (in dBA) were 68.7, 78.2, and 79.6 within passive, 1/2-gain, and full-gain conditions, respectively (see Figure 26b). The

intensity of the peak backup alarm frequency was measured at 73.4 dBA at full gain at this noise intensity.

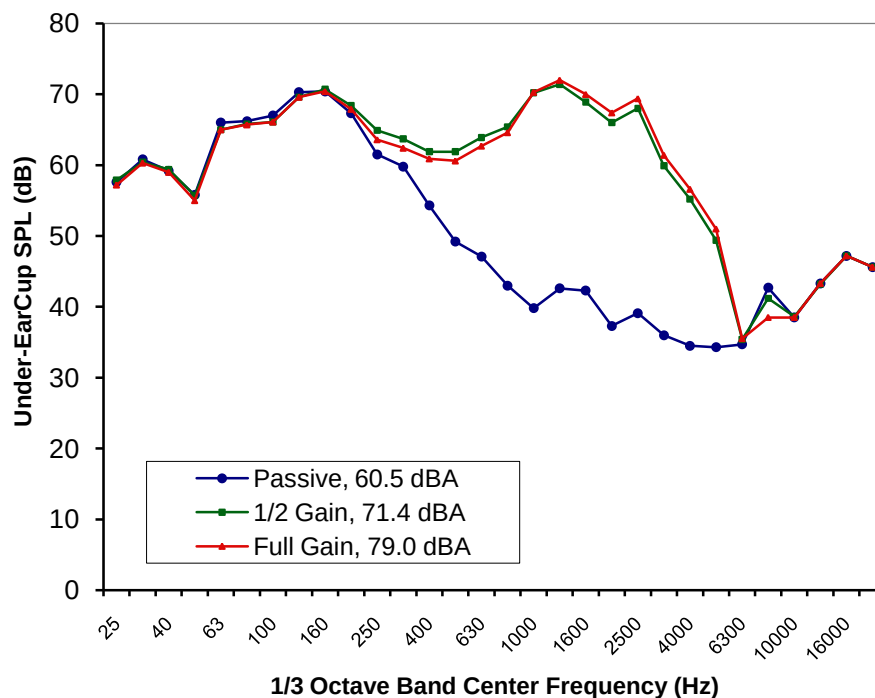


Figure 26a. Under-the-earcup spectra and noise levels for the Deben Slim Electronic amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

The ATF measurements on the amplitude-sensitive HPDs indicated that the passband amplification technologies employed might improve operational signal audibility at various gain settings and in various noise levels (i.e., boosting of the passband in lower intensity noise, but not to levels that exceed OSHA safe limits). The design of the headsets and their features also required consideration; for example, while an AM/FM radio feature may be attractive to operators, if it operates on the same circuitry as does the sound transmission technology, overall elevated under-the-earcup noise levels may result as described above. Also, the use of a user-activated monaural earmuff, while providing some level of user control, is certainly not an optimal solution, because the user typically will not know when to actuate the amplification circuit (e.g., a worker may not detect equipment operating out of his/her line-of-sight), thus obviating detection of an operational signal.

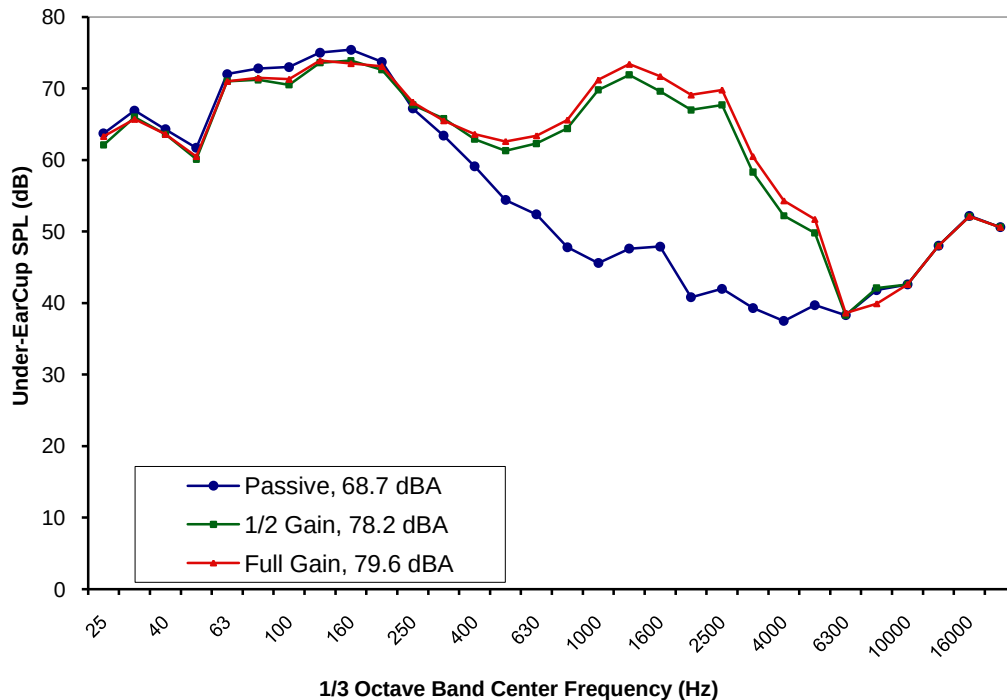


Figure 26b. Under-the-earcup spectra and noise levels for the Deben Slim Electronic amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range of interest.

In general, the results showed that as the intensity of pink noise increases, the tested augmented devices would increase the under-the-headset intensity to foster signal detection in the critical speech and backup alarm frequencies (in a passband from about 1000 Hz to 4000 Hz), but also would maintain that noise level (including amplification) within OSHA “safe” limits (e.g., 85 dBA). Two of the headsets, however, produced under-the-headset noise levels that were above 80 dBA in the presence of 90 dBA noise, which may be due to their design (e.g., comparatively decreased earcup volume or other features contributing to reduced attenuation, and/or other radio electronics that operate on the same circuit as does the augmented technology).

Those devices that appeared to be most promising in the ATF measurements (e.g., the Bilsom Impact™ and the Peltor Tactical Pro™) were then chosen for evaluation in human factors experiments using human subjects to determine the detectability of operational signals, as well as their localization ability, within simulated construction noise. Two additional, passive earmuffs were included in these studies (see ‘Phase IV’ results). These earmuffs, the Bilsom Clarity C2 and the Peltor H7, were the closest available ‘passive counterparts’ to the Bilsom Impact™ and the Peltor Tactical Pro™, respectively, in terms of both construction and labeled NRR. Stratifying the HPD variable in this manner allowed for direct comparison between the electronic sound-transmission (amplitude-sensitive) and the conventional, passive products of similar design with respect to their ability (or lack thereof) to foster signal detection and signal localization. These two passive earmuffs are presented and discussed in turn.

Bilsom Clarity C2. Figure 27 shows the Bilsom Clarity C2, the passive counterpart to the Bilsom Impact™. These two earmuffs have the same basic design and labeled NRR, except

that one is an amplitude-sensitive device (i.e., the Bilsom Impact™), while the Clarity C2 earmuff is not. As such, testing of these two same-manufacturer HPDs, as potential interventions, allowed a direct comparison to be made with respect to how their respective technologies either support or suppress operational signal detection. The Bilsom Clarity C2 has a labeled NRR of 23.



Figure 27. The Bilsom Clarity C2 circumaural earmuff, passive counterpart to the Bilsom Electro™, NRR = 23.

Peltor H7. Figure 28 shows the Peltor H7 circumaural earmuff, the passive counterpart to the Peltor Tactical Pro™. Similar to the above, these two earmuffs have the same design and NRR, except that one is an amplitude-sensitive device (i.e., the Peltor Tactical Pro™), while the H7 earmuff is not. As such, testing of these devices, as potential interventions and as mentioned, allowed a direct comparison to be made with respect to how their respective technologies either support or suppress operational signal detection. The Peltor H7 has a labeled NRR of 26.



Figure 28. The Peltor H7 passive circumaural earmuff, passive counterpart to the Peltor Tactical Pro™, NRR = 26.

Phase IV - Evaluating Interventions to Empirically Determine Effectiveness

Introduction to the Phase IV Experiments

One of the major problems associated with backup alarms is the high attentional demand required by the worker; that is, in the performance of their duties, workers must also pay attention to the activities and locations of equipment and other machinery operating in their immediate vicinity. Additionally, annunciating backup alarms may not be of sufficient sound

intensity, and/or they may not maintain adequate “pitch” distinction from other operational sounds, to overcome the ambient noise. As many workers can attest, the ambient noise generated not only by the vehicles to which backup alarms are attached, but also other equipment operating nearby (which often has its own backup alarm), can be quite loud and mask over backup alarms in the immediate vicinity which need to be heard and heeded. Compounding the issue is ambient noise that is not due to construction operations (e.g., traffic noise), which may also serve to mask the backup alarm. This “masking” can be thought of as a phenomenon wherein an undesirable noise tends to ‘drown out,’ or otherwise make it difficult to hear, a sound that a listener needs or wants to hear.

When any reversing vehicle is operating with a backup alarm on a construction site, workers have three critical, sequential tasks to complete— tasks that must be completed rather quickly, almost automatically on the part of the ground crew. Each of these critical tasks builds upon the one before it. The first of these is detection of the backup alarm—the worker has to be able to hear the reversing vehicle’s backup alarm signal. The issue of detection is exacerbated by not only the factors mentioned above, but also by hearing loss, which may itself pose a significant risk. As mentioned previously, when the Occupational Safety and Health Administration (OSHA) promulgated its construction noise regulation in 1971, it consisted only of what is called its “criterion level” of noise exposure (90 dBA as measured over an 8-hour workshift, called a time-weighted average [TWA]). However, OSHA has yet to adopt what is called an “action” level (85 dBA TWA) toward implementation of a full hearing conservation program for construction in the same vein as it did for general industry in 1983. Thus, some construction workers have long been exposed to high noise levels on construction sites, levels that may have contributed to hearing loss and the resultant difficulty in detecting operational signals such as backup alarms. If such a hearing conservation program had been mandated for all of industry (i.e., including construction), and not just general industry, the issue of hearing loss among construction workers may have been diminished. These issues lend further credence to the guidance that backup alarm signals need to output at levels that are considerably above the ambient noise environment, by 10 to 15 dB more, which may pose a hearing hazard in itself.

The second critical task that construction workers must complete is recognition of the signal—that what is being heard is a backup alarm, and not something else. Again, this task builds upon the task of detection—if workers cannot first hear the signal, they certainly cannot recognize it. Steps have been taken by standards-promulgating bodies to afford spectral (pitch) distinction to the backup alarm signal. To some extent, the extant standards for backup alarms have met with success, in that most construction workers are able to recognize the reversing signal as a backup alarm, but some who have tone deafness may not. However, the backup alarm signal itself may not be sufficient for the critical task of recognition if its frequencies reside at or near those where construction workers’ hearing has been lost, and/or if the spectrum of ambient noise has significant energy at frequencies that are near those of the backup alarm and cause the masking effects discussed earlier. These issues suggest that backup alarms that maintain frequency components that are more spectrally distinct, which annunciate at frequencies that are not near those that are affected by hearing loss, and can increase their intensity output, as needed, may be needed.

The third critical task that construction workers must complete is localization of the

signal—that they can confidently and consistently determine where the backup alarm is sounding from at any given time. If a worker cannot detect or recognize the signal, localizing it is a moot point. Localization of a backup alarm signal can be quite difficult as well due to the factors mentioned above, including ambient noise, hearing loss, and spectral distinction. Most people have heard a siren from a police vehicle, fire engine, or ambulance but, when we slow down or pull to the side of the road to get out of the way, we are typically looking all around us, and in our rear-view mirror, to see where the emergency vehicle is. This is likely due to the inability to localize the sirens, as they are comprised of intensities and frequencies that are typically supportive of detection (i.e., we can hear them) and recognition (it's an emergency siren), but we cannot always determine where the emergency vehicle is located (is it behind us?). The intensities and frequencies of backup alarms are similar in this regard. While they are not always intense enough to be heard over ambient construction site noise, they are usually recognized as backup alarms. But, those same frequencies often reside near frequencies that are first affected by hearing loss, and they also are not optimized in terms of the frequencies that the human ear can best localize.

The research experiments outlined below sought to evaluate the critical tasks of backup alarm detection and backup alarm localization. First, a field study is presented that explored the detection distance of an enunciating backup alarm for normal hearing listeners fitted with a high-attenuation earmuff. The second study explored further the detection of a backup alarm signal within two types of masking noises and across a variety of noise levels, and used both normal hearing and non-normal hearing listeners to test for detection across a variety of HPDs. The third and final study explored the critical task of backup alarm localization across a range of devices (including the open ear), and within differing levels of masking noises.

Experiment 1: Backup alarm detection using ascending and descending method of limits.

Rationale and Objectives. As the first human factors experiment in this research project, an outdoor experiment on backup alarm detection (using the ascending and descending method of limits) utilizing conventional passive hearing protection was conducted. This within-subjects factorial experiment sought to determine the point at which normal-hearing listeners could detect a backup alarm of the type used on construction-equipment in an outdoor, free-field condition with the type of hearing protection now used in construction, such as foam earplugs or heavy-duty passive, non-electronic (conventional) earmuffs. A large construction equipment manufacturer was contacted to determine what type of backup alarm was most commonly used on road construction and other excavation equipment, and with that information, a backup alarm manufacturer was contacted and provided the Research Team with various backup alarm systems for evaluation.

The primary objective of this research was to determine the linear distance at which normal-hearing listeners wearing an earmuff HPD could detect a construction vehicle backup alarm operating in near free-field conditions in an outdoor field environment using the ascending and descending method of limits. Although the experiment was very basic and conducted on one high-attenuation (NRR=29) earmuff with normal listeners only, the results do provide data that may be useful for backup alarm manufacturers, standards committees, and construction

safety officials toward reducing worksite fatalities caused by reversing vehicles, particularly in the realm of establishing work separation envelopes between workers and operating machinery.

Avoiding reversing vehicles with backup alarms requires consideration of both the minimum distance (i.e., d*minimum) separating the construction worker from the location of the reversing construction vehicle, and also the speed of that reversing vehicle. Thus, determination of d*minimum and its relation to vehicle reversing speed provides one indication of accident potential with respect to a construction worker having enough time to step out of the reversing vehicle's path.

As mentioned, construction workers are typically engaged in the performance of their duties and, when a construction vehicle with an annunciating backup alarm is nearby, the workers need time to detect the reversing vehicle's backup alarm signal, recognize what the signal means, and remove themselves from the reversing vehicle's path. The d*minimum that provides sufficient time for the construction worker to step out of the reversing vehicle's path was calculated based on the experiment's results, and is presented herein for various construction vehicle types.

As shown in Figure 29, these calculations were based on different construction vehicles' widths (W) (to account for a worst-case condition wherein worker movement out of the vehicle's path includes traversing the vehicle's whole width) and maximum reversing speeds (MRS) (also as a worst-case condition). The time required (t) for a construction worker to attend to (i.e., detect and recognize) the reversing vehicle's backup alarm signal (estimated at approximately 3.5 sec; Acker, 2006), as well as the average walking speed for humans (HWS) (3.5 mph, reduced by 0.5 to 3.0 mph for a conservative safety margin; Frankel and Nordin, 1989), was included in the calculations.

$$d * minimum \geq MRS \times \left(t + \frac{W}{HWS} \right)$$

Figure 29. d*minimum calculation to determine time needed by a construction worker to get out of the way of a reversing vehicle's path.

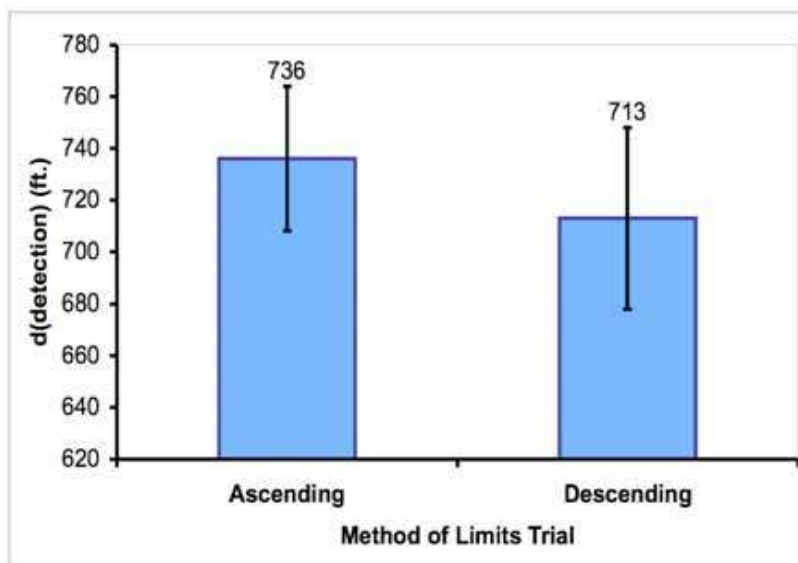
Methodology. A within-subjects design was utilized for the experiment to determine the linear distance at which a 97 dBA backup alarm signal (Preco 'Bac-A-Larm' Model 370, per SAE J994b Type C specifications, and determined to be the most common version for construction vehicle use) could be detected while wearing an experimenter-fitted (for consistency) Peltor H10A earmuff (NRR = 29) in near free-field conditions (a grassy, flat athletic field on the Virginia Tech campus). Five normal-hearing (i.e., audiometrically verified to be $\geq$ 25 dBHL at 125, 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz for both ears) participants were recruited for the experiment.

Procedure. The ascending and descending method of limits was utilized to determine the distance at which the participants could detect the backup alarm signal. First, with the experimenter-fitted earmuff in place, and while facing away from the backup alarm, the participants walked slowly and continuously (i.e., no stopping) away from the alarm source until

audibility to the alarm signal was lost. At this point, the linear distance from the alarm source was measured. Participants then moved 20 feet further from this point, and then walked slowly back toward the alarm source until the alarm signal was again detected. At this point, another linear distance measure was taken. Following this, the participant performed the reverse order of this procedure. Ascending and descending trials were each repeated 3 times for each participant to obtain 6 measurements.

Results and Discussion. A two-sample t-test with a significance level of 0.05 was used to determine whether or not there was a significant difference between the means of the ascending and the descending trials. The mean linear distance at which participants could detect the backup alarm signal in the ascending trials was 736 feet; this distance was 713 feet for the descending trials (see Figure 30). The t-test on the dependent measures revealed no significant difference between the ascending and descending trial means ($p = 0.29$). As such, an overall mean comprising the ascending and descending means (i.e., 725 feet) was used to represent the distance at which the 97 dBA backup alarm signal was detected by the normal-hearing, earmuff-occluded participants (Table 8).

The next step was to determine how this distance related to the reversing speeds and widths of various construction equipment, with the speed and width data taken from manufacturers' product information. Figure 31 depicts the d^* minimum vs. reversing speed relationship as applied to one example vehicle, a John Deere 310 SG backhoe. Note the minimum safe distance (d^* minimum), 153.4 ft, that should separate a ground construction worker from the backhoe, which was determined by including the backhoe's width and maximum reversing speed (i.e., 20.5 mph). At d^* minimum, the backup alarm signal should be detectable to an earmuff-occluded, normal-hearing worker, while allowing enough time for that worker to step out of the backhoe's path.



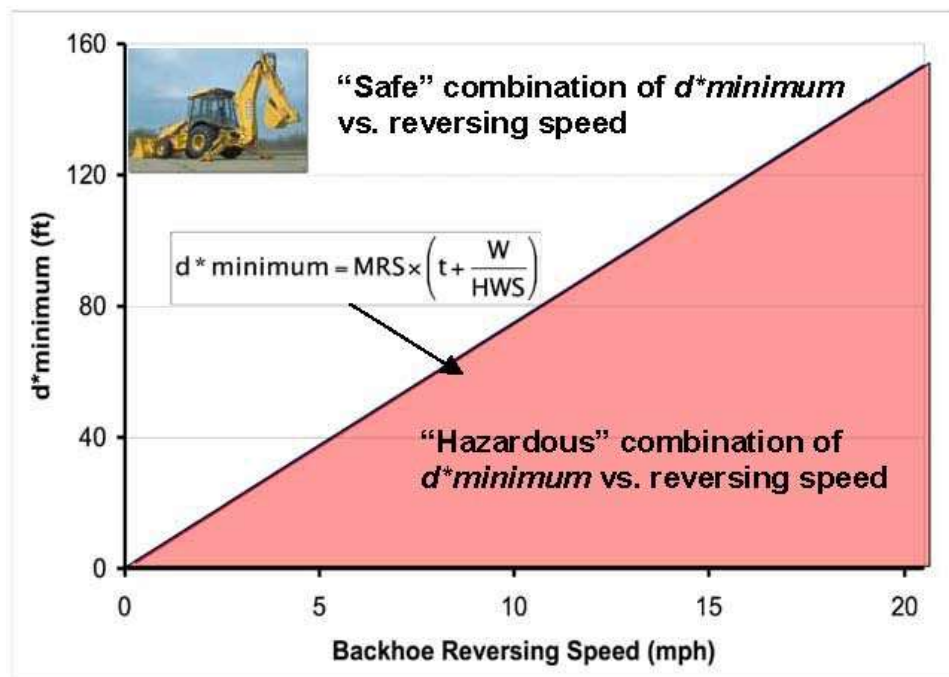
AA

Figure 30. Mean SAE J994b Type C backup alarm (97 dBA) detection distance for normal-hearing participants wearing a high-attenuation earmuff (NRR = 29), with 95% confidence intervals plotted. Means with the same letter are not significantly different.

TABLE 8. t-test summary table for the method of limits data.

<u>Descriptive Statistics: Ascending/Descending (ft.)</u>							
Variable	N	Mean	StDev	Min	Median	Max	CI (95%)
Ascending: 15	736	50	612	753	786		(708, 764)
Descending: 15	713	64	577	728	800		(678, 748)

<u>Two-Sample t-Test & 95% CI: Ascending/Descending (ft.)</u>				
Variable	N	Mean	StDev	SE Mean
Ascending:	15	736	50	13
Descending:	15	713	64	16
Difference = μ (Ascending) - μ (Descending)				
Estimate for difference: 23				
95% CI for difference: (-20, 66)				
t -test of difference = 0 (vs not =): t -value = 1.09				
p -value = 0.285 ; df = 26 (thus, conclude no difference)				



Application of similar calculations to on-site vehicles should allow construction site safety managers and supervisors to (for example) place ground construction workers at safe distances

from reversing vehicles, and/or alert vehicle operators of the heightened safety considerations (e.g., use of slower backing speeds) that are needed when such workers are nearby. See Table 9, where d^* minimum has been calculated for other examples of common construction vehicles based on their manufacturer-published maximum reversing speeds. For example, an excavator operating at a maximum reversing speed of 3 mph provides a relatively safe operating envelope if kept away from workers by 28 feet, whereas faster vehicles, such as a 4WD loader, must maintain a distance of about 153 feet away from workers. This, of course, assumes normal-hearing workers occluded by high-attenuation earmuffs and moving about dynamically, as investigated in the experiment discussed above.

TABLE 9. d^* minimum vs. reversing speed for various John Deere construction equipment (speeds obtained from John Deere website, 2007).

Equipment	Model	Width (ft)	Max Reverse Speed (mph)	d^* minimum (ft)
Backhoe[1]	310 SG	7.05	20.5	153.40
Dump Truck[2]	400D	11.08	4	35.30
Crawler Loader[3]	755C	8.17	6.8	53.42
Excavator[4]	650D LC	12.25	3	27.65
4WD Loader[5]	844J	11.46	17	152.19

[1]http://www.deere.com/en_US/cfd/construction/deere_const/backhoes/brochures/DKAGBHOE.pdf

[2]http://www.deere.com/en_US/cfd/construction/deere_const/media/pdf/adtdKAADT.pdf

[3]http://www.deere.com/en_US/cfd/construction/deere_const/crawlers/brochures/DKA655CII.pdf

[4]http://www.deere.com/en_US/cfd/construction/deere_const/media/pdf/excavator/DKAX650850.pdf

[5]http://www.deere.com/en_US/cfd/construction/deere_const/media/pdf/wheelloader/DKA844J.pdf

Conclusion: Backup Alarm Method of Limits Study. The research results provide initial data with respect to the linear distance at which normal-hearing individuals who are wearing a high-attenuation earmuff HPD can detect a reversing vehicle's backup alarm. Construction site safety managers, equipment manufacturers, and HPD manufacturers can use such data toward reducing injuries and fatalities on construction sites. For example, such accident reductions can be realized by limiting maximum construction vehicles' reversing speeds on a construction site based on available spacing, by maintaining worker-to-vehicle spacing via the use of movable fences, tape, or other barriers, and to increase safety awareness on the part of site supervisors, ground construction workers, and equipment operators.

It could be argued that the foregoing analysis should have been performed using less

than maximal vehicle reversing speeds, since vehicles often operate at such speeds. On the other hand, many types of construction vehicles back up frequently and unexpectedly, and both experienced and inexperienced operators may indeed use the maximum speed for efficiency or other reasons. Thus, in this analysis, the decision was to err on the side of safety and base the calculations on maximum-attainable backup speeds.

This study had a large degree of realism in that it evaluated backup alarm detection distances under field conditions and a high-attenuation earmuff as would be candidate hearing protection in severe construction noises; however, there are many other factors that also have bearing on the worker's ability to hear the alarm and avoid the vehicle which are in need of further study. Such factors include: the ambient noise of the equipment and other sources, the worker's hearing abilities, the attenuation of the HPD, the number of other (potentially confusing) backup alarms within earshot, and the worker's involvement with other activities which divert his/her attention. The authors hope that the evaluation presented herein will stimulate further investigation.

The data from this human subjects experiment helped to determine at what distance HPD users could reliably hear the various backup alarms in outdoor worksite conditions and, as a result (based on the reversing speeds of various construction vehicles), how much time those HPD users would need to escape the vehicle's path and thus avoid a possible run-over incident. The normal-hearing listeners in this experiment performed the listening trials with a conventional earmuff-type HPD, and a high-attenuation one at that. With the results, various options for interventions were thereafter evaluated with an eye towards balancing hearing protection with workplace conditions (i.e., the need to protect hearing while ensuring that backup alarms and other signals can be detected), and by suggesting what interventions may be suitable for construction workers who suffer from hearing loss. With this in mind, the report now turns to a second experiment on backup alarm detection under conventional and augmented HPDs.

Experiment 2: Determination of backup alarm masked thresholds in construction noise with augmented and passive HPDs.

Rationale and Objectives. As the second human factors experiment in this research project, an experiment further investigating the critical task of backup alarm detection was conducted. The experiment utilized both conventional (passive) hearing protection and amplitude-sensitive ("assistive-listening") hearing protection to assess their detection performance using both normal hearing and non-normal hearing listeners.

In an environment such as construction, with its hazardous and intense noise levels, the role of warning signals is of high importance. As discussed above and discovered in the initial task analysis phase of this research project, by far the most common type of signal in the construction environment is the ubiquitous backup alarm, which functions whenever vehicular equipment (e.g., trucks, bulldozers, backhoes) is reversing. However, the existing hearing loss among the population of construction workers (in some cases due to both worksite noise levels and other non-work, outside activities), in combination with the preponderance of noise at construction sites, can contribute to the occurrence of accidents that can result in personal injury and/or death. These accidents may have been due to the fact that an important signal

was not heard. It is likely that at least some of these deaths could have been avoided if the vehicles and their operations had been clearly audible to the workers. Based on the evidence established in earlier phases of this project, it is clear that there is a serious safety-related need to examine the ability to hear auditory signals (e.g., backup alarms, horns) within the construction industry, under different types of hearing protectors.

Assistive-listening HPDs (also called amplitude-sensitive, sound-transmission HPDs) appear to have some promise as interventions on construction sites to not only protect worker hearing, but to also foster signal detection. While the aforementioned research into various HPDs (including assistive-listening devices) has been: 1) very limited, and 2) mixed as to results, newer HPD designs have surfaced in the past several years, suggesting that the potential for these systems to improve signal detection exists (Casali, 2005). Further, in at least one early study (Casali and Wright, 1995) in which there were no significant differences between conventional and sound-transmission HPDs with respect to masked threshold, there may have been too insufficient a resolution in the Hughson-Westlake threshold-seeking method instituted (i.e., 5 dB steps) to discern difference between sound-transmission HPDs and their passive counterparts. Perhaps in a similar, but more realistic experiment in which the resolution was more precise, measurable and significant differences in masked threshold detection between more modern devices may indeed result.

The purpose of this study was, therefore, to evaluate the effectiveness of using up-to-date, commercially-available assistive-listening HPDs of the sound-transmission type to augment signal detection (e.g., backup alarms of construction equipment), both of which are routine and necessary considerations at construction sites, and comparing their performance against existing, conventional HPDs of similar design and passive attenuation.

The primary objective of this research study was to investigate if there was any advantage in using current sound-transmission earmuffs over conventional (passive) HPDs, for both normal and non-normal hearers, in the detection of a backup alarm within the noise produced by certain construction equipment that was measured to be of very high noise output and operated in very dynamic situations which promote runaway, and within pink noise at various sound pressure levels.

Methodology. The hypotheses for the detection experiment were as follows:

H₁: The sound-transmission HPDs were expected to result in a lower masked threshold value, for both normal and non-normal listeners, when compared to passive HPDs of similar design for noise levels at 75 dBA.

H₂: Within noise levels above 85 dBA, both types of HPDs (i.e., sound-transmission and passive) were expected to result in the same masked threshold values for both normal and non-normal listeners.

The experiment was a 2X4X4X2 mixed-factor design with a background noise type variable (2 levels, within-subject), a hearing protection device (HPD) variable (4 levels, within-subject), a background noise level variable (4 levels, within-subject), and a hearing threshold variable (2 levels, between-subject) (see Figure 32). Each independent variable is discussed in more detail below. All experimental conditions were presented in counterbalanced, systematic fashion to avoid order effects using a Latin Square design.

Participants. Initially (and based on a power analysis, discussed below) a total of 16 participants were planned to be used, 8 of which were normal-hearing listeners and the other eight that were individuals with elevated pure-tone thresholds (hereafter termed “non-normal hearing listeners;” specific threshold criteria are described below). However, due to the unavailability of individuals who met the non-normal hearing criteria, only three participants who met the criteria were recruited. (It should be noted that exhaustive efforts were undertaken to identify and recruit non-normal hearing listeners, including advertisements via listserv and postings, contacting local audiologists, and reviews of audiograms from over 700 patients of a local Hearing and Speech Pathology program.) A total of 11 subjects, ranging in age from 19 to 65 years of age, participated in the experiment as paid volunteers. Screening criteria were based on participants’ pure tone hearing threshold, and were stratified as follows:

- 1 Normal-hearing listeners.
- 2 Non-normal hearing listeners (those with elevated hearing levels).

Normal-hearing listeners had pure tone hearing threshold levels in both ears of less than or equal to 25 dBHL at each of the 1/3-octave band center frequencies from 125 -8000 Hz (Davis and Silverman, 1978). Non-normal hearing listeners had an average pure tone hearing threshold level in the better ear that was above (i.e., worse than) 40 dBHL at 1000, 2000 and 3000 Hz.

Power Analysis calculations were conducted to determine the number of subjects that would result in reasonable statistical power for this experimental design. In human factors research, a statistical power of at least 0.8 is normally required. The equation for this analysis is shown below.

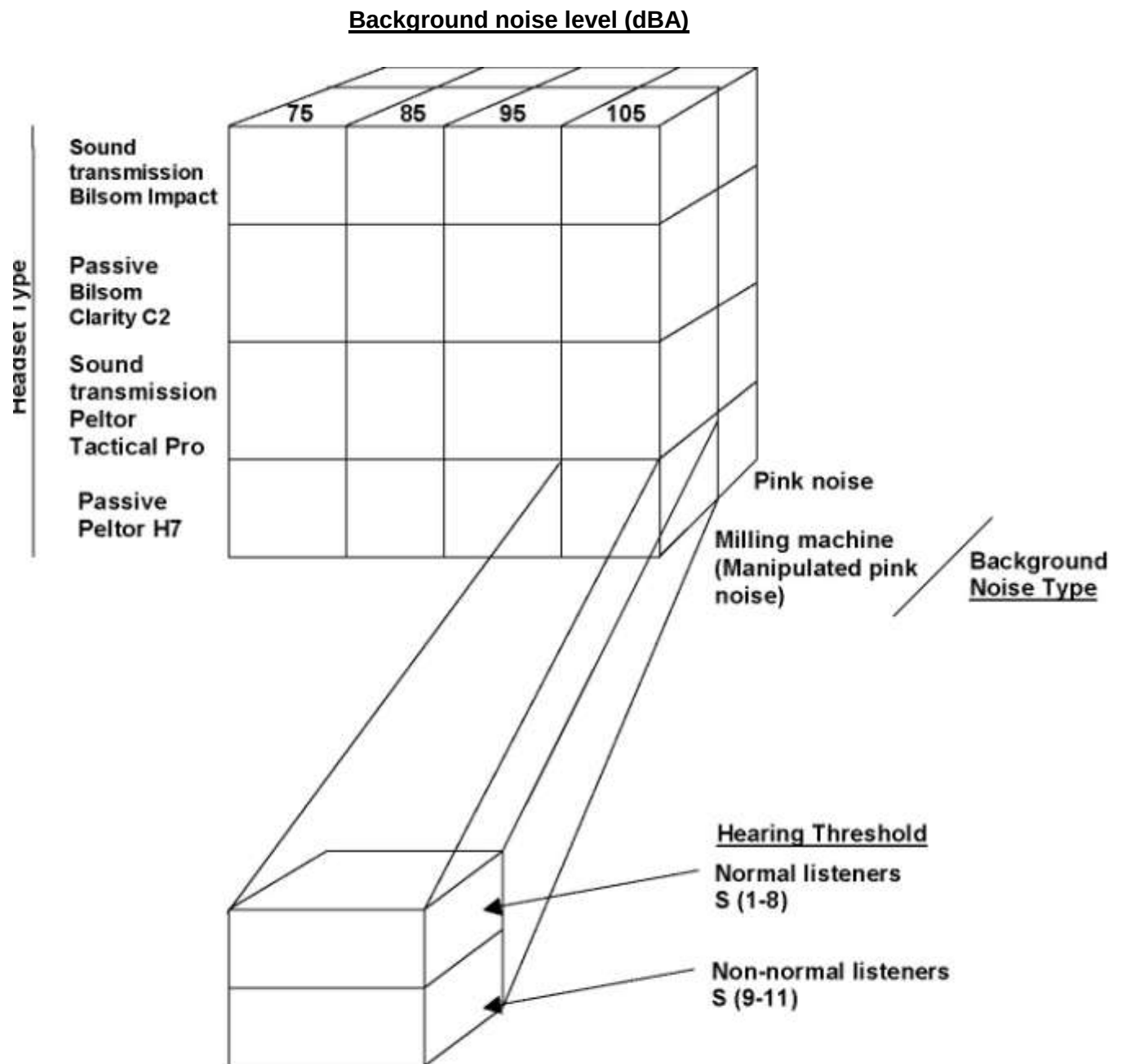


Figure 32. The mixed-factors design for the backup alarm detection experiment.

$$\delta = \frac{A - B}{\sigma \sqrt{\frac{2}{n}}}$$

Where:

A = the mean dB value for normal hearers (25 dB)

B = the mean dB value for non-normal hearers (50 dB)

σ = the standard deviation (15.75 dB)

α = alpha-level of 0.05

This model makes an assumption in the standard deviation value (σ): that there is no one specific standard deviation value that has been recorded for either normal or non-normal hearing individuals. The standard deviation value used in this experiment, therefore, is based on recent research by Hong (2005) on the hearing loss as measured among operating engineers in the construction industry. In the Hong research, audiograms for 623 participants were gathered, which provided the standard deviation of the worst ear (worst case scenario) at 2000 Hz (15.7 dB); this value was used in the power analysis to determine the appropriate sample size for this study (see Table 10).

TABLE 10. Results of the power analysis for the backup alarm detection study.

N	N	df _{N-2}	δ	Power
8	4	6	2.244783	0.470
10	5	8	2.509744	0.665
12	6	10	2.749287	0.688
14	7	12	2.969569	0.778
16	8	14	3.174603	0.827
18	9	16	3.367175	

The results of the power analysis indicated that 16 (Power > 0.8) was a sufficient number of subjects to be used; however, as mentioned earlier, due to the difficulty in recruiting individuals meeting the non-normal hearing criteria, only 3 non-normal hearing individuals participated in the experiment. All independent variables, with the exception of the hearing threshold variable, were presented as within-subjects in that each participant attended all experimental sessions and experienced all levels of each independent variable. The hearing threshold variable was presented as the sole between-subjects variable. Each independent variable is presented first and is discussed in more detail below.

Independent Variables. The *hearing protection device type* independent variable consisted of two electronic sound transmission earmuffs and two other earmuffs, which represented the passive counterparts to the sound transmission devices (with respect to their earcup volume, cushion design, and EPA-labeled noise reduction rating [NRR]). Two of these earmuffs, the Bilsom Impact™ and the Peltor Tactical Pro™, were sound transmission (or assistive-listening) earmuffs. The other two earmuffs, the Bilsom Clarity™ C2 and the Peltor H7™, represented the passive counterparts to the two sound transmission devices (see Laboratory Experiment Using an Acoustical Test Fixture (ATF), above).

Stratifying the HPD variable in this manner allowed direct comparisons to be made between the sound transmission and conventional, passive HPDs of similar design. The brand names/models or any identifying marks of each device were covered with tape to avoid bias in subjects' ratings.

The *background noise type* independent variable included both standard (flat-by-octaves) pink noise as well as a pink noise whose spectrum had been manipulated to match that of a 1994 CMI PR-500B road-milling machine (see Figure 33). The road milling machine noise was selected for two reasons: 1) the milling machine produces intense noise levels (Leq = 97.4, from Table 3) that are typical of construction equipment, and 2) the milling machine presents the need for the detection of its and other vehicles' backup alarm signals by ground personnel (e.g., rakers, screedmen, foremen) in the close vicinity of road milling operations (see Figure 34).

Pink noise is a common type of noise spectrum used in masked threshold research because it provides the maximum opportunity for broadband masking (e.g., intensity changes in s/n ratio are easily noted at each frequency). A similar published example of masked threshold research using pink noise is casali and wright (1995).

The *background noise level* (intensities) independent variable included presentations of 75 dba, 85 dba, 95 dba and 105 dba for each background noise type. The 75 dba background noise level represented a "low" noise level where hpds are not required by osha regulations to be worn by a worker—it is at this level that differences in hpd type were expected to occur due to the amplification qualities of the amplitude-sensitive systems when compared to their passive counterparts. The 85 dba level was selected because it represents the osha (1983) 'action level,' i.e., hearing conservation program action must be taken to protect workers at or above an 8-hour twa of 85 dba.

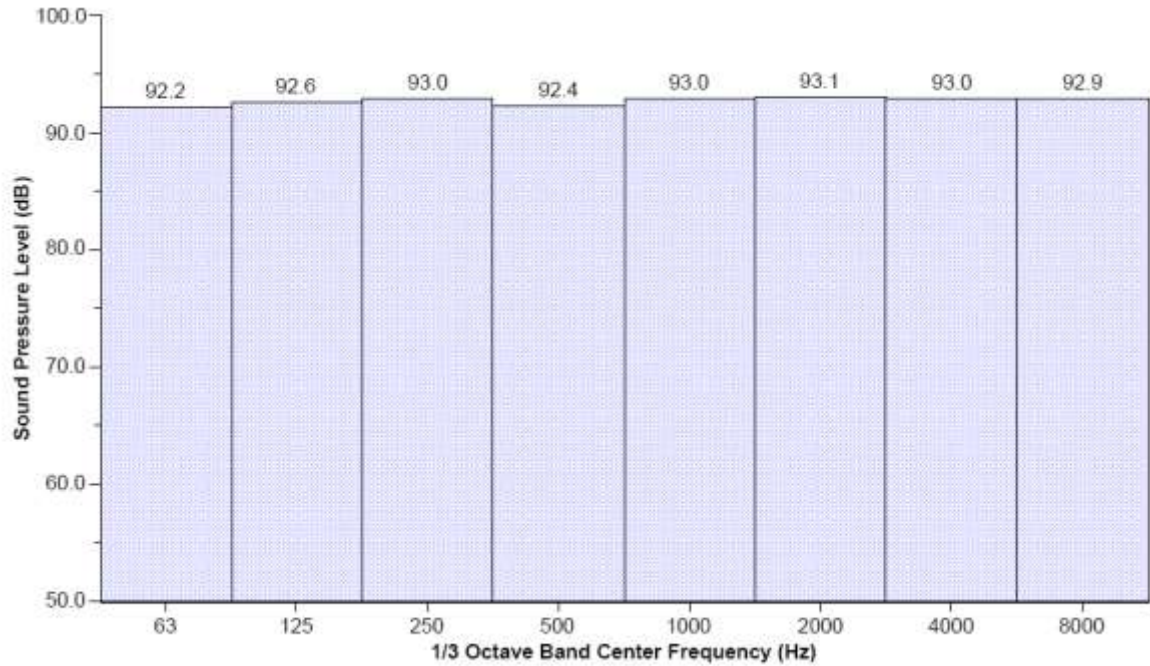


Figure 33. Pink noise spectrum as measured at the subject's head center position.

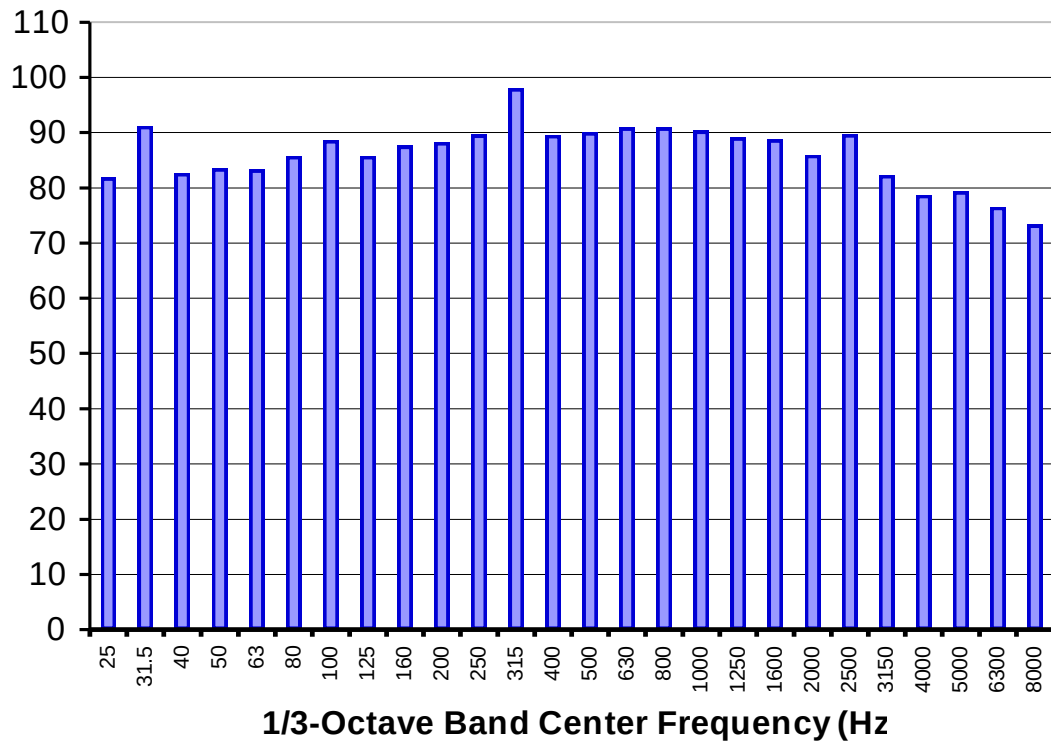


Figure 34. Road milling machine noise spectrum (CMI PR-500B), as measured at subject's head center position.

At this level, and as mentioned previously, a full hearing conservation program is required and HPDs must be supplied to all workers. The 95 and 105 dBA levels were selected because they represent the high noise levels typical of road construction worksites, and the most intense level of 105 dBA approximates the level of a road-milling machine in operation as measured in the initial phase of the research effort.

Hearing ability, as mentioned, was stratified into ‘normal hearing’ and ‘non-normal hearing.’ To control for the traditional hazards in using repeated-measures designs (e.g., carryover effects, practice effects, fatigue), it was important to implement a balancing procedure with respect to the order of presentation of the treatments. Thus, for the experimental sessions, each headset type was tested on different days, with all levels of background noise and each level of background noise type presented in each day.

Dependent Measures. There were three dependent measures in this experiment. The first of these was the *backup alarm masked threshold level*. Specifically, the dependent measure was the sound pressure level of the alarm (in dBA) at the listeners’ threshold, which constituted a *masked* threshold since all trials were in conditions of noise. The backup alarm signal used in this study was from a standard backup alarm that met both the SAE J994b and ISO 7731 standards. This type of backup alarm enunciates at a peak frequency of 1250 Hz (see Figure 35), and produces a level of 97 dBA at a distance of 4 feet from the measurement microphone (with a user-adjustable additional setting of 97 dBA-107 dBA; 107 dBA is the level currently used by many large equipment manufacturers) (John Deere, Inc., personal communication with J. Lancaster, 2006). These alarms have been used in other studies, such as in the previously discussed research conducted by Casali et al. (2004) that investigated the detectability of backup alarms in noisy environments while listeners were wearing active noise reduction and passive HPDs.

The second dependent measure was participants’ ratings of HPD *comfort* and *alarm detectability* under each HPD. A 7-point semantic differential scale was used to tap into these perceptions (see Appendix D). This scale was administered to participants after the completion of each experimental condition.

The third and final dependent measure was *hearing protector comfort*. Other than the above-mentioned dependent measures, comfort can also be an important factor in determining the amount of protection provided by an HPD (Casali, Lam, and Epps, 1987). An HPD that is uncomfortable will result in a worker repeatedly taking the device off and putting the device on again, which will result in reduction in attenuation, and thus, compromised protection from noise. For instance, if an HPD with an NRR of 25 dB is not worn for just 15 minutes out of an 8-hour work period, then the resultant ‘time corrected NRR’ will be 20 dB.

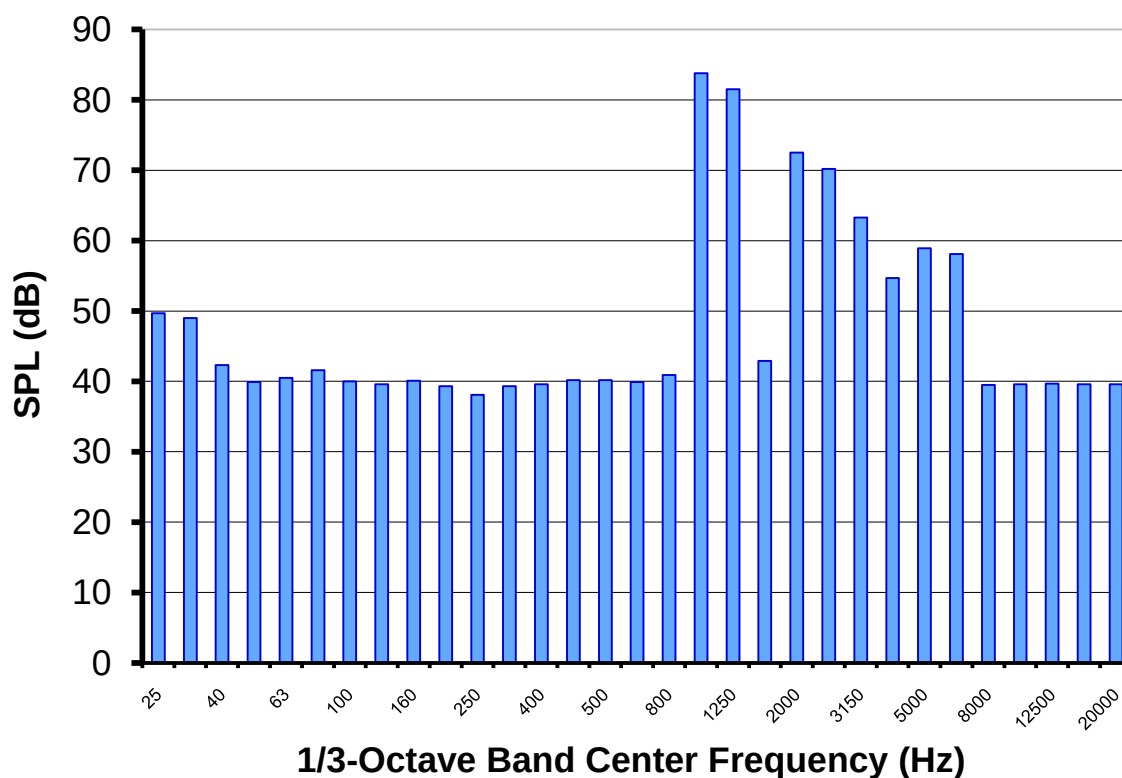


Figure 35. Backup alarm spectrum as measured at subject's head center position. Note the peak energy at 1250 Hz and harmonic at 2500 Hz.

For these reasons, a *subjective rating scale*, specifically an *Osgood semantic differential scale*, was applied as a means of determining comfort from the study's participants; such scales have been prior used at Virginia Tech to collect HPD comfort information. Casali et al. (1987) and Park and Casali (1991) developed a rating scale for HPD comfort, which has been used in many other studies, and it was used in this study. This rating scale is a multidimensional, bipolar descriptor comfort rating scale that consists of 12 seven-step bipolar adjective items, and is shown in Appendix D.

Apparatus. All hardware for the experiment was housed, and all experimental testing was conducted, within the Auditory Systems Lab's Large-Scale Acoustical Test Facility, which is located in room 519N Whittemore Hall on the campus of Virginia Tech. The walls of the facility are lined with Sonex SCOC2 acoustical foam, and the room was tested for diffusivity and non-directionality around the subject's head (seated location) at six different positions per ANSI S3.19-1974. The room met the criteria, except for the up-down positions, which were compensated for by using a chair that could be altered for height (up and down positions); the results are shown in Table 11.

TABLE 11. Test signal at six positions about head center.

1/3-OB Center Freq. (Hz)	Right (-15,0,0)	Left (15,0,0)	R-L Δ^*	Up (0,0,15)	Down (0,0,-15)	Front (0,15,0)	Back (0,15,0)	6 Position Δ^{**}
125	40	39.9	0.1	39.9	39.9	39.9	39.8	0.2
250	39.8	39.7	0.1	39.9	39.9	39.9	39.7	0.2
500	39.8	39.7	0.1	39.8	39.8	39.8	39.8	0.1
1000	65.1	64.2	0.9	55	61.5	57.4	59.6	10.1
2000	51.1	51	0.1	40.4	44.4	46	50.1	10.7
3150	43.8	43.1	0.7	42.9	44.5	43	44.4	1.6
4000	40	40	0	40	39.9	40.1	40.1	0.2
6300	40.1	39.8	0.3	39.9	40.3	39.9	40.6	0.8
8000	39.8	39.8	0	39.8	39.8	39.8	39.8	0

* Absolute value dB difference between right and left microphone position.

** Maximum absolute value dB difference between all pairs of the six microphone positions.

A backup alarm signal wave file was used as the signal source, and was presented to the participants through a Klipsch K-57K horn loudspeaker positioned behind the seated subject, itself amplified by a Sony STR DE-135 amplifier. The background noise was presented to the participants through four Infinity SM-155 loudspeakers, which were powered by a (separate) Sony STR DE-135 amplifier, and positioned at four equidistant locations from, and positioned facing, the seated subjects, as shown in Figure 36. To verify that each speaker produced the same noise intensity at the position of the seated participant, a Larson-Davis model 2559 1/2-inch microphone, calibrated before each experimental trial with a Quest QC-20 calibrator, was used to measure and verify the output of each speaker using a Larson-Davis 2800 Series real-time spectrum analyzer. A laptop computer installed with Labview v8.0 software was configured to track and record the participants' responses using a wireless mouse scroll-wheel (part of the Microsoft wireless desktop 6000). Figure 37 shows the experimental control instruments located at the experimenter's station.

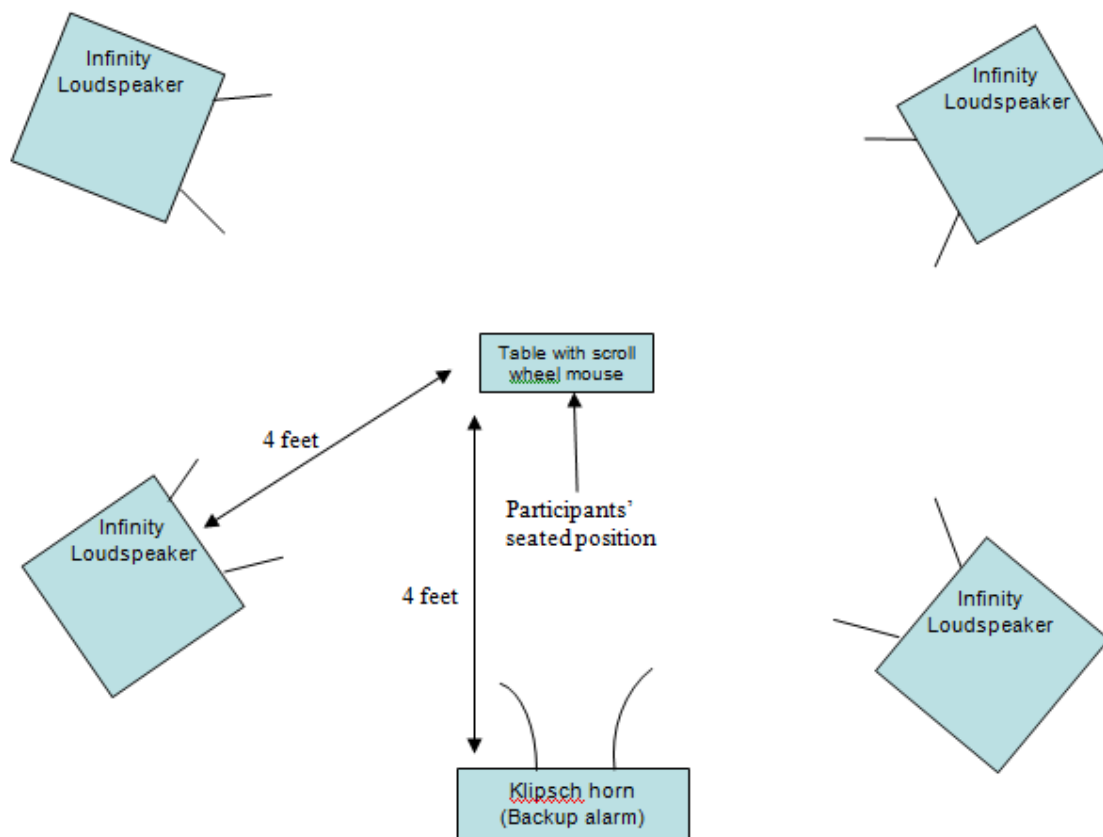


Figure 36. Experimental setup with reference to the participants' seating position.

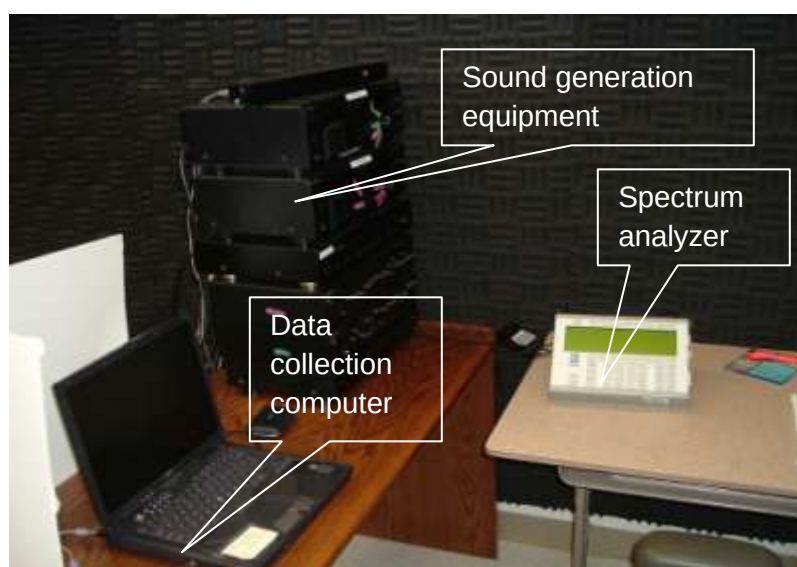


Figure 37. Instrumentation at the experimenter's position.

Procedure. Participants reported to Whittemore 538 (Virginia Tech's Auditory Systems Laboratory) for the initial part of the screening session. Participants first had to undergo an otoscopic inspection of their ears before conduct of a hearing test to ensure that there were no foreign objects or impacted cerumen that might affect their thresholds.

Screening. Participants then underwent an audiogram to determine hearing thresholds for comparison to the criteria specified previously. Then, all four headsets were experimenter-fit to ensure that a proper and consistent fit could be realized.

After successful completion of the audiometric screen, participants were escorted to Whittemore 519N and were instructed in and practiced the threshold tracking task. To do so, participants were fitted with a Peltor H-10A, high-attenuation circumaural earmuff (this earmuff was dissimilar to any of those under test, but it was used to provide a feel for the subjects as to the experience of threshold tracking under an earmuff). Background noise (for practice only) was presented in the form of a Caterpillar tractor in operation (Network Sound Effects, Vol. 5, Track #19) at 95 dBA, and participants tracked a 2 KHz pure-tone using the mouse/scroll-wheel by using the "Bekesy" tracking method (psychophysical method of adjustment), as follows:

- 1) Participants first increased the level of the backup alarm signal by adjusting the scroll wheel until they were absolutely sure that it could be heard.
- 2) Then, participants adjusted the backup alarm signal level until they were absolutely sure that the signal could not be heard.
- 3) Next, participants adjusted the backup alarm signal until they could just barely hear it.
- 4) Then, they adjusted the backup alarm signal until they could no longer hear the alarm.
- 5) Steps 2-4 were continued for 30 seconds (approximately 6 'excursions' between being able to 'just barely hear' and 'not be able to hear' the backup alarm signal).

At the end of the 30-second time period, participants' performance was determined as sufficient if their Bekesy tracking was consistent over three repeated trials. Consistency was realized if, across the three trials, the level at which the signal was heard or was not heard was within 2 dBA, which corresponded to five 'units' or mouse wheel detents, across all Bekesy trackings.

Experimental Trials. Each HPD was tested on different days, with all levels of background noise presented on each day according to a complete Latin Square design. In each session, the experimenter fit the headset to be tested, and the participant sat in the experimental chair facing the table, with a distance of about 6 inches between the participant's nose and about 2 inches from a plumb bob that was positioned as a head reference, and which was used to ensure that participants remained still during the testing (see Figure 38).

Only the "full-gain" setting was utilized for each sound transmission device; the setting was taped in that position to disallow tampering. Background noise was verified at the listener's seated position using a plumb bob (centered over the chair, as pictured in Figure 38) and the sound measurement equipment described earlier. The backup alarm signal's dominant frequency (i.e., 1250 Hz) was verified similarly.



Figure 38. Participant seated during an experimental trial with nose level with and about 2 inches from the plumb bob, and about 6 inches from the table upon which the wireless mouse was located.

In each experimental trial, participants listened for and adjusted the backup alarm intensity using the mouse/scroll wheel (via the process described earlier), which was set to actuate in approximately 1 dB steps. The intensity difference between detents of the mouse scroll wheel were measured and recorded for subsequent data analysis, and these differences were not always in 1 dB steps due to software and hardware constraints. However, since the actual difference in sound level between detents was determined, the level of the backup alarm (i.e., the masked threshold) as determined through use of the scroll wheel could be ascertained. Participants were given 30 seconds to complete the tracking task for each background noise variable (i.e., noise type and level using a particular headset). At the completion of testing for a particular experimental condition, participants were given the semantic differential scale to rate their ability to detect the backup alarm with the HPD used, followed by the comfort rating scale to elicit their subjective impressions regarding comfort of the HPD. (Please see Appendix E for a step-by-step listing of the procedures used in each experimental trial.)

Data Reduction and Analysis. As mentioned earlier, Labview software was used to capture the raw numerical data for the masked threshold values. The raw data were then exported into a MS Excel file, where they were graphed. The graphed data for all of the noise levels (75, 85, 95 and 105 dBA) maintained a scale that ranged from 0-50 with one unit increments; this scale corresponded to the number of scroll wheel detents that were used for

the Bekesy tracking. The “0” value on the scale represented the minimum scroll wheel detent position (zero) on the mouse, and “50” represented the maximum number of scroll wheel detents (50) on the mouse. Separate scales were created for each background noise level (75, 85, 95 and 105 dBA), which represented the dBA value at each scroll wheel detent. The intensity values (dBA) were then determined by equating the maximum and minimum levels on the 0-50 scale to the new dBA scale. Masked threshold values (dBA) for each trial were then determined by calculating the mean values of the peaks and troughs for each oscillating “zig-zag response” function that was traced by the participant for a given condition.

The *first* peak and trough for a given tracing response was not included in the masked threshold calculation, because as is typical in audiometric technique practice, this first excursion is not considered as reliable. But more importantly, on their first response, participants were instructed to increase the initial backup alarm intensity until they were absolutely sure that they could hear the signal, and to decrease the initial backup alarm intensity until they were absolutely sure that they could *not* hear the signal, as opposed to threshold detection or loss of detection of the alarm for subsequent excursions after the initial one. Thus, in subsequent excursions, each *peak* corresponded to a *trough* such that an equal number of peaks and troughs were realized. For an acceptable response, the oscillations in tracing consisted of at least six excursions per experimental trial. The position of the mean value (Y-axis) defined the value of masked threshold, as shown in Figure 39; in this example, the mean masked threshold value was 17.2 dBA.

The Statistical Analysis Software (SAS) program was used to conduct all analyses to test for significant differences at an alpha level of 0.05, and Tukey’s test was used for post-hoc analyses (also at an alpha level of 0.05). Threshold tracking results were analyzed using a four-way analysis of variance (ANOVA) to test for significance, with three within-subject factors and one between subject factor. The main effects under investigation in the ANOVA were hearing ability (HA, between-subjects), hearing protection device (HPD), background noise level (NL), background noise type (NT), and all of the associated interactions (see Table 11).

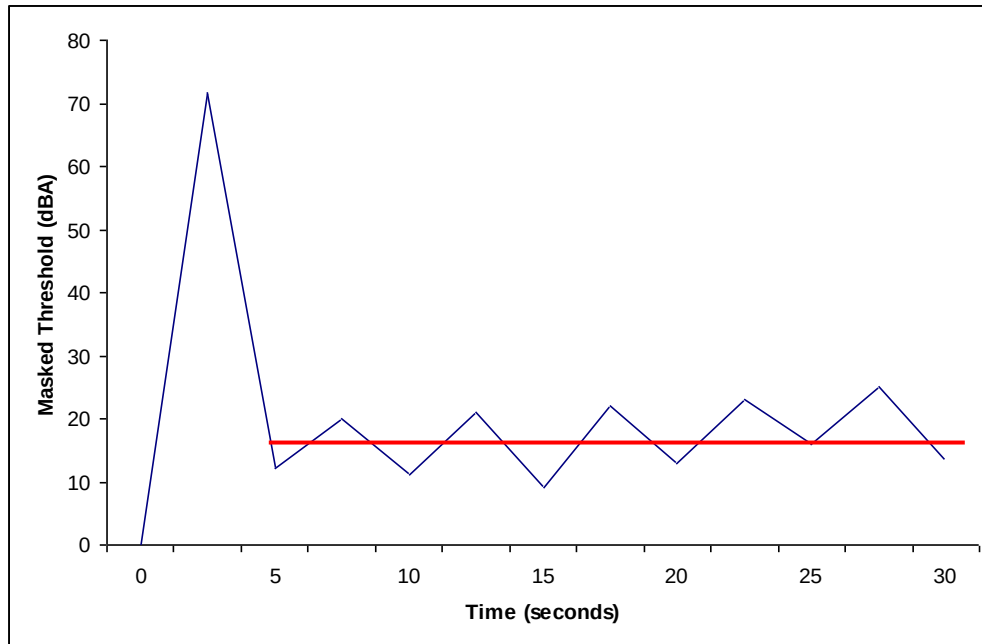


Figure 39. Example threshold tracking data, with midline between peaks and troughs. Mean threshold value for this example, excluding first excursion, is 17.2 dBA.

Least-square (LS) mean values were used instead of regular arithmetic mean values because they allowed comparisons to be made between means for unequal sample sizes, in this case normal-hearing and non-normal hearing listeners (See Table 12). By definition, LS means are predicted population margins; i.e., they predict the estimated marginal means over a balanced population. In other words, LS means are to unbalanced designs as the arithmetic means are to balanced designs (Searle, Speed, and Milliken, 1980).

TABLE 12. ANOVA Summary table for *main effects* (**bold** values indicate significance) in the backup alarm detection experiment.

Source	DF	ANOVA SS	MS	F Value	Pr > F
Between-Subjects					
Hearing Ability (HA)	1	6534.4950	6534.4950	622.50	<.0001
S/HA	20	209.9436	10.4972		
Within-Subjects					
Hearing Protector Device (HPD)	3	665.3798	221.7933	21.13	<.0001
HA X HPD	3	29.1348	9.7116	0.93	0.429
HPD X S/HA	60	626.5555	10.4426		
Noise Level (NL)	3	35923.8027	11974.6009	1140.74	<.0001
HA X NL	3	195.2749	65.0916	6.20	0.0004
NL X S/HA	60	629.9190	10.4987		
Noise Type (NT)	1	7.3892	7.3892	0.70	0.4022
HA X NT	1	0.6605	0.6605	0.06	0.8021
NT X S/HA	20	220.1733	11.0087		
NT X HPD	3	4.1228	1.3743	0.13	0.9417
HA X NT X HPD	3	1.1222	0.3741	0.04	0.991
NT X HPD X S/HA	60	561.0900	9.3515		
NT X NL	3	18.0131	6.0044	0.57	0.6339
HA X NT X NL	3	7.7058	2.5686	0.24	0.8651

NT X NL X S/HA	60	642.1500	10.7025		
HPD X NL	9	150.1193	16.6799	1.59	0.1179
HA X HPD X NL	9	18.4444	2.0494	0.20	0.9946
HPD X NL X S/HA	180	1844.4330	10.2469		
NT X HPD X NL	9	48.1440	5.3493	0.51	0.8673
HA X NT X HPD X NL	9	39.6105	4.4012	0.42	0.9244
NT X HPD X NL X S/HA	180	1886.2157	10.4790		
Total	703	50263.8991			

Results and Discussion. Outlined below are the results and discussion of the experiment described above.

Masked Threshold. The ANOVA revealed a significant main effect of hearing ability (HA) on masked threshold, $F(1,20) = 622.5$, $p < 0.0001$, with the LS-mean threshold values for normal hearing listeners and non-normal hearing listeners as 73.8 dBA and 83.5 dBA, respectively (See Figure 40). Non-normal hearing listeners required about 10 dBA of additional backup alarm intensity before the alarm was detected when compared to normal hearing listeners.

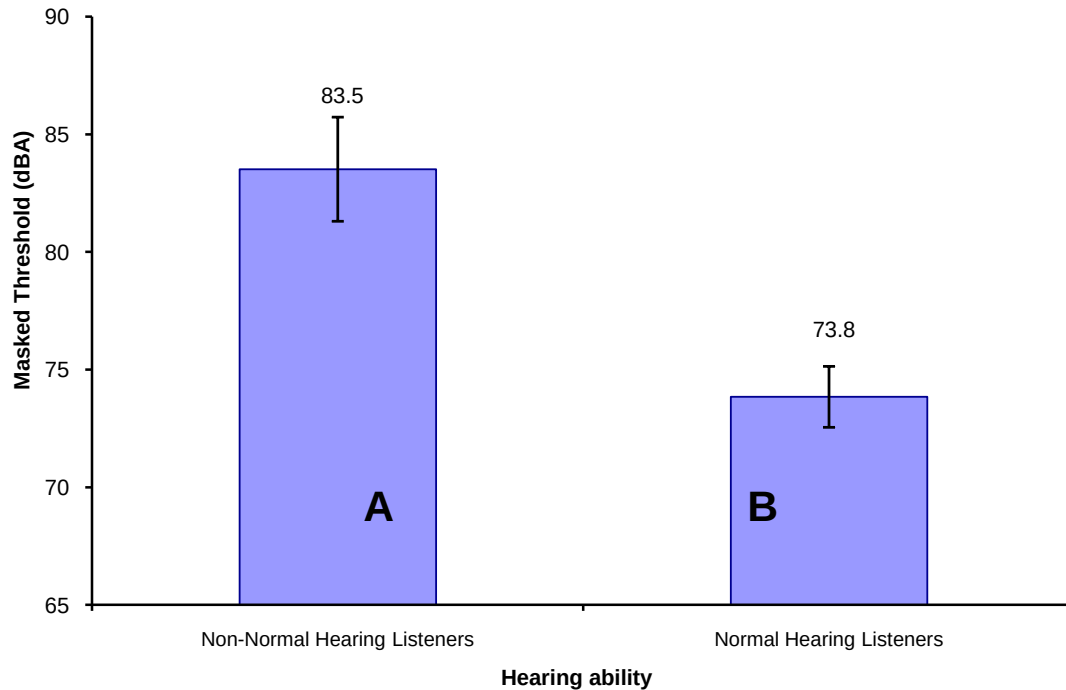


Figure 40. Main effect of hearing ability on masked threshold, with 95% confidence interval plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

ANOVA revealed a significant main effect of *HPD* on masked threshold $F(3,60) = 21.1$, $p < 0.0001$, with the LS means ranging from 77.1 dBA for the Bilsom® Clarity™ C2 to 80.5 dBA for the Bilsom Impact™ (see Figure 41). Post hoc analysis using the Tukey's test indicated that the use of the two sound transmission devices—the Bilsom Impact™ and the Peltor Tactical Pro™—resulted in higher masked threshold values (80.5 dBA and 79.8 dBA, respectively) than did their passive counterparts, the Bilsom Clarity™ C2 and the Peltor H7™ (77.1 dBA and 77.3 dBA, respectively). The passive headsets resulted in an *improved* ability to detect the backup alarm when compared to the sound transmission headsets, which required higher levels for detection. This suggests that the sound transmission devices amplified both the signal and the noise, and/or had an inherent earphone noise output (“hum”) thereby affecting the ability of listeners to detect the backup alarm in noise when compared to the passive headsets.

ANOVA revealed a significant main effect of noise level *NL* on masked threshold, $F(3,60) = 1140.7$, $p < 0.0001$, with the LS means ranging from 65.0 dBA for 75 dBA background noise to 92.7 dBA for the 105 dBA background noise (see Figure 42). Post hoc analysis using Tukey's test revealed that there were differences in masked threshold between all four noise levels, with increasing values as the noise levels were increased.

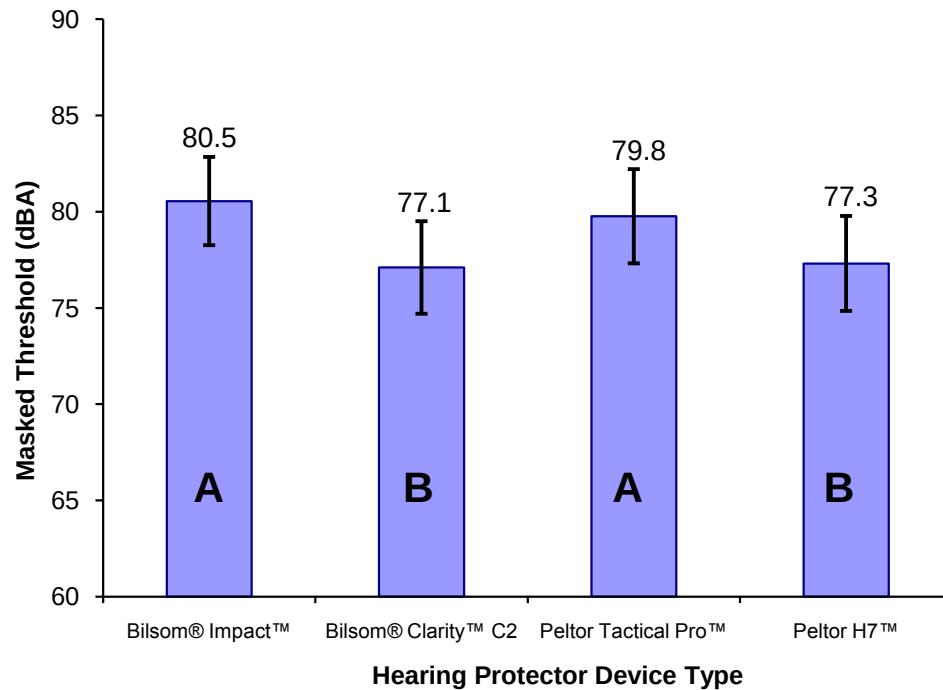


Figure 41. Effect of hearing protection device type on masked threshold with 95% confidence intervals. LS means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

ANOVA revealed a significant interaction of *HA* by *NL* on masked threshold, $F(3,60) = 6.2$ $p < 0.0004$ (see Figure 43). Post hoc analysis for the interaction of Noise Level *NL* and Hearing Level *HL* showed that non-normal hearing listeners had a statistically higher masked threshold values across all noise levels than did the normal hearing listeners. From looking at the graph of these results, it appears that a trend is present, where in noise levels below the lowest noise level (75 dBA) and in noise levels above the highest noise level (105 dBA), the masked thresholds between normal-hearing listeners and non-normal hearing listeners may converge. However, this apparent convergence is less dramatic in noise levels above 105 dBA.

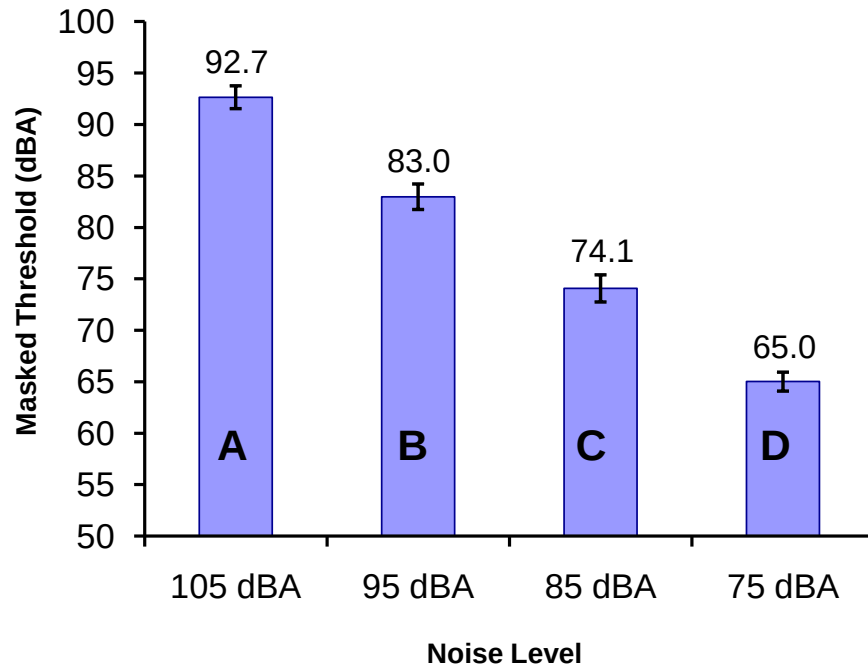


Figure 42. Main effect of Noise Level (NL) on masked threshold, with 95% confidence intervals plotted. LS Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

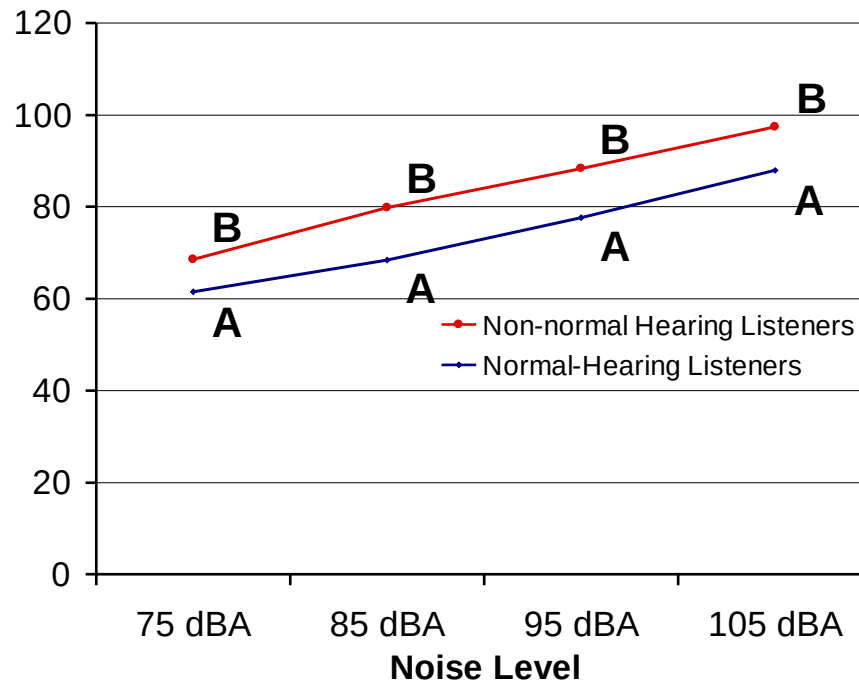


Figure 43. Interaction of hearing ability and noise level. LS Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

This suggests that, in noise levels below 75 dBA and perhaps in noise levels above 105 dBA, whatever advantages that the HPDs afforded to normal-hearing listeners when compared to non-normal hearing listeners with respect to masked threshold were reduced.

ANOVA did not show any significant main effects for noise type (pink noise versus milling machine noise), with means of 78.5 dBA and 78.8 dBA, respectively (see Figure 44).

ANOVA revealed a significant simple effect of *HPD* on masked threshold for normal hearing listeners in 75 dBA, $F(3, 63) = 5.4$, $p < 0.002$. Post hoc analysis using Tukey's test indicated that the Bilsom Impact™ resulted in significantly higher masked threshold values (63.8 dBA) than did the passive devices (59.7 and 60.9 dBA for the Bilsom Clarity™ C2 and the Peltor H7™, respectively) (see Figure 45 and Table 13). Masked threshold when using the Peltor Tactical Pro™ did not differ significantly from the other headsets. These results indicate that the electronic amplification of the Peltor Tactical Pro™ did not improve (or degrade) masked threshold when compared to the passive devices to the extent that the other sound transmission device (Bilsom® Impact™) did. Perhaps some elements of the latter headset (e.g., design, cushion composition, electronics) negatively affected masked threshold in this lowest noise condition when compared to the passive devices.

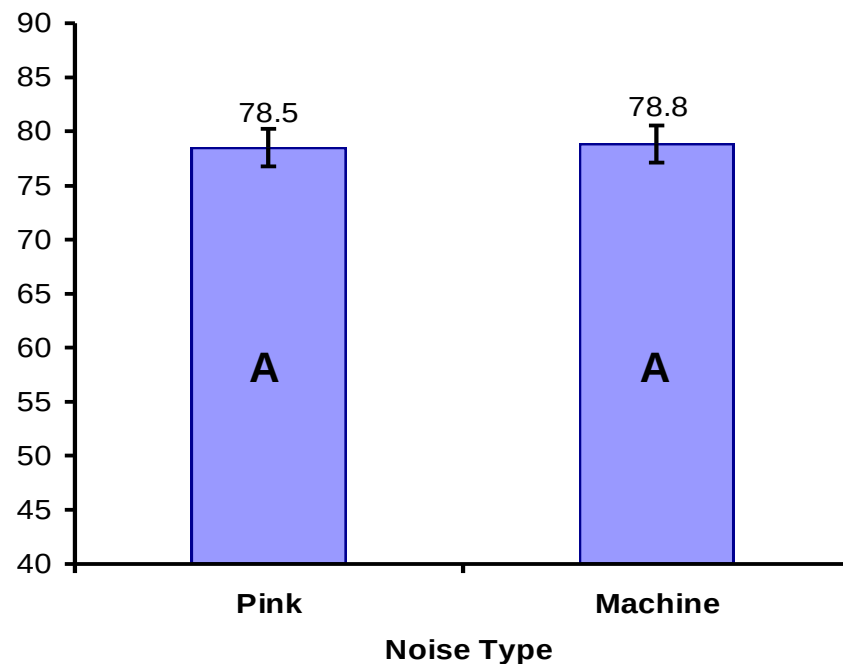


Figure 44. (Nonsignificant) effect of Noise Type (NT) on masked threshold on masked threshold, with 95% confidence intervals plotted. LS Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

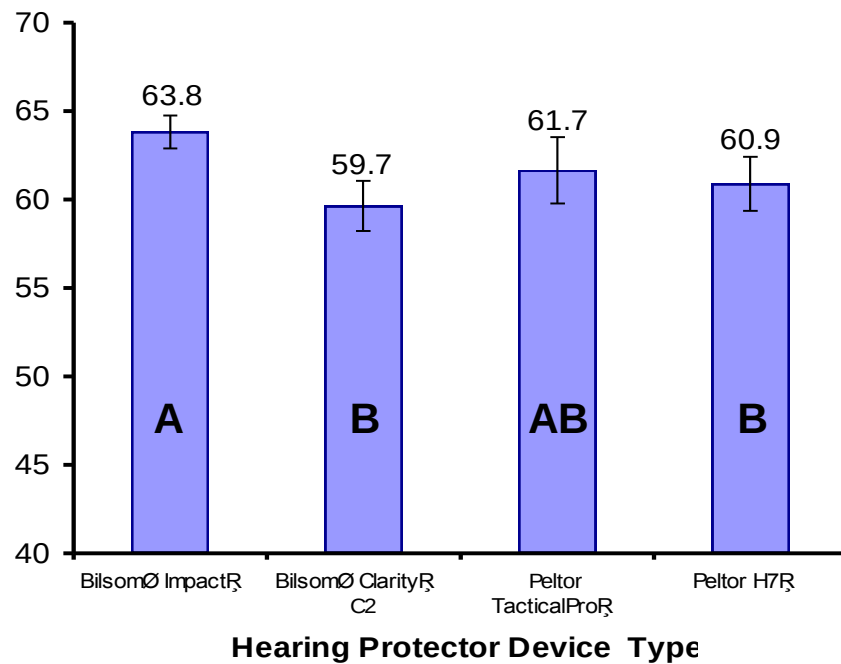


Figure 45. Partitioned simple effect of hearing protection device type and noise level on masked threshold for normal hearing listeners at 75 dBA. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

TABLE 13. ANOVA Summary table for normal hearing listeners in 75 dBA noise (partitioned data) (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	F Value	Pr > F
Model	7	183.9	26.3	2.9	0.0119
Error	56	508.8	9.1		
Corrected Total	63	692.8			
HPD	3	147.8	49.3	5.4	0.0024
NT	1	11.8	11.8	1.3	0.2590
HPD*NT	3	24.4	8.1	0.9	0.4500

There were no significant differences in masked threshold for normal-hearing listeners between HPDs in any of the background noise levels above 75 dBA (i.e., 85, 95, or 105 dBA) for normal listeners. In 85 dBA background noise, masked threshold values were 70.4, 67.7, 69.2, and 66.2 dBA for the Bilsom Impact™, Bilsom Clarity™ C2, Peltor Tactical Pro™, and Peltor H7™, respectively (see Figure 46). In 95 dBA background noise, masked threshold

values were 78.9, 76.8, 79.2, and 75.5 dBA for the Bilsom Impact™, Bilsom Clarity™ C2, Peltor Tactical Pro™, and Peltor H7™, respectively (see Figure 47).

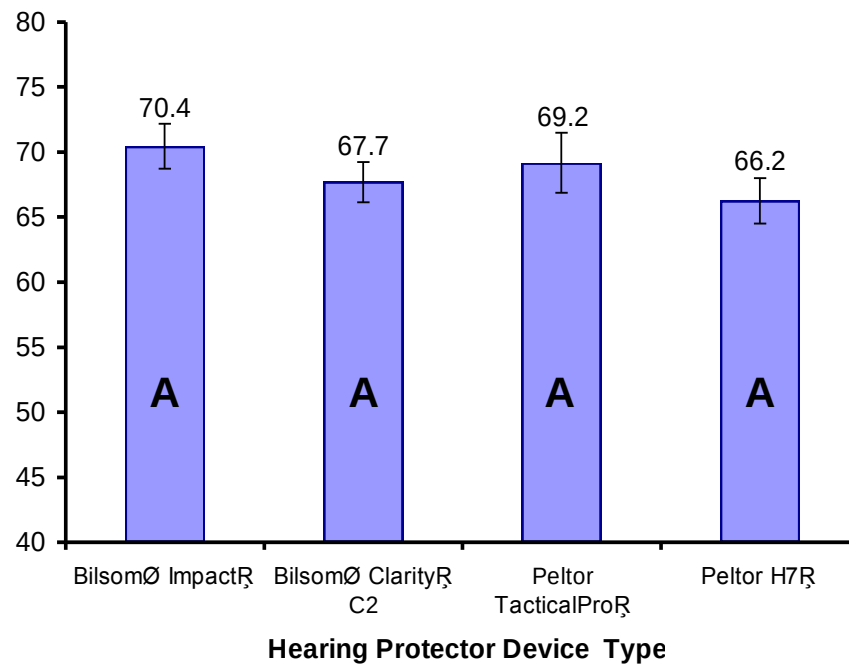


Figure 46. (Nonsignificant) effect of hearing protection device type and noise level on masked threshold for normal hearers in 85 dBA background noise, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

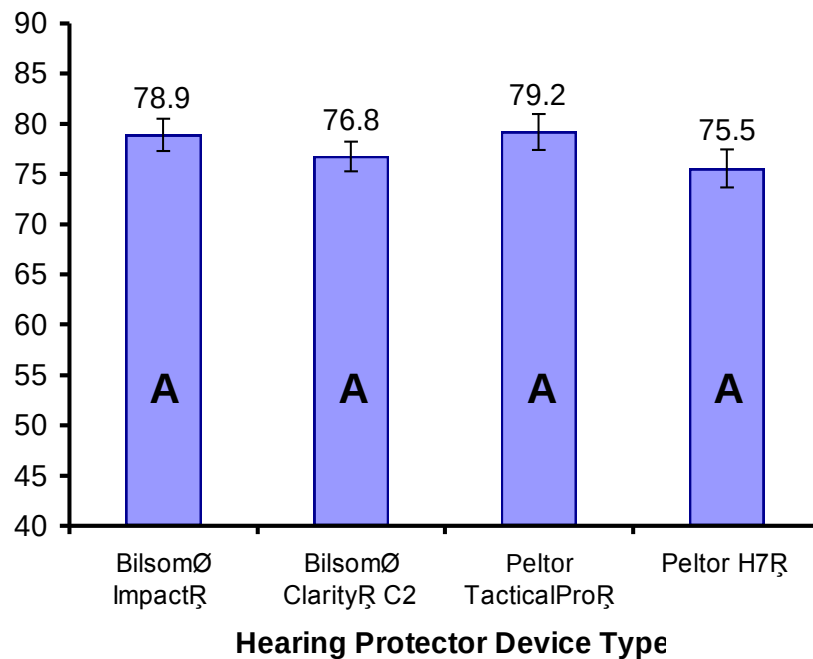


Figure 47. (Nonsignificant) effect of hearing protection device type and noise level on masked threshold for normal hearers in 95 dBA background noise, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

In 105 dBA background noise, masked threshold values were 88.9, 86.8, 88.1, and 87.8 for the Bilsom Impact™, Bilsom Clarity™ C2, Peltor Tactical Pro™, and Peltor H7™, respectively (see Figure 48).

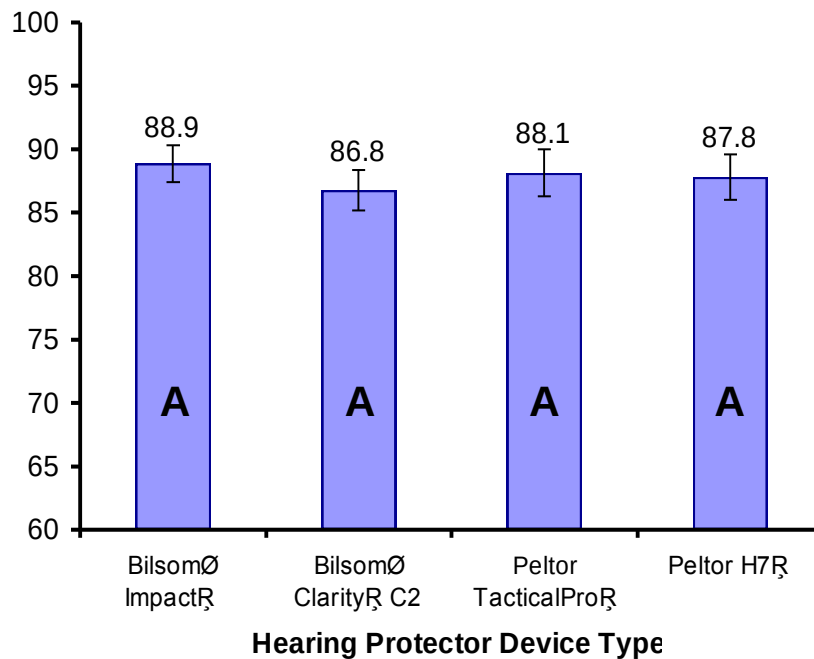


Figure 48. (Nonsignificant) effect of hearing protection device type and noise level on masked threshold for normal hearers in 105 dBA background noise, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

ANOVA revealed a significant difference in masked threshold for non-normal listeners across *HPD* in 75 dBA background noise, $F = 9.8$, $p < 0.006$ (See Table 14). Post hoc analysis using Tukey's test revealed that the Bilsom Impact™ and the Peltor Tactical Pro™ resulted in a significantly higher masked threshold values (70.8 and 70.2 dBA, respectively) than for the Bilsom Clarity™ C2 (65.8 dBA). The Bilsom Impact™ also resulted in a significantly higher masked threshold than did the Peltor H7™ (67.4 dBA). The Peltor Tactical Pro™, however, did not differ from the Peltor H7™ with respect to masked threshold. Also, the Peltor H7™ did not differ from the Bilsom Clarity™ C2 with respect to masked threshold (see Figure 49).

TABLE 14. ANOVA Summary table for non-normal hearing individuals in the 75 dBA noise level (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	F Value	Pr > F
HPD	3	100.0	33.3	9.8	0.0006
NT	1	0.1	0.1	0.0	0.8525
HPD X NT	3	11.4	3.8	1.1	0.3659
HPD X NT X S/HA	16	54.0	3.4		
Total	23	165.6			

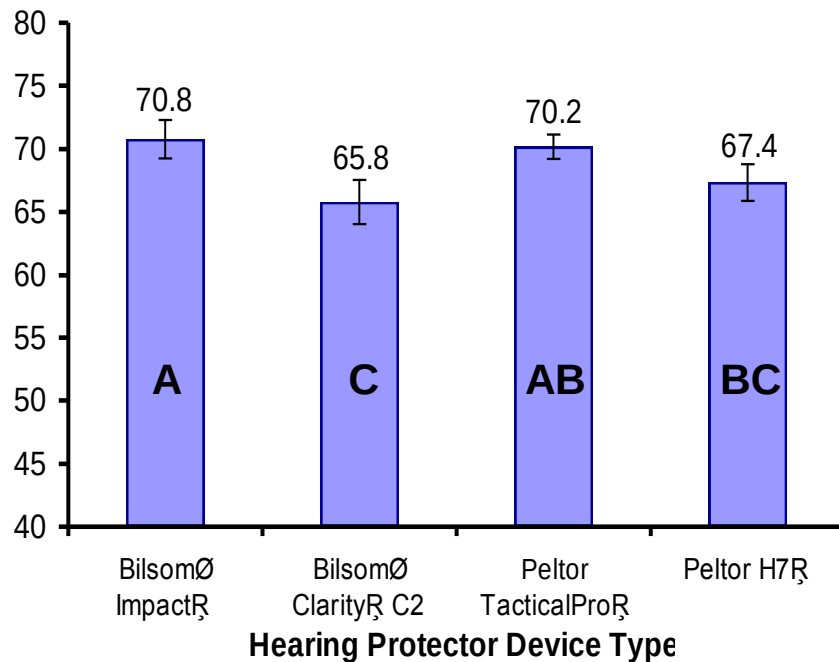


Figure 49. Effect of hearing protection device type and noise level on masked threshold for non-normal hearers in 75 dBA noise, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

The results in this low-noise condition (75 dBA) are difficult to interpret. They suggest that the Bilsom Impact™ sound transmission headset resulted in greater difficulty for non-normal listeners to detect the backup alarm when compared to the passive devices. However, the other sound transmission headset (Peltor Tactical Pro™), while resulting in increased masked thresholds when compared to one of the passive devices (Bilsom Clarity™ C2), did not

differ from the other passive device (Peltor H7™) with respect to masked threshold, nor from the Bilsom electronic muff.

The two Bilsom HPDs, as mentioned previously, had identical NRRs (23); similarly, the Peltor HPDs also had identical NRRs (26). The fact that the Bilsom Impact™ and the Peltor H7™ differed with respect to masked threshold was not surprising, given the combination of technologies (sound transmission vs. passive) and labeled NRRs. However, the two Peltor products, both also having different technologies, did not differ with respect to masked threshold; conversely, the two Bilsom products *did* differ for this metric. This result suggests that the sound transmission technology of the Peltor Tactical Pro™ (and the added cost when compared to its passive counterpart) provides no real benefit in backup alarm masked threshold for non-normal listeners when compared to the Peltor H7™. However, the sound transmission technology of the Bilsom Impact™ not only does *not* provide a masked threshold or cost benefit for non-normal listeners with respect to masked threshold when compared to its passive counterpart (Peltor H7™), it actually hinders signal detection in noise. The fact that the sound transmission headset technology again results in increased masked threshold, or does not differ from passive headsets in masked threshold for non-normal listeners, again calls into question the efficacy of these systems for construction environs.

ANOVA revealed a significant difference in masked threshold for non-normal listeners across HPD in 85 dBA background noise, $F = 15.5$, $p < 0.0001$ (See Table 15). Post hoc analysis indicated that the two sound transmission devices resulted in significantly higher masked threshold values (82.9 and 81.7 dBA for the Bilsom Impact™ and Peltor Tactical Pro™, respectively), than did the passive devices (77.7 and 76.8 dBA for the Bilsom® Clarity™ C2 and Peltor H7™, respectively) (see Figure 50). These results indicate that, *as the background noise level reached the OSHA action level (85 dBA), the passive devices outperformed the sound transmission devices with respect to masked threshold for non-normal listeners*. The results further suggest that the amplification abilities of the electronic devices, which were hypothesized to *reduce* the masked threshold for listeners with hearing impairments, did not afford any advantage in backup alarm signal detection when compared to passive devices.

TABLE 15. ANOVA Summary table for non-normal hearing individuals in the 85 dBA noise level (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	F Value	Pr > F
HPD	3	158.4483	52.8000	15.50	0.0001
NT	1	2.5350	2.5350	0.70	0.4010
HPD X NT	3	2.5883	0.9000	0.25	0.8578
HPD X NT X S/HA	16	54.4867	3.4000		
Total	23	218.0583			

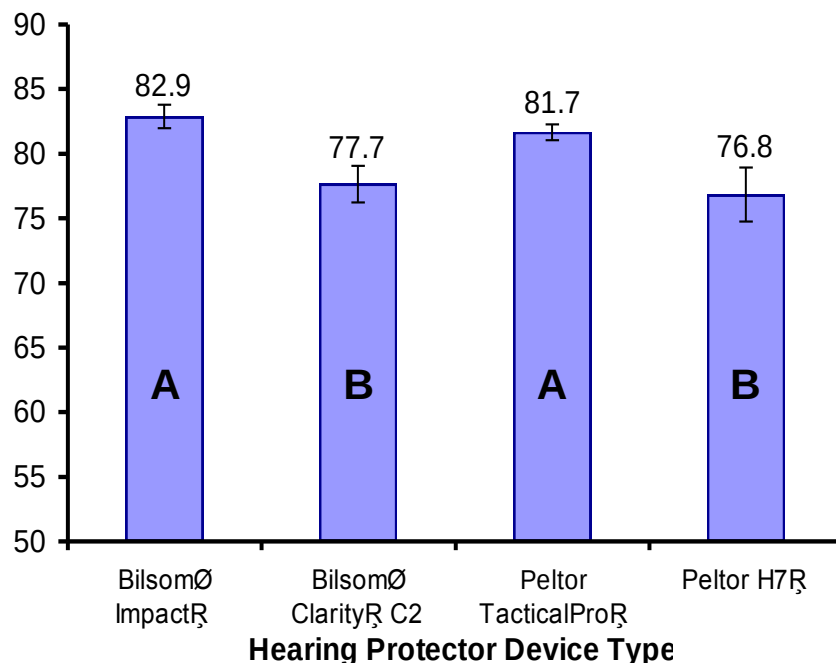


Figure 50. Effect of hearing protection device type and noise level on masked threshold for non-normal hearers in 85 dBA noise, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

ANOVA revealed a significant difference in masked threshold for non-normal listeners across HPD in 95 dBA background noise, $F = 7.0$, $p < 0.031$ (see Table 16). Post-hoc analysis using Tukey's test indicated that the Bilsom Impact™ resulted in a significantly higher masked threshold value (90.7 dBA) than did the passive devices (86.7 and 86.1 dBA for the Bilsom Clarity C2 and Peltor H7™, respectively) (See Figure 51). The two sound transmission devices did not differ with respect to masked threshold (90.7 dBA for the Bilsom Impact™, 90.0 dBA for the Peltor Tactical Pro™). Masked threshold for the Peltor Tactical Pro™, however, did not differ from that for the Bilsom Clarity™ C2, which resulted in a value of 86.7 dBA for this metric. Finally, the masked threshold value for the Peltor H7™ device did not differ from that of the Bilsom Clarity™ C2.

Somewhat similar to the data measured in the 75 dBA noise condition, the masked threshold results across HPD in the 95 dBA noise condition are difficult to interpret. The sound transmission devices resulted in increased masked thresholds, but only when compared to the passive Peltor H7™. The Bilsom Clarity™ C2, while affording a reduced masked threshold when compared to the electronic Bilsom Impact™, still did not differ from the electronic Peltor Tactical Pro™ with respect to this metric. But, the overall conclusion in this noise level is that, as a general rule, the electronic devices do not by virtue of their sound transmission technologies result in improved signal detection when compared to passive devices.

TABLE 16. ANOVA Summary table for non-normal hearing individuals in the 95 dBA noise level (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	F Value	Pr > F
HPD	3	94.1913	31.3971	7.04	0.0031
NT	1	0.7004	0.7004	0.16	0.6972
HPD X NT	3	3.2513	1.0838	0.24	0.8652
HPD X NT X S/HA	16	71.4067	4.5000		
Total	23	169.5496			

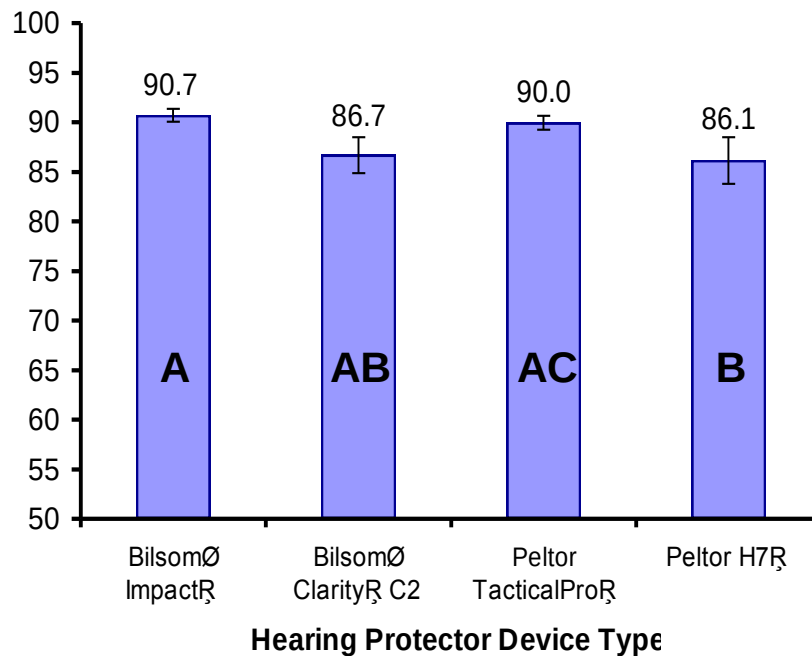


Figure 51. Effect of hearing protection device type and noise level on masked threshold for non-normal hearers at 95 dBA, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

ANOVA did not reveal any significant differences in masked threshold for non-normal listeners across HPD in 105 dBA background noise (see Figure 52). The Bilsom Impact™ resulted in a masked threshold value of 98.0 dBA, while the Bilsom Clarity™ C2, Peltor Tactical Pro™, and the Peltor H7™ resulted in masked threshold values of 95.8, 98.2, and 97.6 dBA, respectively. Thus, there were no advantages of any HPD type as to signal detection in the most intense noise level of the experiment.

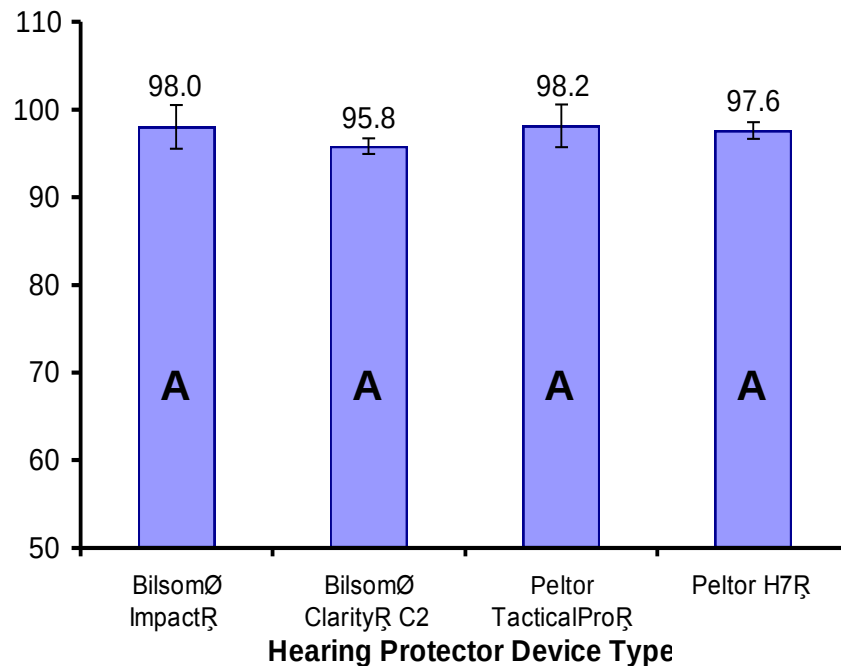


Figure 52. (Nonsignificant) effect of hearing protection device type and noise level on masked threshold for non-normal hearers at 105 dBA, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Comfort and Detectability Ratings. Data obtained from the rating scale (Appendix D) were used to elicit and quantify a hearing protection device wearer's subjective feeling of comfort. As explained earlier, each rating consisted of a seven-point bipolar scale with an adjective at both ends. Descriptors at one end connoted an opposite subjective perception to those at the other end. Also, the descriptors on the rating scale did not have a particular directional orientation (left to right) with respect to the first scale ("Uncomfortable/Comfortable" scale), which was considered the essential scale to the participant's perception of the HPD comfort. This was done as a way to reduce the 'halo' effect on participants. If choices were based on halo effect, participants may have rated the scale consistently with one persistent impression instead of marking the different scales based on independent judgments.

The first step of data reduction for the rating scale involved altering the direction on some of the scales (i.e., 7 to 1, 6 to 2, etc.) such that all scales had the same polarity with the Uncomfortable/Comfortable scale. The Uncomfortable/Comfortable scale was used as an anchor, since the overall scale was aimed at evaluating the comfort levels of each HPD. The correlation of each scale was then determined against the Uncomfortable/Comfortable scale because those scales with a higher correlation with the Uncomfortable/Comfortable scale would be indicative of feelings influencing a participant's perception of the HPD's comfort. The Pearson correlation coefficients (R) are presented in Table 17. Statistically significant correlations ($|R| > 0.045$) are shown in **bold** and were used to develop the *Comfort Index (CI)*, including the Uncomfortable/Comfortable scale. These indices are defined as the linear sum of

all 12 items on the scales that had a significant correlation with the Uncomfortable/Comfortable scale (per Casali and Park, 1991).

TABLE 17. Pearson Correlation Coefficients (*R*) for each Bipolar Comfort Descriptor with the Uncomfortable-Comfortable Scale (boldface indicates a statistically-significant correlation at $p < 0.5$).

HPD Scale Descriptors	R
Uncomfortable/Comfortable	1.00
Painless/Painful	0.65
No uncomfortable pressure/Uncomfortable pressure	0.62
Intolerable/Tolerable	0.70
Tight/Loose	-0.03
Not Bothersome/Bothersome	0.71
Heavy/Light	0.60
Cumbersome/Not cumbersome	0.34
Soft/Hard	0.56
Cold/Hot	0.19
Smooth/Rough	0.68
Feeling of complete Isolation/No feeling of complete Isolation	0.20

Table 18 summarizes the mean and standard deviation values for each HPD. The minimum possible CI score was “0” and the maximum possible CI score was “56,” with higher scores relating to greater comfort. A non-parametric Kruskal-Wallis Test was performed on the CI data, which indicated no significant difference ($p \geq 0.05$) in comfort between the four devices. This result suggests that participants did not rate any HPD as more comfortable than any other HPD in the experiment.

TABLE 18. Comfort Index means and standard deviations for the hearing protection devices.

	Bilsom Impact™	Bilsom Clarity™ C2	Peltor Tactical Pro™	Peltor H7™
Mean	32.73	37.70	34.45	34.73
S.D.	(9.78)	(10.11)	(6.9)	(11.18)

At the completion of each experimental session, participants ranked the devices from 1 to 4 (easiest to hardest) based on their perceived ability to detect the backup alarm using a semantic differential detectability scale (shown in Appendix D). The mean and standard deviation values from the questionnaire are presented in Table 19. The minimum possible score was zero and the maximum possible score was 7 (higher scores relate to greater difficulty in detecting the alarm). Again, a non-parametric Kruskal-Wallis Test was performed on the data, which showed that there were no significant differences ($p \leq 0.05$) between the four devices with respect to the participants' perceived ability to detect the backup alarm.

TABLE 19. Detectability index means and standard deviations for the hearing protection devices.

	Bilsom Impact™	Bilsom Clarity™ C2	Peltor Tactical Pro™	Peltor H7™
Mean	4.09	3.81	3.72	3.45
S.D.	(1.76)	(1.72)	(1.10)	(1.75)

Conclusions: Backup Alarm Masked Threshold Study. It is important to outline the limitations of this research and how they can influence the interpretation of the results. Most notable is the fact that out of all of the resources and numerous potential participants that were contacted through fliers, emails, word of mouth, and other hearing clinics, only three participants with hearing abilities meeting the non-normal hearing criteria were recruited and participated in the study. This had an effect of reducing the overall power ($1 - \beta$) of the ANOVA, thus enhancing the potential of making a type II error (β – failing to reject the null hypothesis when, in fact, it is false). ***Passive Devices vs. Sound Transmission Devices***

Passive Devices vs. Sound Transmission Devices. The results suggest that sound transmission HPDs do not offer advantage over passive devices with respect to the *detection* of a backup alarm signal within the 4 various levels of pink and milling machine noise. *For the most part, the passive devices displayed a masked threshold advantage (i.e., better detection)*

of (on average) 3 dBA over the sound transmission devices. This result can most likely be attributed to the fact that the latter devices amplified both the broadband background noise and the signal, therefore making it difficult for the listener to detect the signal, and also due to the fact that the electronic devices produced some earphone “hum” which may have served as masking source which affected detection of the signal.

Sound transmission devices were expected to have lower masked threshold values for both normal and non-normal hearers for noise levels below 85 dBA, and to have the same masked threshold values for noise levels above 85 dBA. However, the results displayed different outcomes for both normal and non-normal hearers at most noise levels. According to the manufacturer of the Bilsom Impact™, the device has electronic filtering abilities that protect the ear from harmful background noise and amplify the sound the listener wants to hear; its amplification limiting levels are a “safe” 82 dBA

(http://www.labsafety.com/store/Safety_Supplies/Hearing_Protection/Earmuffs/39998/). In congruence with the above, the manufacturers of the Peltor Tactical Pro™ (the other sound transmission device) also confirmed that the device offers active protection from dangerous noise levels, while still amplifying safe sounds such as safety alarms. The built-in inhibitor in the device is claimed to restrain the sound amplification levels at a safe 82 dBA (Peltor Tactical Pro™ user manual).

Normal hearing Listeners. Based on partitioned data obtained in this study, the sound transmission devices offered no advantage over the passive devices in terms of masked threshold detectability for individuals with normal hearing. Particularly for the background noise level at 75 dBA, the Bilsom Impact™ and the Peltor Tactical Pro™ had higher masked threshold values (63.8 dBA and 61.7 dBA, respectively) than did the passive devices (Bilsom® Clarity™ C2 and Peltor H7™, masked threshold values of 59.7 dBA and 60.1 dBA, respectively), as illustrated earlier in Figure 39. This was inconsistent with the first hypothesis (H_1), which anticipated that the sound transmission devices would have a lower masked threshold value than the passive devices. In particular, the Bilsom Impact™ device had the highest masked threshold value. A number of the participants verbally complained that with the electronics turned on, it was difficult for them to distinguish the backup alarm from the background noise, suggesting that both the unwanted harmful background noise and the essential backup alarm were amplified. These results suggest that, contrary to the manufacturer’s indications, both devices were not able to distinguish ‘unwanted’ background noise from ‘the sound the listener wants to hear;’ in this case, the backup alarm. Instead, the devices amplified all sounds in the passband, regardless of whether or not they were safety-critical. Another participant complained of the loudness of the Peltor Tactical Pro™ when the electronics were turned on without any background noise present, and was causing pain in that participant’s ears each time the background was presented while wearing the device. This anecdote suggests that the Peltor Tactical Pro™ was presenting internal electrical or other sounds to the listener in the absence of noise.

For the rest of the background noise levels (i.e., 85 dBA, 95 dBA and 105 dBA), the sound transmission devices did not show any advantages in masked threshold over the passive devices for normal-hearing listeners. These results support the second hypothesis (H_2), which anticipated that both device types should have a same masked threshold values for background noise levels above 85 dBA. This might be due to the fact that the sound transmission devices,

in noise levels above 82 dBA, did indeed shut off as stated earlier, inhibiting the amplification ability, and acting as passive devices.

Non-normal Hearers. Results obtained from this study indicate that the sound transmission devices result in a disadvantage for hearing-impaired individuals in backup alarm masked threshold when compared to their counterpart, passive devices in 75, 85 and 95 dBA noise levels. This, again, might be due to the fact that the sound transmission devices amplified both the signal and the background noise, therefore making it difficult to perceive the backup alarm. In 105 dBA noise, the sound transmission device did not differ from the passive devices in backup alarm masked threshold, which suggests that whatever benefit received by the passive devices in lower noise levels disappeared in the highest tested noise level. The results of this research also tend to confirm the results of the Casali and Wright (1995) study, which also found no differences in masked thresholds between passive and sound transmission devices; but those authors wrote at the time that the lack of differences may have been due to the relatively low resolution (5 dBA) between the stimulus levels used in that study. That is, had a more precise resolution step between stimuli been used, that differences in masked threshold between device types may have been realized. The current research used a 1 dBA resolution, yet *still* did not find differences in masked threshold between passive and sound transmission devices. So it must be the case, at least for the HPDs tested (and they were considered by the Research Team, based on analyses and use, to be at the higher performance end of those currently available) that sound transmission earmuffs offer no advantage in backup alarm detectability over passive earmuffs.

Effects of Background Noise Level on Masked Threshold. As anticipated, background noise level was found to directly affect the masked threshold values in a systematic manner—the higher the background noise, the higher the masked threshold value. This effect was illustrated previously in Figure 37, and is consistent with the research of Hawkins and Stevens (1950).

Effects of Noise Type on Masked Threshold. In this study, noise type was not found to have an effect on masked threshold values. This result was surprising because, theoretically, one would expect upward spread of masking to occur in the higher levels of lower frequency noise presented by the milling machine noise (see Figure 34). That is, the more intense noise presented at 315 Hz in the milling machine noise would be expected to result in harmonics at 630 Hz and at about 1250 Hz (the latter of which is the backup alarm primary frequency) that would mask the signal more efficiently than would the equal-energy-by-octaves pink noise, hence increasing the masked threshold values.

Comfort and Detectability Ratings. There were no differences in comfort ratings for any of the devices, indicating that no HPD had any advantage over the other in terms of comfort. However, this result is tempered by the fact that participants completed the comfort rating scale based only on short duration in using the devices in controlled laboratory conditions. No differences in detectability of the backup alarm signal were found between the devices, indicating that no particular HPD was perceived as providing better backup alarm detection than any other HPD. Of course, this subjective rating of detectability was generally corroborated by the masked threshold data given the lack of any advantage of detectability of any HPDs in most conditions in those objective, quantitative data.

Experiment 3: Backup alarm localization.

Rationale and Objectives. As the third human factors experiment in this research project, an experiment investigating the critical task of backup alarm *localization* in the azimuth dimension was conducted. This critical task, which follows after both backup alarm *detection* and *recognition*, is an important one that helps the construction worker to determine from where a backup alarm-enunciating vehicle is located. Similar to the backup alarm masked threshold experiment just presented, this study sought to compare the capabilities of various conventional (passive) hearing protection and amplitude-sensitive (“assistive-listening”) hearing protection, but instead of detection, the focus was on localization ability.

As discussed previously, various HPD designs exist, including earplugs and earmuffs (of both supra-aural and circumaural varieties). Of those earmuffs that maintain electronic functionality, and as discussed, there is merit in ascertaining the ability of both *diotic* (i.e., one microphone being used to present the same signal to both ears) and *dichotic* (i.e., two or more microphones being used to present a different signal to each ear, typically one on each earcup [left and right]). Thus, the latter technology *should theoretically* provide improved ability to localize a signal, as multiple microphones may be able to ‘preserve’ or otherwise mitigate the loss of the open-ear localization ability afforded through head shadow and binaural phase differences. This study included a variety of conventional and augmented earplugs and earmuffs, as well as an open-ear condition, toward ascertaining localization ability under each type of HPD available for this application.

Another component of this study was that of the backup alarm itself. Based on human factors heuristics and auditory display design, the research team decided to ‘modify’ the current, standardized backup alarm signal’s frequency content in an effort to determine whether it would foster improved localization performance when compared to the SAE-standardized backup alarm (SAE J994b). The modified backup alarm included frequencies that should assist human localization ability (i.e., the addition of frequencies that make use of the aforementioned head shadow and binaural phase differences). As in the previous detection study, varying levels of a masking noise were used toward real-world applicability; that is, an attempt to recreate an ambient construction noise environment that would be found in the field, and which might affect the ability of construction workers to localize backup alarm signals.

Methodology. The hypotheses for the localization experiment were as follows:

- H₁:** Earplugs, as a class of HPD, were expected to provide more accurate (i.e., more correct responses and fewer errors) localization decisions compared to earmuffs, because they do not occlude the pinnae of the outer ear.
- H₂:** When compared to all other HPD conditions, the diotic earmuff would result in the least accurate localization decisions.
- H₃:** The modified backup alarm signal would result in more accurate localization decisions when compared to the standard backup alarm signal.
- H₄:** The high background noise level would result in less accurate localization decisions when compared to the low background noise level.

H₅: Localization accuracy when using the foam earplug would be improved when compared to the premolded earplugs. (This contention was hypothesized as a potential adverse affect of the premolded earplugs' stem handle on the spectral cues afforded by the pinnae.)

The design of the experiment (sound localization in azimuth dimension) is an $8 \times 2 \times 2$ completely within-subjects design with three independent variables and four dependent measures (see Figure 53). The first independent variable was *hearing protection device (HPD)* (8 levels, within-subject). The second independent variable was *backup alarm type* (2 levels, within-subject), and the third was *background noise level* (2 levels, within-subject). Each independent variable is discussed in more detail below.

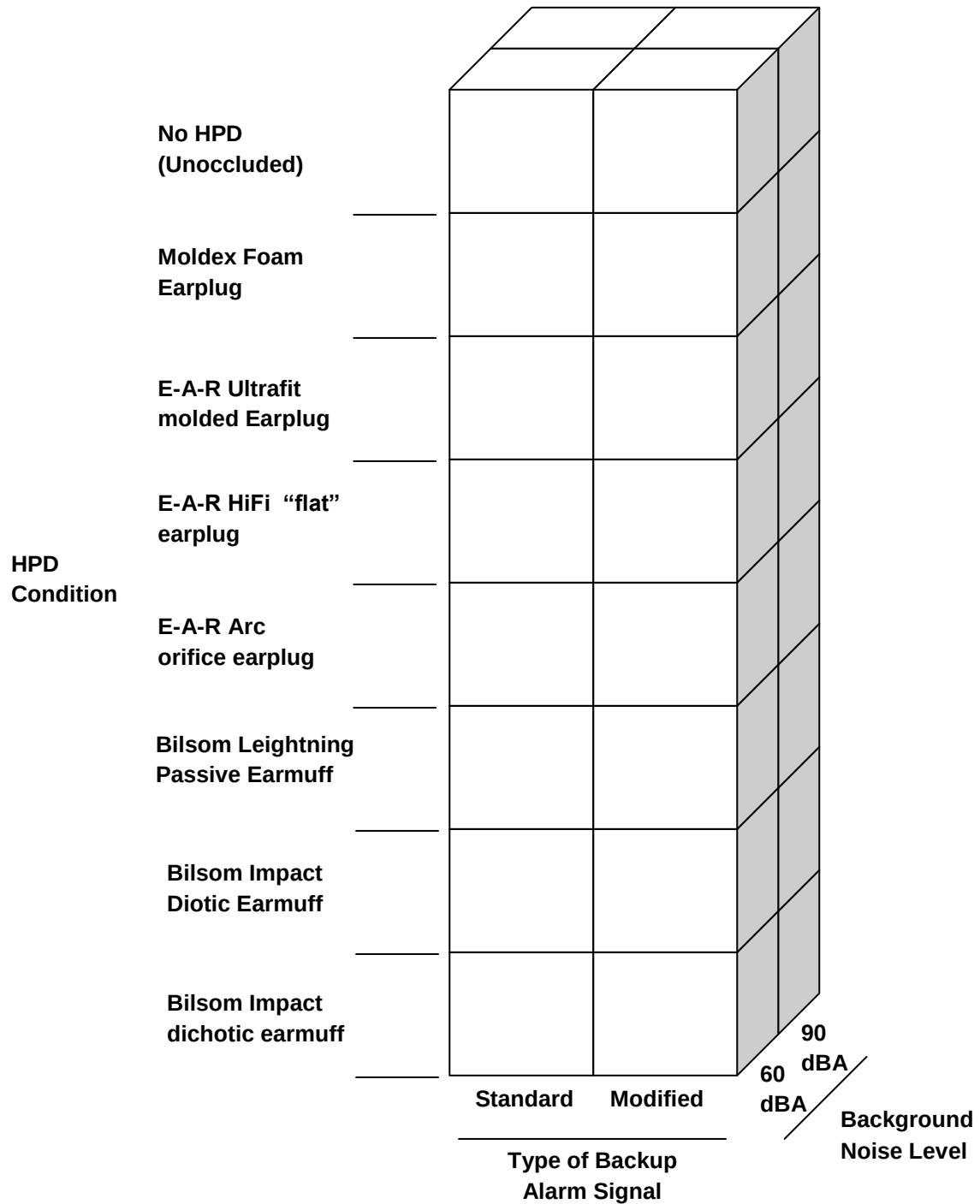


Figure 53. Experimental design for the backup alarm localization study.

Participants. Twelve normal hearing participants (i.e., ≤ 25 dBHL between 250 and 6000 Hz, with a symmetry difference of ≤ 15 dBHL between the two ears) participated in this experiment. Participants ages were 18 or older.

Independent Variables. The *hearing protection device (HPD)* independent variable (8 levels) consisted of 1) an unoccluded (i.e., no HPD) condition, 2) the Moldex Model #6604 foam earplug (Spark Plug™), 3) the E-A-R Ultrafit™ premolded earplug, 4) the E-A-R HI-FI™ earplug (a “flat” attenuation device), 5) the E-A-R Arc™ earplug (an industrial version of the Combat Arms earplug), 6) the Bilsom Lightning™ Hi-Visibility L3HV passive earmuff, 7), modified-to-diotic Bilsom Impact sound transmission earmuff, and 8) the Bilsom Impact™ dichotic sound transmission earmuff (see Figure 54).

The selection of the Moldex foam earplug (NRR=33) was made based upon its prevalence in the HPD industry, while the selection of the E-A-R Ultrafit™ premolded earplug (NRR=25) and E-A-R HI-FI™ earplug (NRR=12) was made based on their hygienic benefits (an important concern in the often-dirty environments of road construction), including the fact that they do not require ‘roll-down’ for appropriate ear fitting. Additionally, and with respect to the E-A-R HI-FI earplug, it is a flat and moderate attenuation device, having the ability to provide a near-uniform amount of attenuation between 100-8000 Hz, which increases the ability of pitch perception.

The E-A-R Arc earplug was selected for inclusion in this study because its level-dependent side (NRR=0) provides little to no attenuation at frequencies below 1000 Hz when compared to other earplugs used in this experiment, under incident impulsive sound levels reach about 120 dB, where its attenuation sharply increases. Such qualities may aid the listener in that the effect of the Interaural Time Difference (ITD)—as a cue for azimuthal sound localization—may be enhanced. The Bilsom Lightning Hi-Visibility L1HHV passive earmuff (NRR=30) was selected because it provides a relatively high attenuation when compared with many other available earmuffs. High attenuation can be considered advantageous with respect to hearing protection in the high noise environments of construction sites, but may degrade signal detection and localization. In addition, the Bilsom Lightning passive earmuff is the conventional passive counterpart of the augmented active earmuffs used in this experiment. The Bilsom Impact modified-to-diotic (NRR=23) and dichotic (NRR=23) earmuffs were selected for this experiment since they can be used efficiently in intermittent noise environments, such as construction sites, due to their sound transmission capabilities, described earlier herein and also in Casali (2005). The Bilsom diotic earmuff is not a production product, but was custom-produced by Bilsom for this study on request, so that the diotic effect on localization could be investigated.

Unoccluded (No HPD) HPD Condition (a)	(b)
(c)	(d)
(e)	(f)
(g)	(h)

Figure 54. HPD levels for the backup alarm localization experiment. The HPDs are (a) Unoccluded (No HPD) (b) Moldex Foam Earplug (Sparkplug Model#6604), (c) E-A-R Ultrafit premolded earplug, (d) E-A-R HI-FI earplug, (e) E-A-R Arc earplug, (f) Bilsom (Leightning Hi-Visibility L1HHV) Passive Earmuff, (g) Bilsom Impact modified-to-diotic earmuff (one microphone feeds 2 earcups; not a production product, but custom-manufactured for this study only), and (h) the Bilsom Impact dichotic earmuff (two microphones, one feeding each earcup).

The *background noise level* independent variable included two levels: 60 dBA and 90 dBA of pink (i.e., flat-by-octave) noise (i.e., “low” and “high”, respectively). The higher level, 90 dBA, was selected because it comprises the Permissible Exposure Limit (PEL) (i.e., criterion level) of OSHA, and because it is representative of many noise levels produced from various construction equipment as measured on construction sites (see Figure 3).

The *backup alarm type* represented the third independent variable manipulated in this study. Based on the frequency of the backup alarm signal, two types were used: the standard backup alarm and a modified backup alarm. The standard backup alarm (SAE J994b) includes a dominant frequency of 1250 Hz and a strong harmonic at 2500 Hz, while the modified type of the backup alarm was based on the human localization characteristics discussed above, and included 400 Hz, 1250 Hz, 2500 Hz, and 4000 Hz. It was expected that the modified backup alarm signal would provide more accurate sound localization decisions in the azimuth dimension than would the standard backup alarm signal. The rationale for this contention is because the additional frequencies (i.e., 400 Hz and 4000 Hz) would allow participants to make use of the Interaural Level Difference (ILD, the difference in sound intensity between the two ears) and Interaural Time Difference (ITD, the difference in sound arrival time between the two ears) in localizing the source of the signal out of the median plane. Additionally, the spectral cues in the modified signal (the broad bandwidth of the backup alarm signal and the frequencies available in the 1000 to 4000 Hz range) may increase the performance of listeners with respect to front/rear localization.

Dependent Measures. There were four dependent measures that were analyzed in the experiment. These measures were used to assess sound localization accuracy, and included: 1) the *number of accurate (i.e., correct) localization responses*, 2) the *number of left/right localization errors*, 3) the *number of front/rear localization errors*, 4) the *absolute deviation in degrees from the source of sound*. A pictorial illustration of these measures is depicted in Figure 55.

As illustrated in Figure 55(a), any response within the range of 22.5° to the left or right of the stimulus source was considered *correct*. Right-left localization errors could result from listeners judging any stimulus emanating from right sources as being emanating from left sources or vice-versa, see Figure 55(b). Figure 55(c) depicts how front-rear localization errors were determined; any stimulus emanating from front sources and judged by the listeners as emanating from rear sources or vice-versa was considered a front-rear error. Finally, Figure 55(d) depicts how the absolute deviation in degrees was measured. This metric indicated, in absolute value, what were the listeners’ deviations from the actual source of the stimulus. This measure ranged from 0 to 180° .

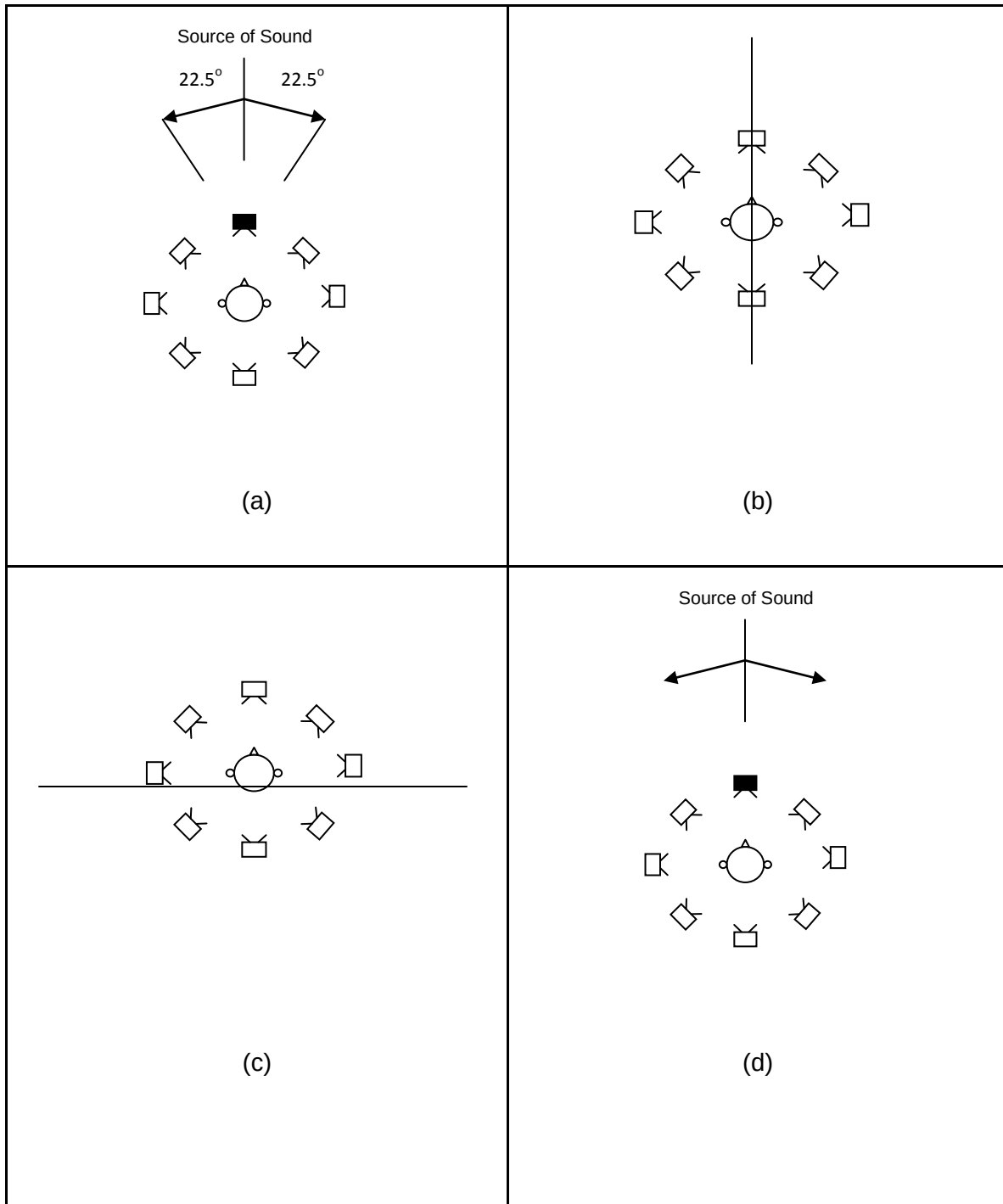


Figure 55. Dependent measures for the backup alarm localization experiment (see text preceding figure for detailed explanation of each of the 4 measures).

Apparatus. A semi-anechoic room (free-field over a reflecting tile floor) at Virginia Tech was used as the test environment for this experiment. A Dell laptop computer and two Sony STR DE-135 amplifiers were used to present the backup alarm signal and the background noise through 8 Bose CMS Satellite loudspeakers, positioned on speaker stands 4 feet above the

floor, and in a circle about the listener's seated position (see Figure 56). One amplifier presented the backup alarm signal from the laptop computer to a Phoenix Gold ISM-8 8-channel speaker selector, which then output the signal to one of the 8 Bose loudspeakers. The background noise amplifier presented the background pink noise generated from an Atlas Soundolier Model GPN-1200A to 2 Phoenix Gold VSS2 speaker selectors at the background noise levels of 60 dBA and 90 dBA using four Infinity SM-155 loudspeakers, one positioned at each corner of the 8-speaker array (i.e., positions A-D, behind loudspeakers #2, 4, 6, and 8) (see Figure 56).

For the purpose of producing the modified backup alarm signal, Adobe Audition software v1.0 was used to add the 400 Hz and 4000 Hz to the standard backup alarm signal. The spectral composition of the backup alarm signal and the background noise was verified before each experimental trial using a Larson-Davis 2800 Series Real-time Spectrum Analyzer and a Larson-Davis model 2559 ½-inch microphone, which was calibrated to 94 dBA @ 1KHz using a Quest QC-20 calibrator.

Listeners used a stylus connected to the Fujitsu tablet PC to mark their localization responses. A LabVIEW program installed on the tablet PC presented a circle to the listeners; the program was also used to store the participant's response. A Dell 17" monitor, connected to the video-out port of the PC, was used by the experimenter to monitor listeners' use of the LabVIEW program. A Microframe Model 6300 digital timer was used to determine the time required for the listeners to make their localization decisions.

Procedure. Each participant attended a total of five sessions, one screening session and four experimental sessions with two HPDs tested in each. The first session was a screening session wherein the participants' normal hearing was verified (i.e., ≤ 25 dBHL in both ears). After successful passing of the audiogram, participants were instructed in the procedures of the experiment and practiced them in a familiarization session. For familiarization, the participant was asked to localize the modified backup alarm signal in a quiet background condition (60 dBA) while being unoccluded (open ear). To meet the familiarization criterion, the participant must have been able to achieve at least 50% correct in his/her localization responses. All participants met this criterion.

For the experimental sessions, wherein two HPD conditions were utilized in each of four sessions to assess localization performance, participants completed localization tasks in both background noise levels, and with either the modified backup alarm or the regular backup alarm being presented through each of the eight Bose loudspeakers. Presentation of either backup alarm through the Bose loudspeakers was accomplished in random fashion, as were the HPD conditions and background noise levels to avoid order effects.

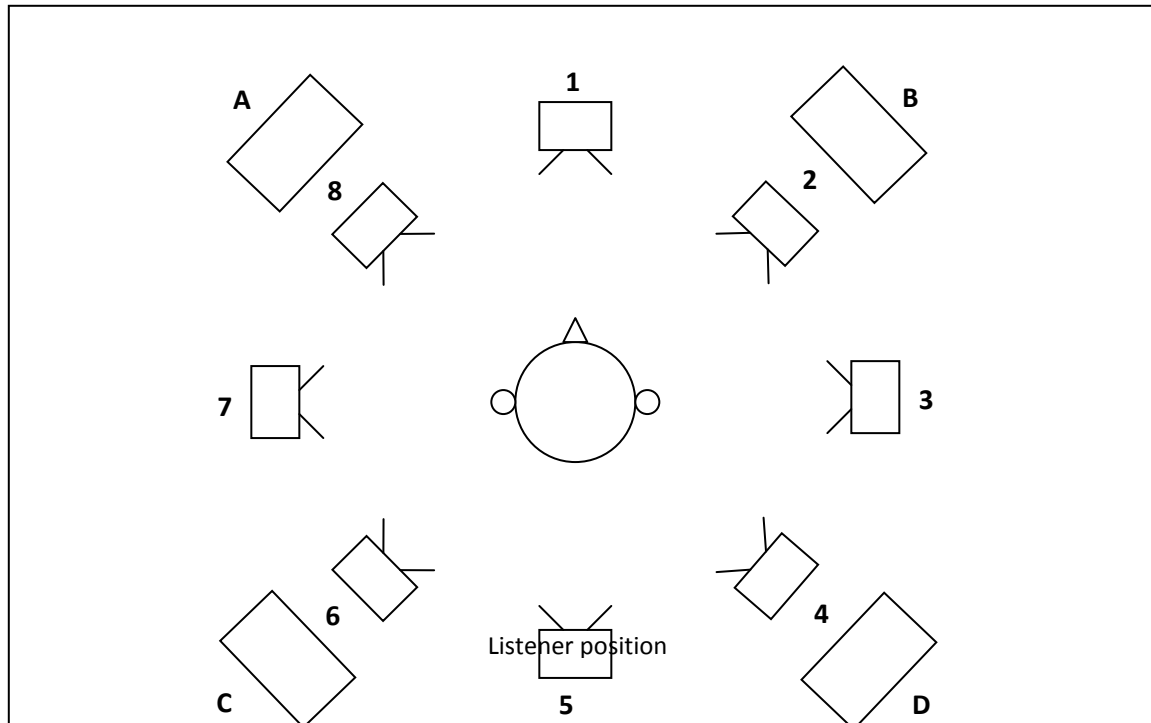


Figure 56. Loudspeaker and listener positions for the localization experiment. Positions 1-8 were Bose CMS Satellite loudspeakers for the backup alarm signal, while positions A-D were Infinity SM-155 loudspeakers for the background noise.

Participants were seated in the chair by the experimenter. The participant was then asked to read the following instructions:

- a. On the desk in front of you is a tablet laptop PC that you will use to make your responses. Positioned around you in a circle (behind the curtains) are several small loudspeakers.
- b. In this experiment, you will hear a backup alarm signal presented from one of the small loudspeakers, and you will hear background noise.
- c. At the start of the experimental trial the noise will be presented to you. Immediately after this, you will begin to hear a backup alarm signal.
- d. You should try to determine from where you think the backup alarm is sounding. Head movement (not torso movement) is allowed but it is not required. When you have made your decision as to where the backup alarm seems to be coming from, press the 'stop' button on the right side of your desk, which will turn off both the backup alarm and the background noise. You will have 15 seconds to depress the 'stop' button once the backup alarm starts sounding.
- e. Look at the tablet PC's screen, and note the circular dial on it, which represents a compass. The circular compass dial is a top-down view of your seated position, with you at the center of the dial. Using the stylus, touch/press the compass line and drag it to the point on the compass dial that corresponds to the location from where you thought you heard the backup alarm. Once you have made your decision, press the ENTER DIRECTION button to store your response.

- f. Once you have stored your response, a green-colored light located on the right of the compass dial on the tablet PC screen will flash up, indicating that your response was successfully stored.
- g. Be prepared for the next trial by saying 'I am ready.'

After the participant finished reading the above instructions, the experimenter placed the HPD on him/her and began presenting the experimental stimuli. Simultaneous with stimulus presentation, the experimenter started the digital timer toward assessment of the duration of the localization decisions made by the listeners. Participants were given 30 seconds with which to make their localization decision.

Data Reduction and Analysis. As mentioned earlier, LabVIEW software was used to capture the raw numerical data for the localization declarations. The raw data were then exported into a MS Excel file, where they were graphed, and reduced to obtain the 4 dependent measures. The Statistical Analysis Software (SAS) program was used to conduct all analyses to test for significant differences at an alpha level of 0.05, and Tukey's test was used for post-hoc analyses (also at an alpha level of 0.05). Threshold tracking results were analyzed using an analysis of variance (ANOVA) to test for significance, and the *F*-ratio for each source of variance used that source of variance crossed with subjects for the mean square in the error term.

Results and Discussion. As mentioned previously, backup alarm signal localization performance was assessed by evaluating: 1) the percentage of the correct responses, 2) the percentage of right-left errors (i.e., judging a backup alarm signal emanating from the left speakers to be emanating from the right speakers, or vice versa), 3) the percentage of front-rear errors (i.e., judging a backup alarm signal emanating from the front speakers to be emanating from the rear speakers, or vice versa), and 4) the absolute deviation value, which was a measure of how far off the listeners' response was from the actual azimuthal position of the backup alarm signal.

Percent correct localization responses. ANOVA revealed a significant main effect of HPD on the percentage of correct responses, $F(7,77) = 59.2$, $p < 0.0001$, with the means ranging from 15.8% for the Bilsom Impact™ diotic-modified earmuff to 83.9% for the E-A-R HiFi™ earplug see Figure 57 and Table 20. Post hoc analyses using Tukey's test indicated that the modified Bilsom Impact™ diotic earmuff (15.8%) was worse than all other HPD conditions with respect to percent correct localization, and that there were no differences in percent correct localization between any of the other conditions, including open ear.

TABLE 20. ANOVA Summary table for the *percent correct localization* of backup alarm response (**bold** values indicate significance).

Source	df	SS	MS	F	Pr>F
HPD*	7	169252.9	24178.9	59.2	<.0001
BNL*	1	68400.0	68400.0	103.7	<.0001
BU*	1	1464.8	1464.8	11.3	0.0063
S*	11	16551.1	1504.6	-----	-----
HPD×S	77	31420.8	408.0	-----	-----
BNL×S	11	7249.3	659.0	-----	-----
BU×S	11	1425.7	129.6	-----	-----
HPD×BNL	7	12918.2	1845.4	9.5	<.0001
HPD×BU	7	1308.5	186.9	2.2	0.0432
BNL×BU	1	366.2	366.2	3.82	0.0765
HPD×BNL×S	77	14947.9	194.1	-----	-----
HPD×BU×S	77	6542.9	84.9	-----	-----
BNL×BU×S	11	1054.6	95.8	-----	-----
HPD×BNL×BU	7	447.5	63.9	0.7	0.6121
HPD×BNL×BU×S	77	6373.6	82.7	-----	-----

HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects

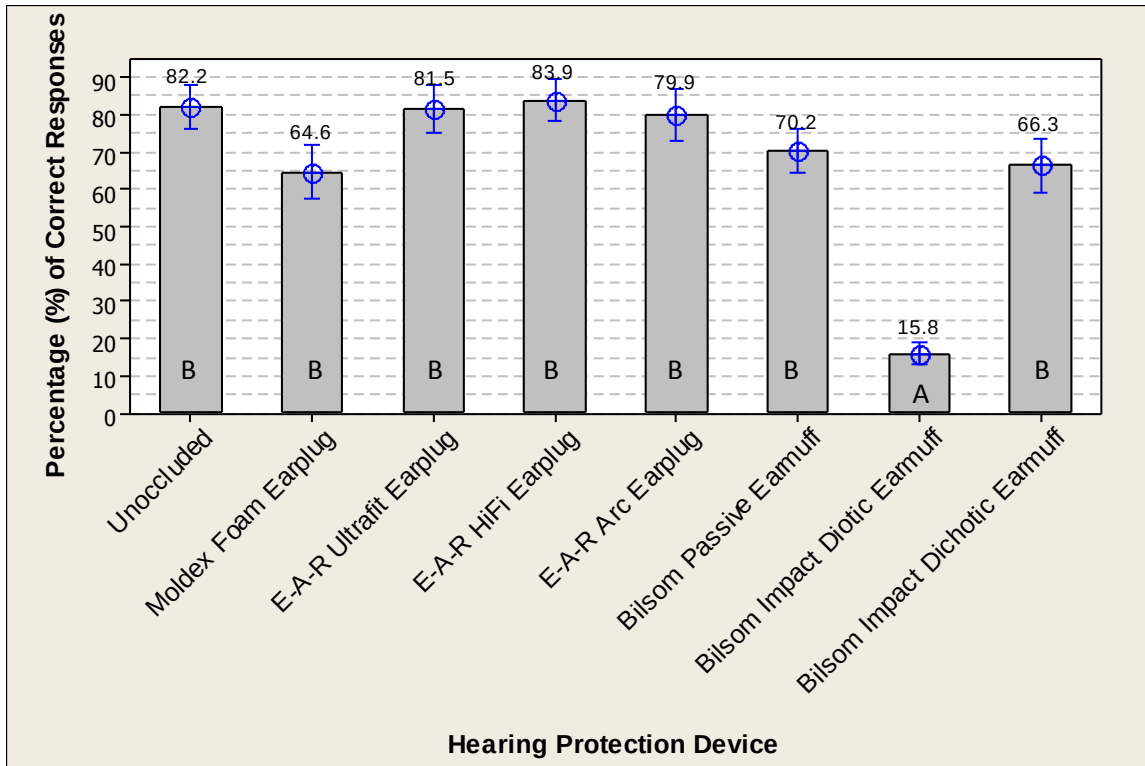


Figure 57. Main effect of HPD on *percent correct localization* of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

The results suggest that the diotic earmuff presented great difficulty for the listeners in overall percent correct localization—a full 49% worse than the next poorest-performing HPD (Moldex earplug). The diotic technology of the modified Bilsom Impact™, which presented the *same* signal to both ears electronically, resulted in marked decrements in localization ability when compared to all other conditions.

ANOVA also revealed a significant main effect of *background noise level* on the percentage of correct responses $F(1,11) = 103.7$, $p < 0.0001$, with the means at 81.4% correct in the 60 dBA noise level to 54.6% correct in the 90 dBA noise level (see Figure 58). The 90 dBA background noise level greatly degraded affected the participants' ability to localize backup alarm signals.

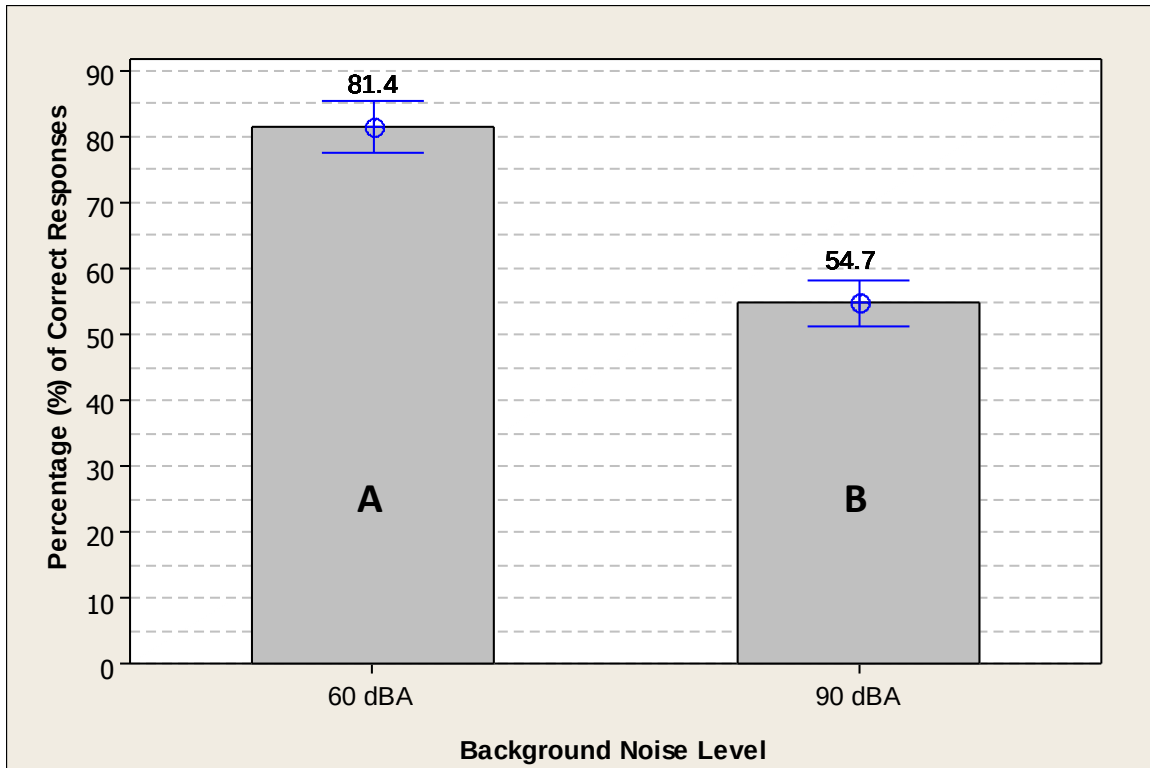


Figure 58. Main effect of background noise level on *percent correct localization* of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different.

ANOVA revealed a significant main effect of the *backup alarm type* on the percentage of correct responses, $F(1,11) = 11.3$, $p = 0.0063$, with the means comprising 70% for the modified backup alarm to 66% for the standard backup alarm (see Figure 59). Participants were able to realize a higher percentage of correct localization decisions when listening for the modified backup alarm than when listening for the standard backup alarm. This is a very important result with implications for the need for improved backup alarm designs to afford better localization.

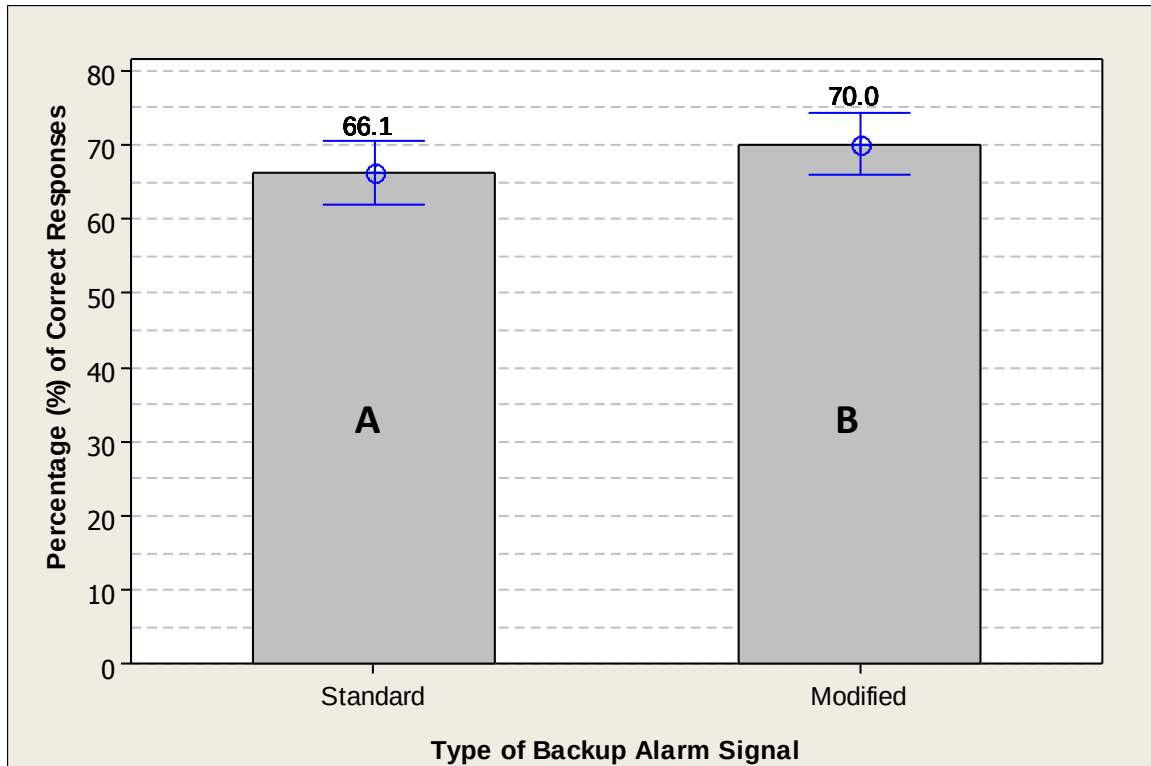


Figure 59. Main effect of backup alarm type on *percent correct localization* of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different.

ANOVA revealed a significant interaction between *HPD* and *background noise level* on percent correct localization, $F(7,77) = 9.5$, $p < 0.0001$. For post hoc analysis, the background noise level interactions with HPD were partitioned between noise levels. In the 60 dBA background noise level, the percent correct localization means ranged from 14.8% to 98.9% (see Figure 60); in the 90 dBA background noise level, the percent correct localization means ranged from 16.7% to 71.1% (see Figure 61). In the 60 dBA background noise level, the unoccluded ear resulted in 98.9% correct response, the Moldex earplug 76.8%, the E-A-R Ultrafit™ 97.1%, the E-A-R HiFi™ 96.6%, the E-A-R Arc™ 97.7%, the Bilsom Leightning™ 84.1%, the modified Bilsom Impact™ diotic 14.8%, and the Bilsom Impact dichotic 84.9%. In the 90 dBA background noise level, the unoccluded ear resulted in 65.4% correct response, the Moldex earplug 52.3%, the E-A-R Ultrafit™ 65.9%, the E-A-R HiFi™ 71.1%, the E-A-R Arc™ 62.2%, the Bilsom Leightning™ 56.3%, the modified Bilsom Impact™ diotic 16.7%, and the Bilsom Impact dichotic 47.7%.

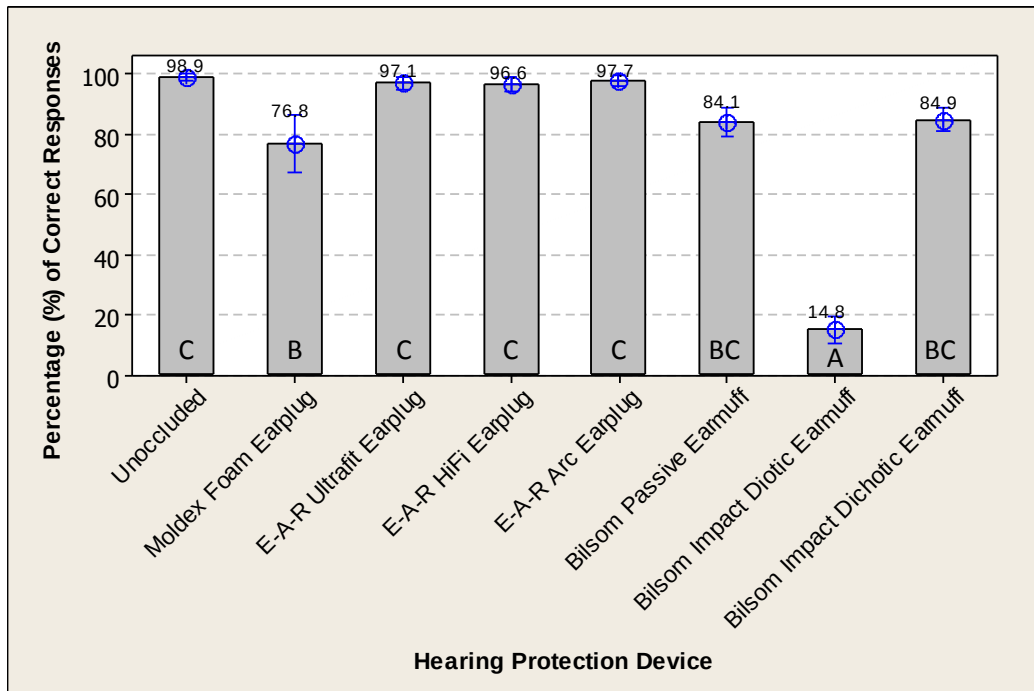


Figure 60. Interaction of HPD and background noise level at 60 dBA on *percent correct localization* of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

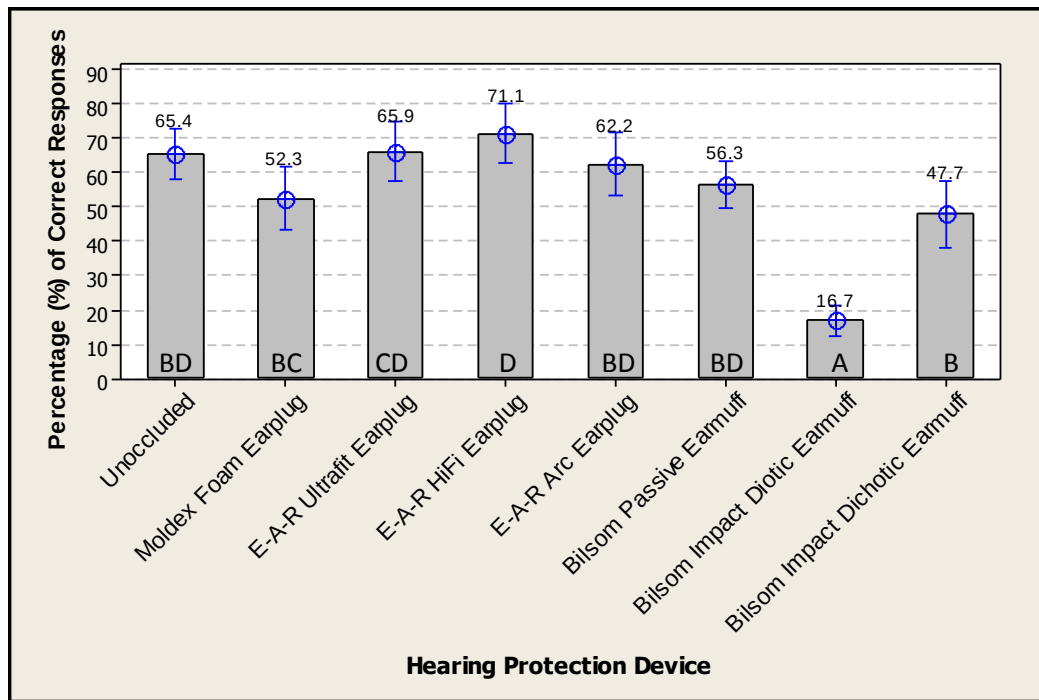


Figure 61. Interaction of HPD and background noise level at 90 dBA on *percent correct localization* of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

In the 60 dBA background noise level, post hoc analysis using Tukey's test indicated that the modified Bilsom Impact™ diotic earmuff resulted in the lowest percentage of correct responses (Figure 60). The unoccluded ear, all three of the E-A-R earplugs, the Bilsom Lightning™, and the Bilsom Impact™ dichotic earmuff, did not differ with respect to percent correct localization response. The Moldex earplug, Bilsom Lightning™, and the Bilsom Impact™ dichotic earmuff did not differ with respect to this metric. In the lower background noise level, the modified Bilsom Impact™ diotic earmuff presented great difficulty for the listeners to localize a backup alarm signal. The E-A-R products, as well as the dichotic and Bilsom Lightning™ earmuffs, appeared to provide an overall percent correct localization ability that was as good as the open ear. The Moldex earplug provided overall percent localization ability that was at the same level as two of the three circumaural earmuffs, but poorer than the other earplugs.

In the 90 dBA background noise level, post hoc analysis using Tukey's test again indicated that the modified Bilsom Impact™ diotic earmuff resulted in the lowest percentage of correct responses. The unoccluded ear, Moldex earplug, E-A-R Arc earplug™, Bilsom Lightning™ earmuff, and the Bilsom Impact™ dichotic earmuff did not differ with respect to this metric. The E-A-R Ultrafit™, E-A-R HiFi™, E-A-R Arc™, and Bilsom Lightning™ earmuff did not differ in percent correct localization response. The E-A-R Ultrafit™ did not differ from the Moldex earplug with respect to this metric. The Moldex foam earplug, E-A-R Arc™, Bilsom

Leightning™ earmuff, and Bilsom Impact™ dichotic earmuff did not differ from the open ear with respect to this metric in 90 dBA noise. There is no discernable pattern that emerges when looking at the percent correct means across HPD condition in 90 dBA noise other than the fact that diotic sound transmission design negatively affects localization ability (Figure 61).

ANOVA also revealed a significant interaction between *HPD* and *backup alarm type* with respect to percent correct localization, $F(7,77) = 2.2$, $p = 0.04$. For analysis, the backup alarm type interactions with HPD were partitioned between backup alarm types. In the standard backup alarm condition, percent correct localization under different HPD conditions ranged from 16.1% for the modified Bilsom Impact™ diotic earmuff to 83.6% for the E-A-R HiFi™ earplug (see Figure 62). In the modified backup alarm condition, percent correct localization under different HPD conditions ranged from 15.4% for the Bilsom Impact™ diotic earmuff to 84.4% for the E-A-R Ultrafit™ earplug (see Figure 63).

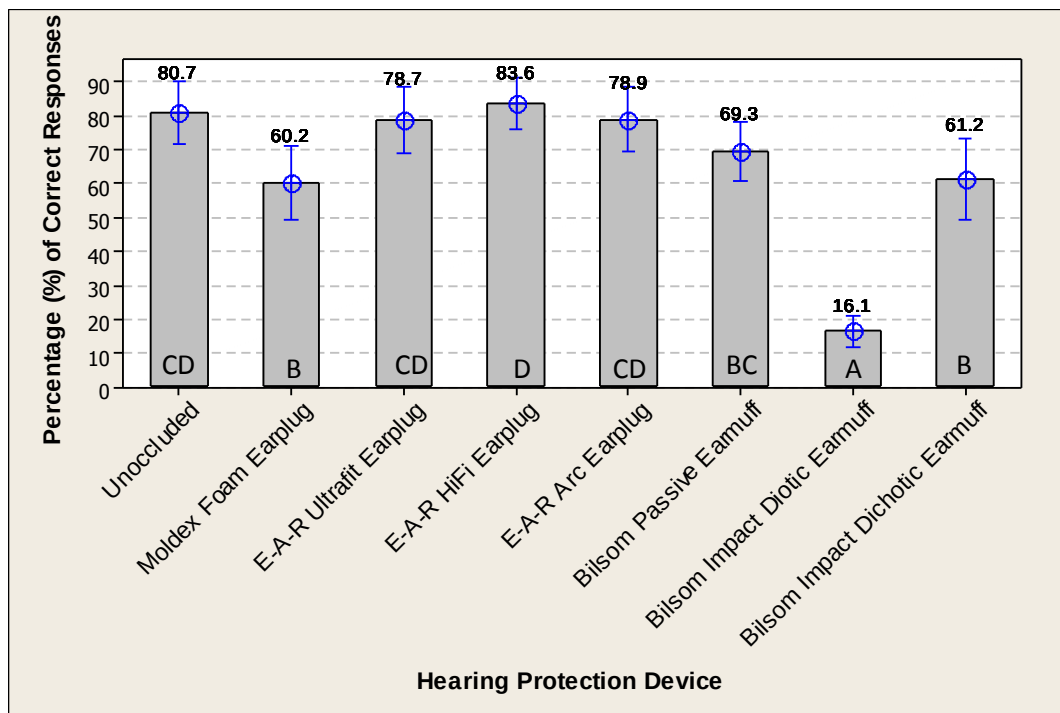


Figure 62. Effect of HPD on *percent correct localization* for the *standard* backup alarm, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

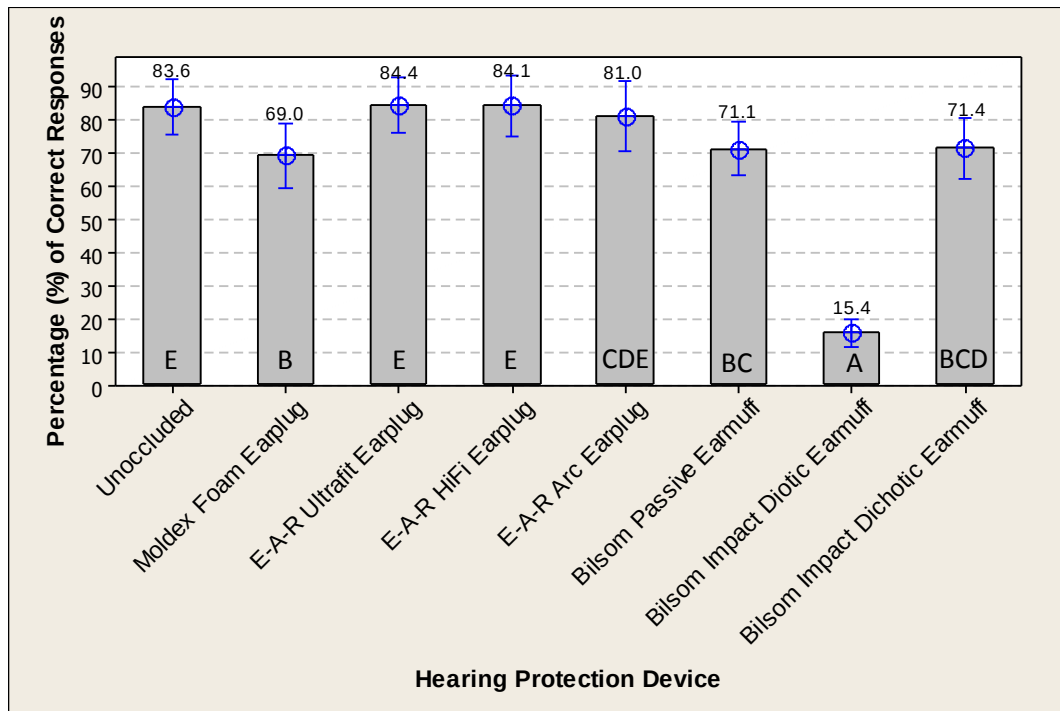


Figure 63. Effect of HPD and on *percent correct localization* for the *modified* backup alarm, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Post hoc analysis using Tukey's test for the standard backup alarm condition indicated that the modified Bilsom Impact™ diotic earmuff differed from all other HPD conditions with respect to percent correct localization, with the lowest score. The E-A-R Ultrafit™ earplug, the E-A-R Arc™ earplug, and the Bilsom Lightning™ earmuff did not differ from the unoccluded ear with respect to percent correct localization. The E-A-R HiFi™ also did not differ from the unoccluded ear, nor did it differ from the other two E-A-R products. The Moldex foam earplug did not differ from the Bilsom Lightning™ earmuff and the Bilsom Impact™ dichotic earmuff with respect to percent correct localization. The results again suggest that the diotic earmuff technology resulted in poor localization performance, and thus has a negative effect on standard backup alarm localization. The Moldex foam earplug resulted in localization performance on a par with the two non-diotic circumaural earmuffs. The E-A-R products appeared to provide the highest percent correct localization ability, again on a par with the unoccluded ear, suggesting that their design fosters the ability to localize a standard backup alarm signal, while maintaining some level of hearing protection (via labeled NRR).

Post hoc analysis using Tukey's test for the modified backup alarm condition indicated that the modified Bilsom Impact™ diotic earmuff again differed from all other HPD conditions with respect to percent correct localization, with the lowest percent correct localization responses. All three of the E-A-R products did not differ from the unoccluded ear with respect to this metric, suggesting that their design fosters the ability to localize a modified backup alarm signal while maintaining some level of hearing protection (via labeled NRR). Similar to the

results in the standard backup alarm condition, the Moldex foam earplug resulted in localization performance on a par with the two non-diotic circumaural earmuffs.

Percent of right-left errors. ANOVA revealed a significant main effect of *HPD* on the percentage of right-left errors $F(7,77) = 42.78$, $p < 0.0001$, with the means ranging from 2.4% for the E-A-R HiFi™ earplug to 36.5% for the modified Bilsom Impact™ diotic earmuff (see Figure 64 and Table 21).

TABLE 21. ANOVA Summary table for the *percent of right-left errors* in backup alarm localization response (**bold** values indicate significance).

Source	df	SS	MS	F	Pr>F
HPD*	7	41838.6	5976.9	42.7	<.0001
BNL*	1	5924.6	5924.6	20.8	0.0008
BU*	1	1497.5	1497.5	15.4	0.0024
S*	11	4589.6	417.2	-----	-----
HPD×S	77	10759.0	139.7	-----	-----
BNL×S	11	3126.9	284.2	-----	-----
BU×S	11	1069.6	97.2	-----	-----
HPD×BNL	7	1105.1	157.8	1.8	0.0946
HPD×BU	7	1301.9	185.9	2.7	0.0128
BNL×BU	1	764.0	764.0	18.0	0.0014
HPD×BNL×S	77	6666.1	86.5	-----	-----
HPD×BU×S	77	5175.9	67.2	-----	-----
BNL×BU×S	11	466.3	42.3	-----	-----
HPD×BNL×BU	7	658.0	94.0	1.8	0.1001
HPD×BNL×BU×S	77	4031.5	52.3	-----	-----

HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects

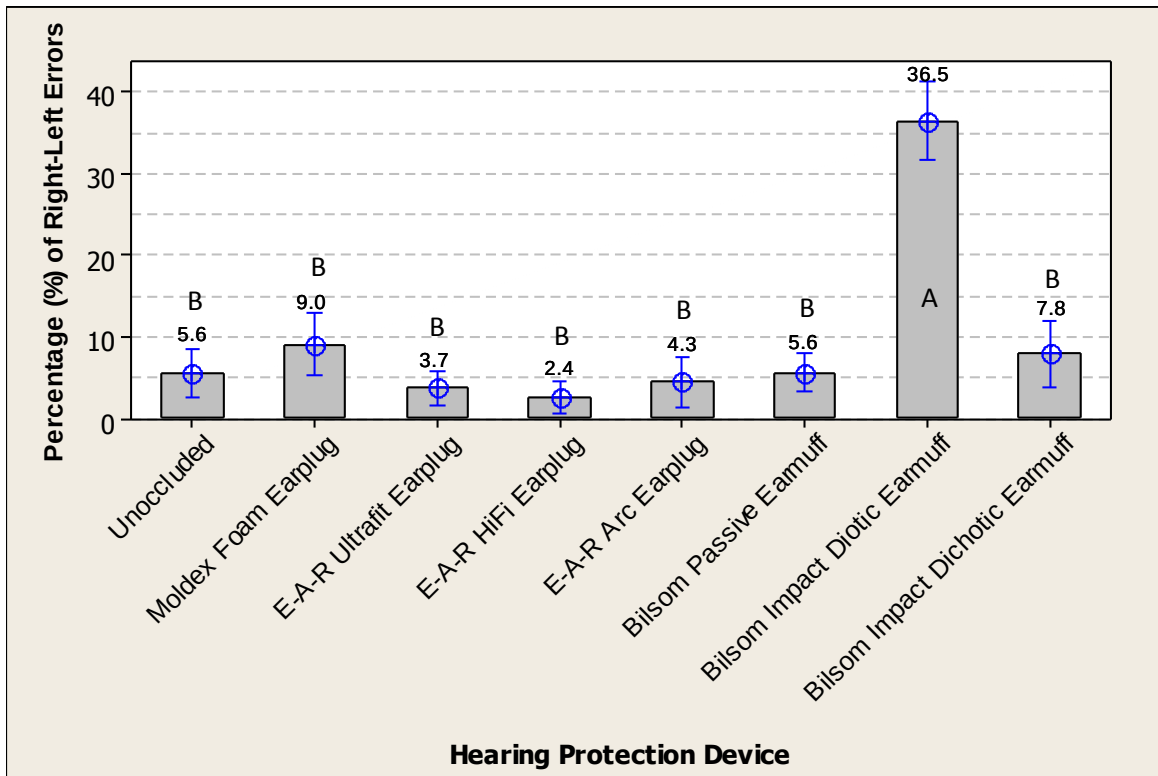


Figure 64. Main effect of HPD on the *percent of right-left errors* on localization of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

The percent of right-left errors was 5.6% for the open ear, 9.0% for the Moldex earplug, 3.7% for the E-A-R Ultrafit™ earplug, 2.4% for the E-A-R HiFi™ earplug, 4.3% for the E-A-R Arc™ earplug, 5.6% for the Bilsom Lightning™ earmuff, 36.5% for the modified Bilsom diotic earmuff, and 7.8% for the Bilsom Impact™ dichotic earmuff. Post hoc analyses using Tukey's test indicated that there was a difference in the percentage of right-left errors only when comparing the modified Bilsom diotic earmuff to all other HPD conditions, which did not differ among themselves. The difference in right-left localization performance between the diotic earmuff and the other HPD conditions was quite marked. These results suggest that the diotic technology caused listeners great difficulty in distinguishing between right-left backup alarm presentations.

ANOVA also revealed a significant main effect of *background noise level* on the percent of right-left errors, $F(1,11) = 20.8$, $p = 0.0008$, with the means comprising 5.4% in the 60 dBA background noise level and 13.3% in the 90 dBA background noise level (see Figure 65). Listeners experienced greater difficulty in localizing whether a backup alarm was emanating from the left or the right in the higher background noise condition when compared to the lower background noise condition.

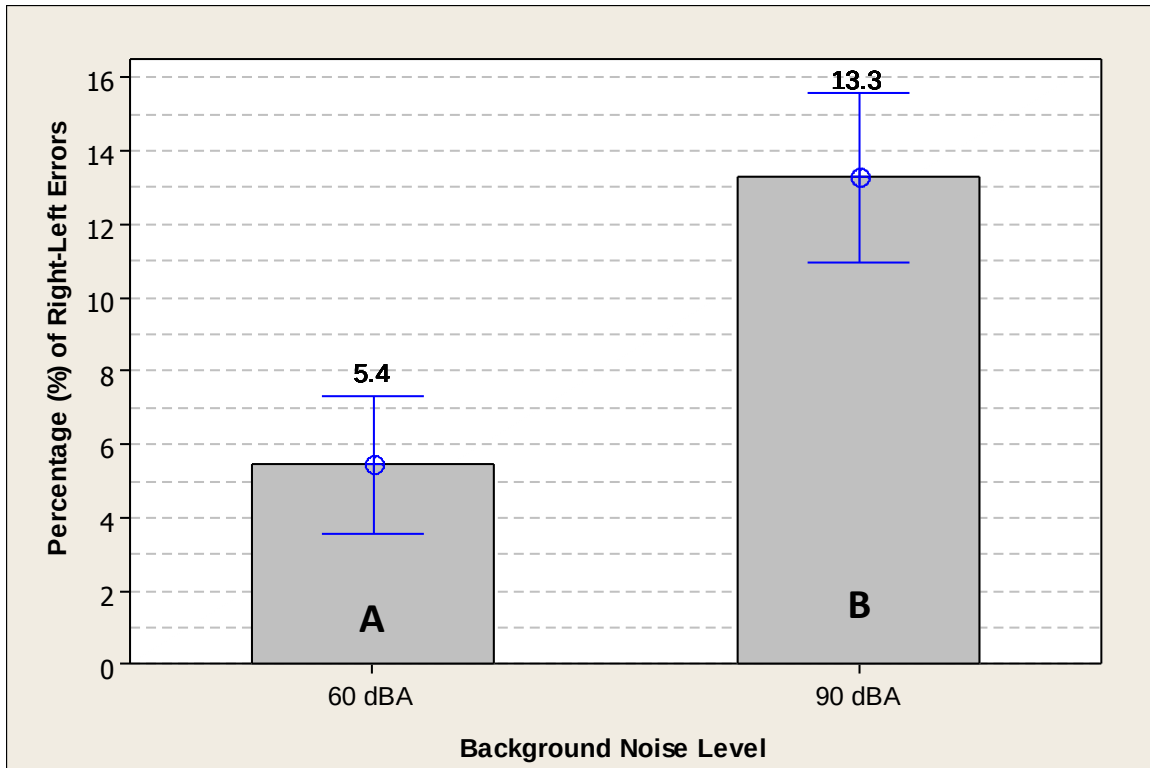


Figure 65. Main effect of background noise level on the *percent of right-left errors* on localization of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$).

ANOVA revealed a significant main effect of *backup alarm type* on the percent of right-left errors, $F(1,11) = 15.4$, $p = 0.0024$, with the means comprising 11.3% for the standard backup alarm and 7.4% for the modified backup alarm (see Figure 66). Listeners experienced significantly greater difficulty in localizing whether the standard backup alarm was emanating from the left or the right when compared to the modified backup alarm.

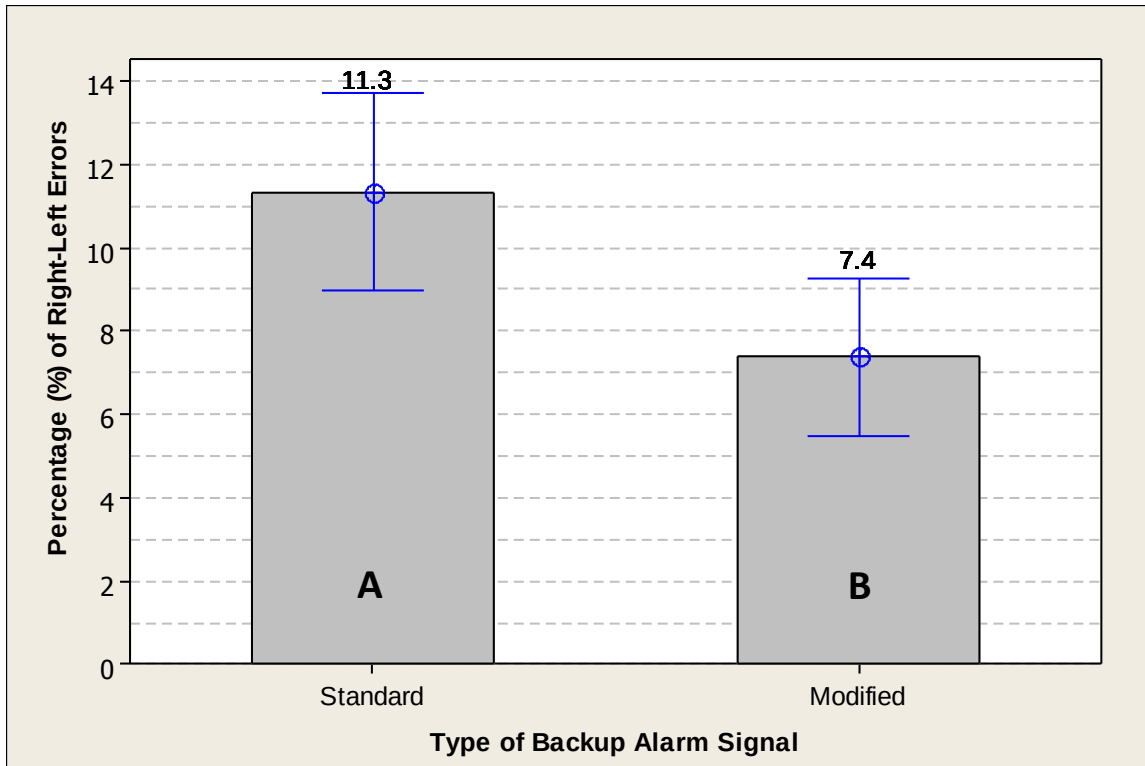


Figure 66. Main effect of backup alarm type on the *percent of right-left errors* on localization of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$).

ANOVA revealed a significant interaction of *HPD* and *backup alarm type* with respect to the percent of right-left errors, $F(7,77) = 2.7$, $p = 0.01$. For analysis, the backup alarm type interactions with HPD were partitioned between backup alarm types. With the standard backup alarm, mean percent right-left errors ranged from 1.4% for the E-A-R HiFi™ earplug to 40.3% for the modified Bilsom Impact™ diotic earmuff (see Figure 67). With the modified backup alarm, mean percent right-left errors ranged from 2.8% for the E-A-R Ultrafit™ earplug to 32.6% for the modified Bilsom diotic earmuff (see Figure 68).

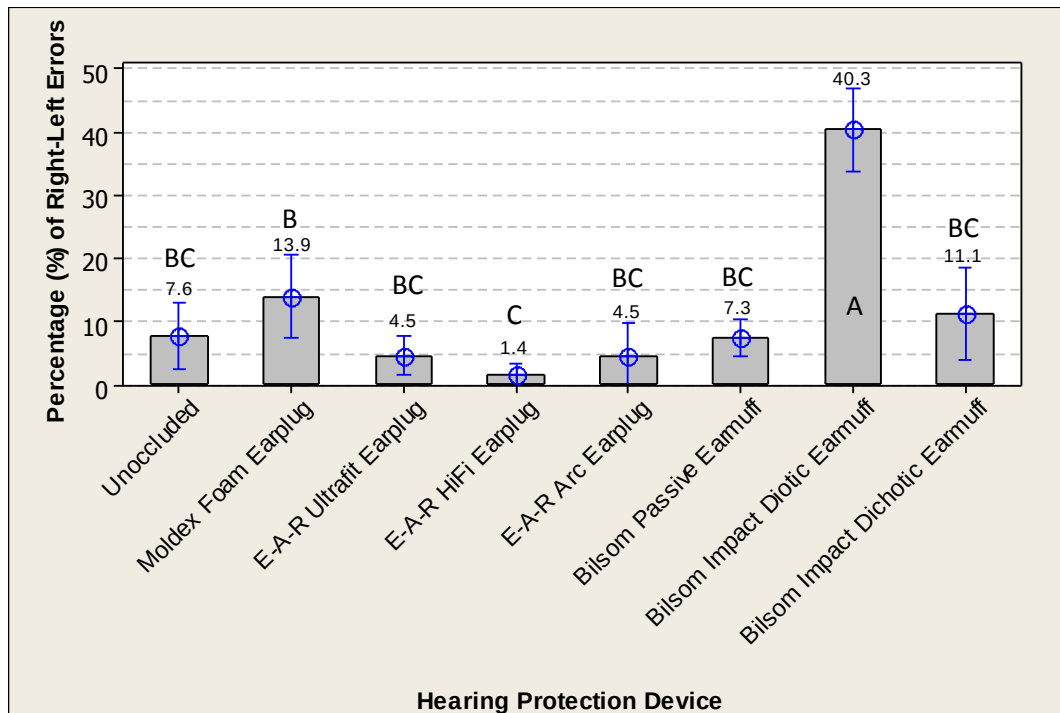


Figure 67. Effect of HPD on *percent right-left localization errors* for the *standard* backup alarm, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

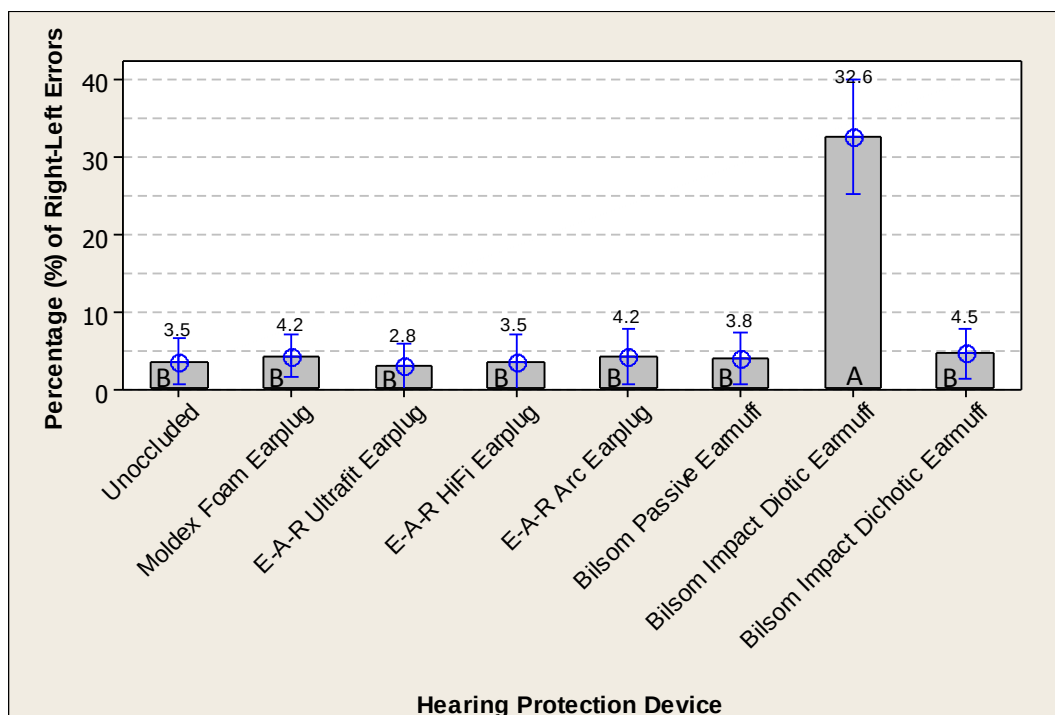


Figure 68. Effect of HPD on *percent right-left localization errors* for the *modified* backup alarm, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Post hoc analysis using Tukey's test in the standard backup alarm condition indicated that all HPDs, with the exception of the modified Bilsom Impact™ diotic earmuff, did not differ from the unoccluded ear with respect to percent right-left localization errors. The Moldex foam earplug was found to differ from the E-A-R HiFi™ with respect to this metric. Again, the pattern of diotic technology as applied to the Bilsom Impact™ earmuff resulting in a large percentage of localization errors when compared to all other HPD conditions. The fact that all of the other HPD conditions outside of that device resulted in very similar amounts of right-left errors to those of the open ear shows that the HPD conditions tested in this experiment have little effect on right-left localization errors when compared to the open ear for the standard backup alarm.

Post hoc analysis using Tukey's test in the modified backup alarm condition indicated that the modified Bilsom Impact™ diotic earmuff resulted in the poorest right-left localization performance when compared to all other HPD and open ear conditions, which did not differ. The uniformity of right-left localization errors across HPD condition (outside of the diotic earmuff) suggests that the modified backup alarm signal fosters right-left localization ability to a greater extent than does the standard backup alarm signal.

ANOVA revealed a significant interaction effect of *background noise level* and *backup alarm type* on percent right-left localization errors, $F(1,11) = 18.0$, $p = 0.001$. In the 60 dBA background noise level, the mean right-left localization error for the standard backup alarm and the modified backup alarm was 6% and 4.9%, respectively, and these were not significantly different. Also, in the 90 dBA background noise level, the mean right-left localization errors for the standard backup alarm and the modified backup alarm were not significantly different at

16.7% and 9.9%, respectively. Post hoc analysis using Tukey's test indicated that the mean right-left localization errors did not differ between the backup alarm types in the 60 dBA background noise level, nor in the 90 dBA background noise level (see Figure 69). There was a trend toward better localization in high noise levels with the modified alarm, but it was not significant from a statistical standpoint.

From Figure 69, it appears that as the background noise level increased from 60 dBA to 90 dBA, the modified backup alarm resulted in right-left localization performance that did not appreciably change; however, the performance for the standard backup alarm did change as the background noise level increased—it became worse. The results suggest that, as the background noise levels increase, the modified backup alarm helps listeners maintain an ability to localize the alarm when compared to the standard backup alarm, possibly due to the hypothesized improvement in localization ability afforded through the additions of 400 Hz and 4000 Hz to the standard backup alarm signal. Thus, it appears that the ability to localize the modified backup alarm in the right-left dimension remains robust as noise levels increase.

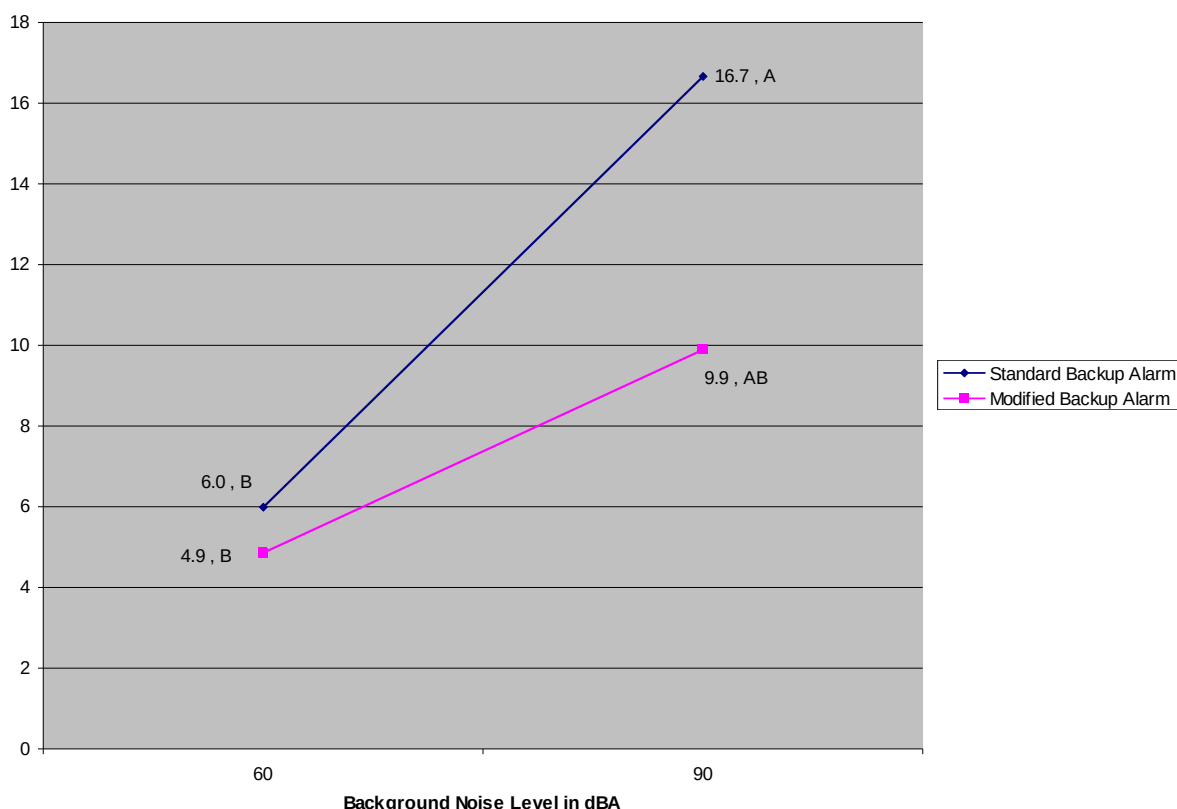


Figure 69. Interaction of backup alarm type and background noise level on *percent right-left localization errors*. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Percent of front-rear errors. ANOVA revealed a significant main effect of *HPD* on the percent of front-rear errors, $F(7,77) = 43.03$, $p < 0.0001$, with the means ranging from 4.0% for the E-A-R HiFi™ To 43.8% for the modified Bilsom Impact™ diotic earmuff (see Figure 70 and Table 22). The percent of front-rear errors was 6.3% for the open ear, 12.7% for the Moldex

earplug, 5.0% for the E-A-R Ultrafit™ earplug, 4.0% for the E-A-R HiFi™ earplug, 6.6% for the E-A-R Arc™ earplug, 8.0% for the Bilsom Leightning™ earmuff, 43.8% for the modified Bilsom diotic earmuff, and 11.6% for the Bilsom Impact™ dichotic earmuff.

Post hoc analyses using Tukey's test indicated that there was a difference in the percentage of front-rear errors only when comparing the modified Bilsom diotic earmuff to all other HPD conditions, which did not differ among themselves, similar to the percentage of right-left errors. The difference in front-rear localization performance between the diotic earmuff and the other HPD conditions was again quite marked. These results suggest that the diotic technology presented listeners with great difficulties in distinguishing between front-rear backup alarm enunciations.

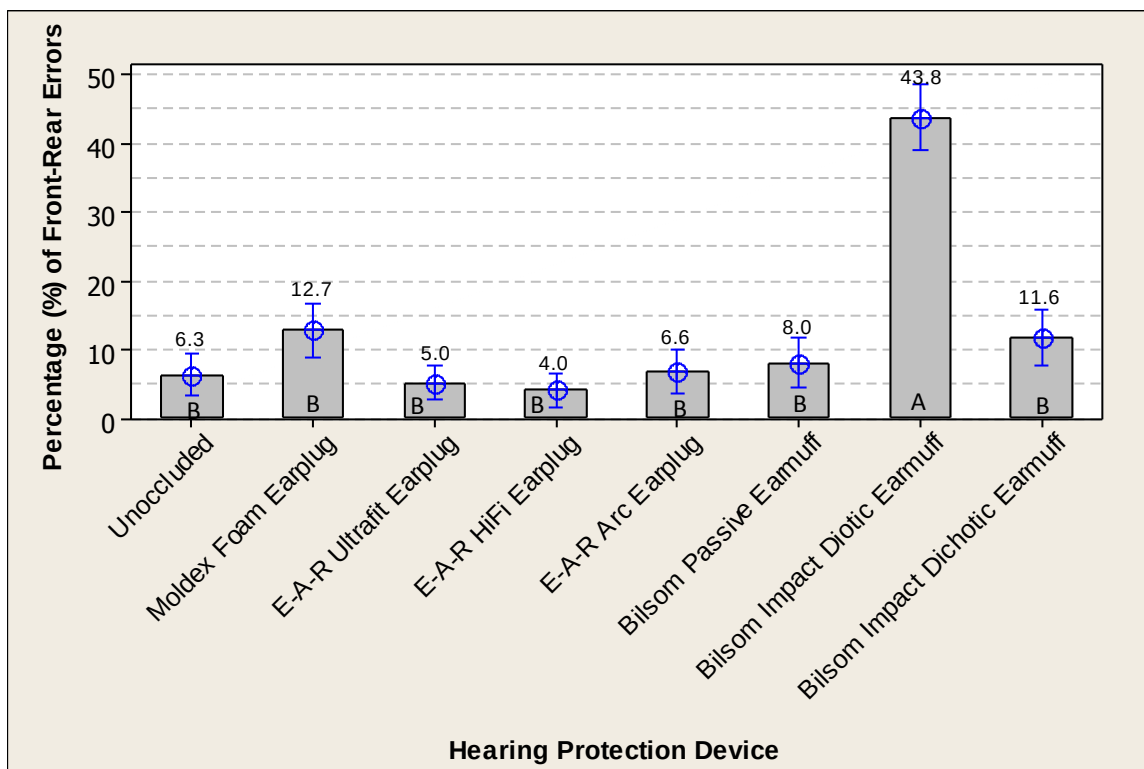


Figure 70. Main effect of HPD on the *percent of front-rear errors* on localization of a backup alarm signal, with mean values shown on bars with 95% confidence intervals.. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

TABLE 22. ANOVA Summary table for the *percent of front-rear errors* in backup alarm localization response (**bold** values indicate significance).

Source	df	SS	MS	F	Pr>F
HPD*	7	57560.7	8222.9	43.0	<.0001
BNL*	1	9733.7	9733.7	28.3	0.0002
BU*	1	234.3	234.3	4.3	0.0623
S*	11	5928.8	538.9	-----	-----
HPD×S	77	14713.5	191.0	-----	-----
BNL×S	11	3781.8	343.8	-----	-----
BU×S	11	598.9	54.4	-----	-----
HPD×BNL	7	3049.7	435.6	4.8	0.0001
HPD×BU	7	633.6	90.5	1.7	0.1033
BNL×BU	1	350.1	350.1	5.7	0.0349
HPD×BNL×S	77	6941.5	90.1	-----	-----
HPD×BU×S	77	3914.9	50.8	-----	-----
BNL×BU×S	11	665.5	60.5	-----	-----
HPD×BNL×BU	7	506.3	72.3	1.0	0.3966
HPD×BNL×BU×S	77	5248.8	68.1	-----	-----

HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects

ANOVA also revealed a significant main effect of *background noise level* on the percent of front-rear errors, $F(1,11) = 28.31$, $p = 0.0002$, with the means at 7.2% for the 60 dBA noise level and at 17.3% for the 90 dBA noise level (see Figure 71). Listeners experienced greater difficulty in localizing whether a backup alarm was emanating from the front or from the rear in the higher background noise condition when compared to the lower background noise condition.

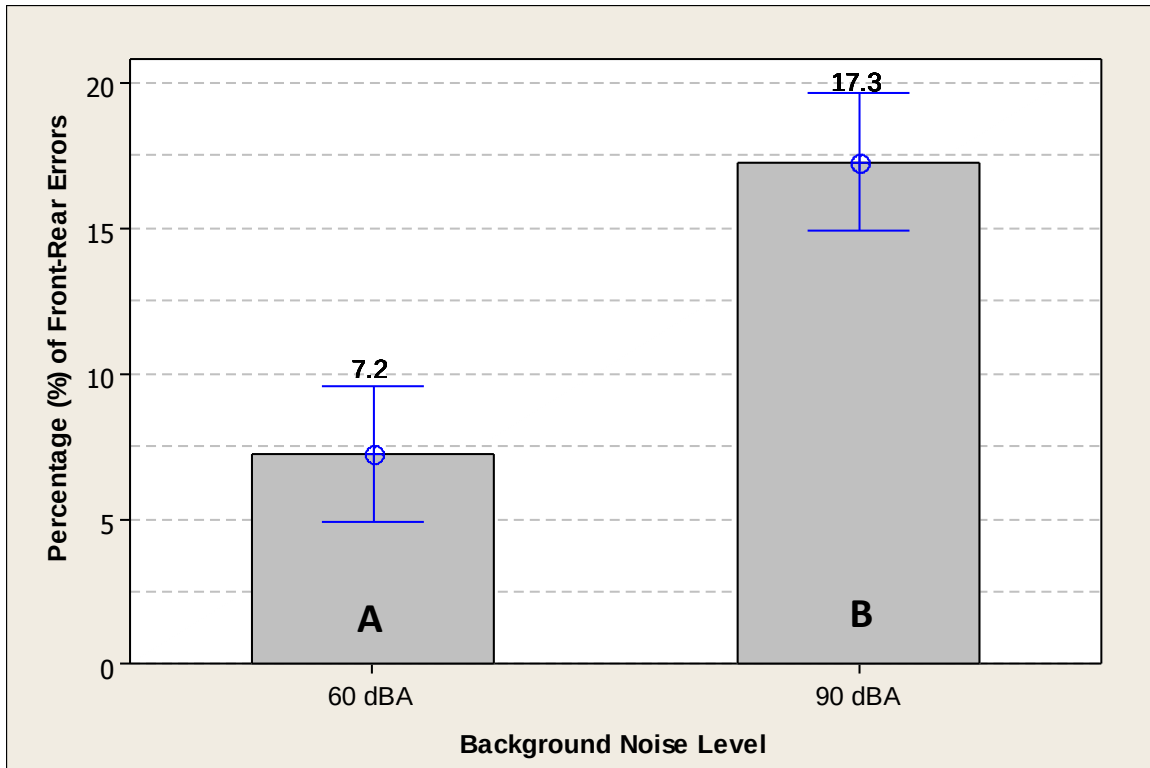


Figure 71. Main effect of background noise level on the *percent of front-rear errors* on localization of a backup alarm signal, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$).

ANOVA revealed a significant interaction of *HPD* and *background noise level* on the percent of front-rear localization errors, $F(7,77) = 4.8$, $p = 0.001$. For analysis, the HPD interactions with background noise level were partitioned between background noise levels. In the 60 dBA background noise level, the means ranged from zero errors (for both the unoccluded ear and the E-A-R Arc™ earplug conditions) to 43.8% errors for the modified Bilsom Impact™ diotic earmuff (see Figure 72). In the 90 dBA background noise level, the means ranged from 7.6% errors for the E-A-R HiFi™ earplug to 43.8% errors for the modified Bilsom diotic earmuff (see Figure 73).

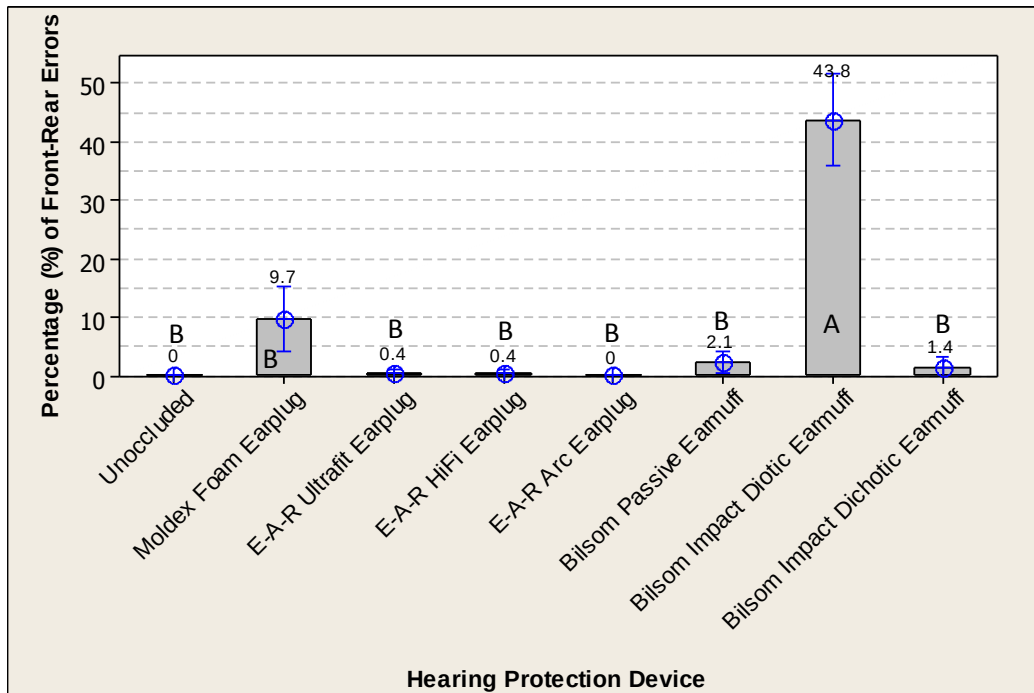


Figure 72. Effect of HPD on *percent front-rear errors* for the 60 dBA background noise level, with mean values shown on bars with 95% confidence intervals.. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

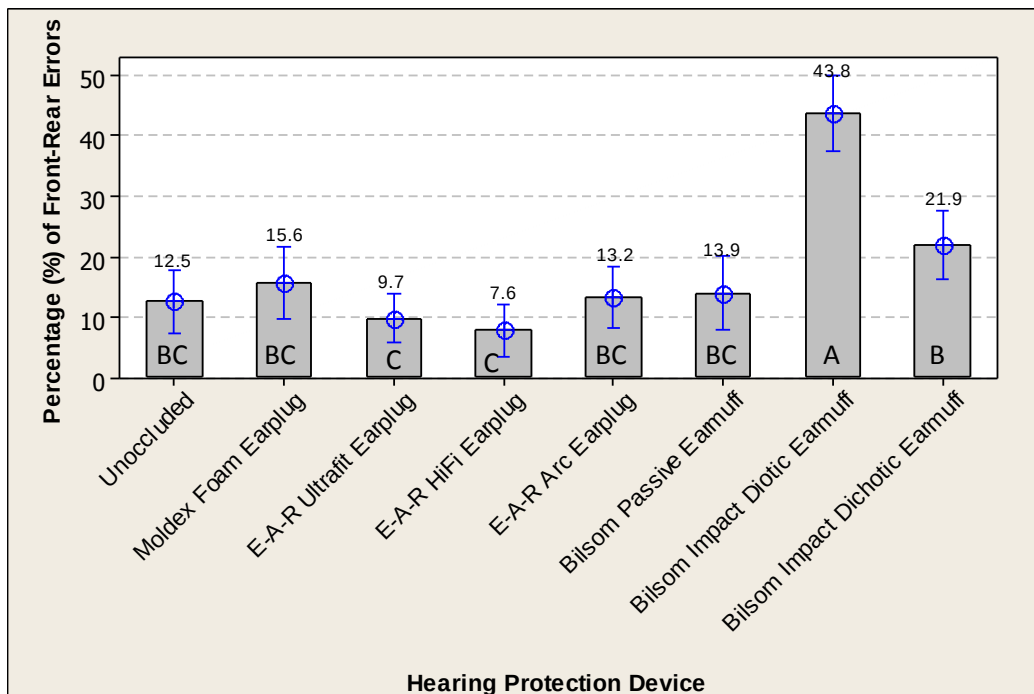


Figure 73. Effect of HPD on *percent front-rear errors* for the 90 dBA background noise level, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

In the 60 dBA background noise condition, the unoccluded ear resulted in 0% front-rear error, the Moldex earplug 9.7%, the E-A-R Ultrafit™ 0.4%, the E-A-R HiFi™ 0.4%, the E-A-R Arc™ 0%, the Bilsom Leightning™ 2.1%, the modified Bilsom diotic earmuff 43.8%, and the Bilsom Impact dichotic earmuff 1.4%. In the 90 dBA background noise condition, the unoccluded ear resulted in 12.5% front-rear error, the Moldex earplug 15.6%, the E-A-R Ultrafit™ 9.7%, the E-A-R HiFi™ 7.6%, the E-A-R Arc™ 13.2%, the Bilsom Leightning™ 13.9%, the Bilsom Impact™ diotic earmuff 43.8%, and the Bilsom Impact dichotic earmuff 21.9%.

Post hoc analysis using Tukey's test indicated that all HPD conditions as well as the open ear, except the modified Bilsom Impact™ diotic earmuff, did not differ with respect to front-rear error. Again, the diotic technology negatively affected listeners' ability to correctly localize a backup alarm with respect to whether it was enunciating from the front or from the rear in the lower noise condition. The fact that no other HPD condition resulted in front-rear localization errors that were any worse than the open ear suggests that the low noise level of 60 dBA did not appreciably affect the listeners' front-rear localization ability.

Post hoc analysis using Tukey's test indicated that there was no difference in front-rear localization ability for listeners fit with the Moldex foam earplug, any of the E-A-R products, and any earmuff (except the diotic model) when compared to the open ear. As before, the diotic technology of the Bilsom Impact™ earmuff negatively affected listeners' ability to correctly localize a backup alarm with respect to whether it was enunciating from the front or from the rear in the higher noise condition. The modified Bilsom Impact™ dichotic earmuff differed with respect to front-rear localization error when compared to the E-A-R Ultrafit™ and the E-A-R HiFi™ earplugs. The higher noise level of 90 dBA resulted in more differentiation across HPD condition with respect to front-rear localization errors when compared to the lower (60 dBA) noise level, but the same general trend is evident, which is that no HPD condition (except the diotic earmuff) resulted in front-rear localization errors that were any worse than the open ear.

ANOVA revealed a significant interaction in front-rear localization errors between *background noise level* and *backup alarm type*, $F(1,11) = 5.7$, $p = 0.03$ (Table 22). In the 60 dBA background noise level, the mean right-left localization errors for the standard backup alarm and the modified backup alarm were 7% and 7.4%, respectively. In the 90 dBA background noise level the mean right-left localization error for the standard backup alarm and the modified backup alarm was 19% and 15.5%, respectively. Post hoc analysis using Tukey's test indicated that the mean right-left localization errors differed between the two backup alarm types in the 90 dBA background noise condition (see Figure 74).

From Figure 74, it appears that, as the background noise level increased from 60 dBA to 90 dBA, the modified backup alarm resulted in front-rear localization performance that did not significantly change; however, the performance for the standard backup alarm did significantly change as the background noise level increased—it became worse. As the background noise levels increased, the modified backup alarm helps maintain the ability for listeners to localize the alarm when compared to the standard backup alarm, possibly due to the hypothesized improvement in localization ability afforded through the additions of 400 Hz and 4000 Hz to the standard backup alarm signal. Thus, here again it appears that the ability to localize the modified backup alarm in the front-rear dimension remains robust as noise levels increase.

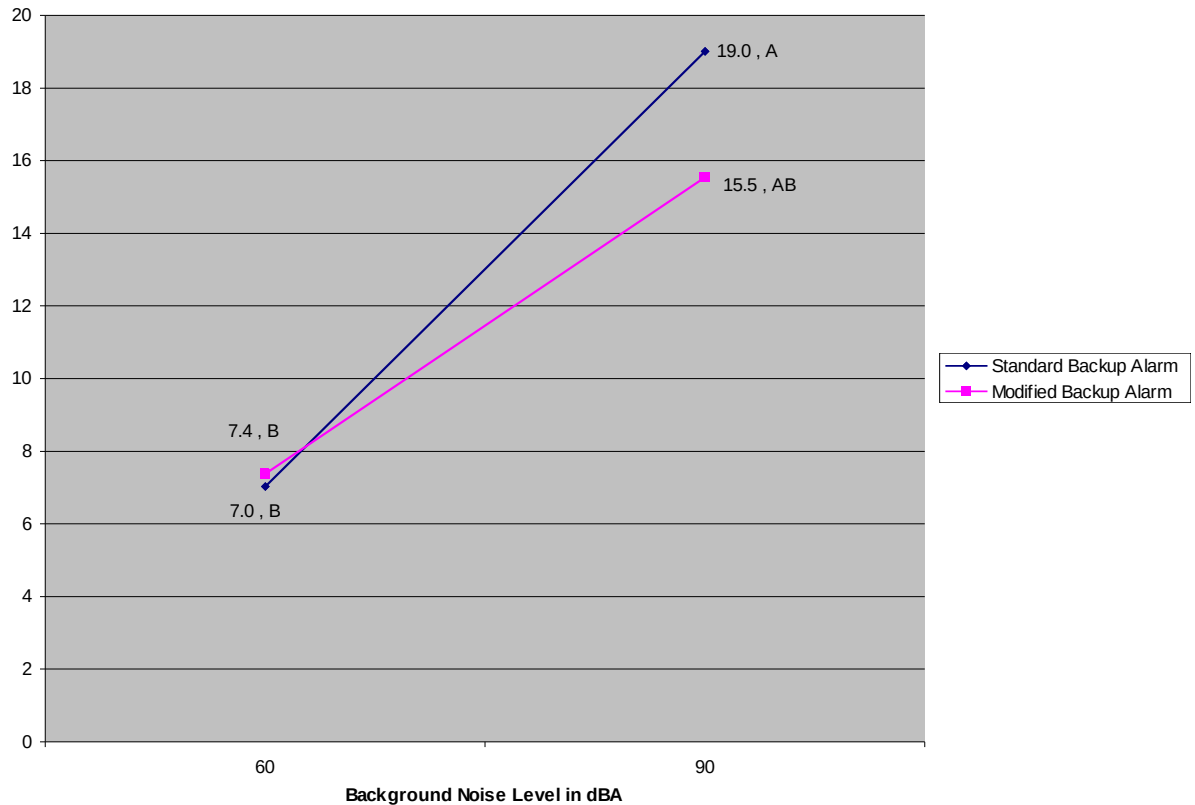


Figure 74. Interaction of backup alarm type and background noise level on *percent front-rear localization errors*. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Absolute deviation in degrees. ANOVA (Table 23) revealed a main effect of HPD on the absolute deviation in degrees from the emanating backup alarm source, $F(7,77) = 92.6$, $p < 0.0001$, with the means ranging from 11.8° for the E-A-R HiFi™ earplug to 83.2° for modified Bilsom diotic earmuff (see Figure 75 and Table 23). Post hoc analyses using Tukey's test indicated that the modified Bilsom diotic earmuff differed from all other HPD conditions with respect to the absolute deviation in degrees; however, there were no other differences among any of the other HPDs or the open-ear condition, in percent front-rear errors.

TABLE 23. ANOVA Summary table for the *absolute deviation in degrees* from the backup alarm source (**bold** values indicate significance).

Source	df	SS	MS	F	Pr>F
HPD*	7	187451.6	26778.8	92.6	<.0001
BNL*	1	31079.2	31079.2	80.3	<.0001
BU*	1	2207.7	2207.7	25.9	0.0003
S*	11	11867.7	1078.8	-----	-----
HPD×S	77	22249.7	288.9	-----	-----
BNL×S	11	4257.1	387.0	-----	-----
BU×S	11	936.8	85.1	-----	-----
HPD×BNL	7	6769.6	967.0	7.2	<.0001
HPD×BU	7	1236.9	176.7	3.3	0.0039
BNL×BU	1	1146.8	1146.8	11.2	0.0065
HPD×BNL×S	77	10241.9	133.0	-----	-----
HPD×BU×S	77	4106.1	53.3	-----	-----
BNL×BU×S	11	1125.2	102.2	-----	-----
HPD×BNL×BU	7	669.1	95.5	1.2	0.2649
HPD×BNL×BU×S	77	5691.6	73.9	-----	-----

HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects

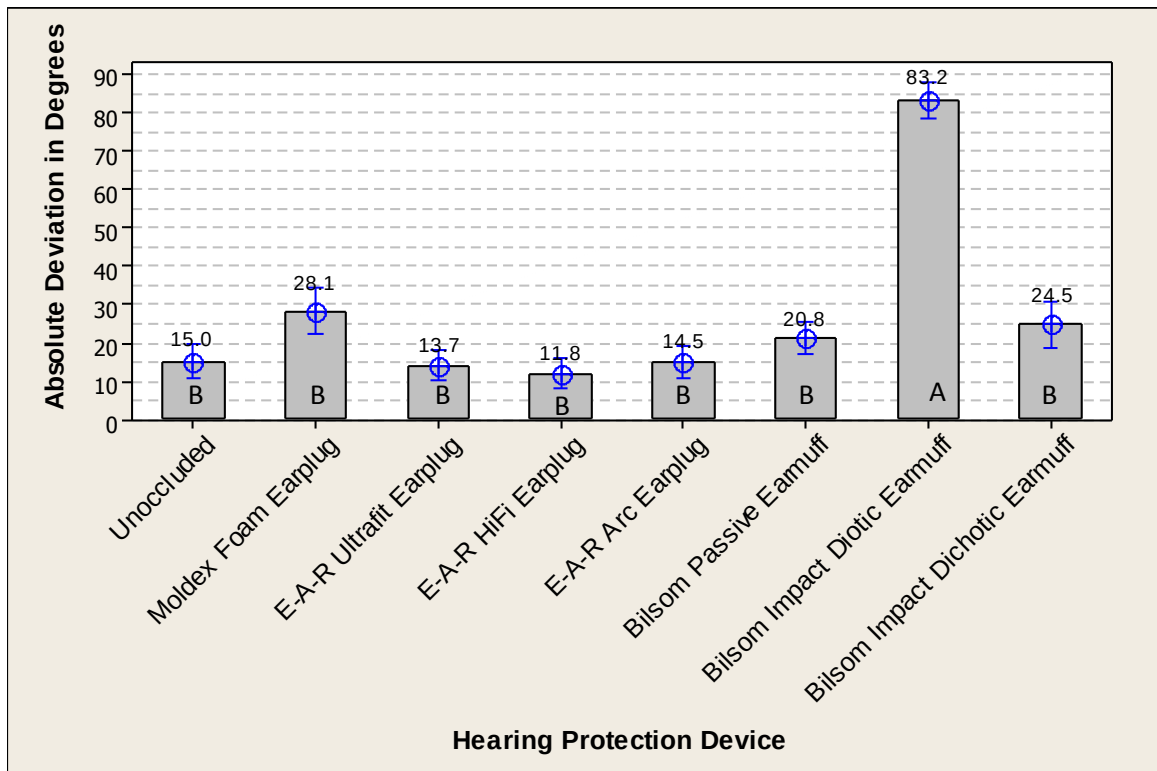


Figure 75. Main effect of HPD on the *absolute deviation in degrees* from the backup alarm source, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

The diotic technology of the modified Bilsom Impact™, which presented the *same* signal to both ears electronically, again resulted in marked decrements in localization ability when compared to all other conditions. It appears that the E-A-R Ultrafit™, E-A-R Hifi™, and E-A-R Arc™ earplugs, the Bilsom Lightning™ earmuff, and the Bilsom Impact™ dichotic earmuff performed as well as the open ear with respect to absolute deviation in degrees.

ANOVA also revealed a significant main effect of *background noise level* on the absolute deviation in degrees from the emanating backup alarm source, $F(1,11) = 80.3$, $p < 0.0001$, with the means at 17.5° in the 60 dBA background noise level and at 35.5° in the 90 dBA background noise level (see Figure 76).

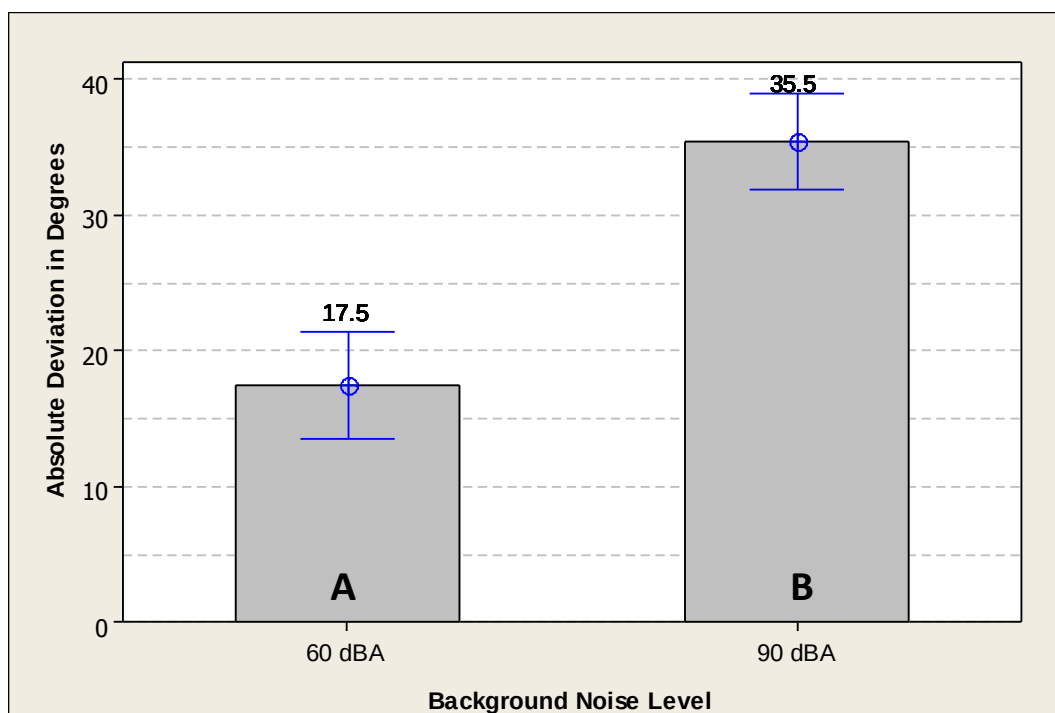


Figure 76. Main effect of background noise level on the *absolute deviation in degrees* from the backup alarm source, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$).

Listeners experienced greater absolute deviations in degrees from the emanating backup alarm source when localizing in the higher background noise level when compared to the lower background noise condition.

ANOVA (Table 23) revealed a significant main effect of *backup alarm type* on the absolute deviation in degrees from the emanating backup alarm source, $F(1,11) = 25.92$, $p = 0.0003$, with the means of 28.9° for the standard backup alarm and 24.1° for the modified backup alarm signal (see Figure 77). Listeners experienced greater absolute deviations in degrees from the backup alarm source when localizing the standard backup alarm as compared to the modified backup alarm.

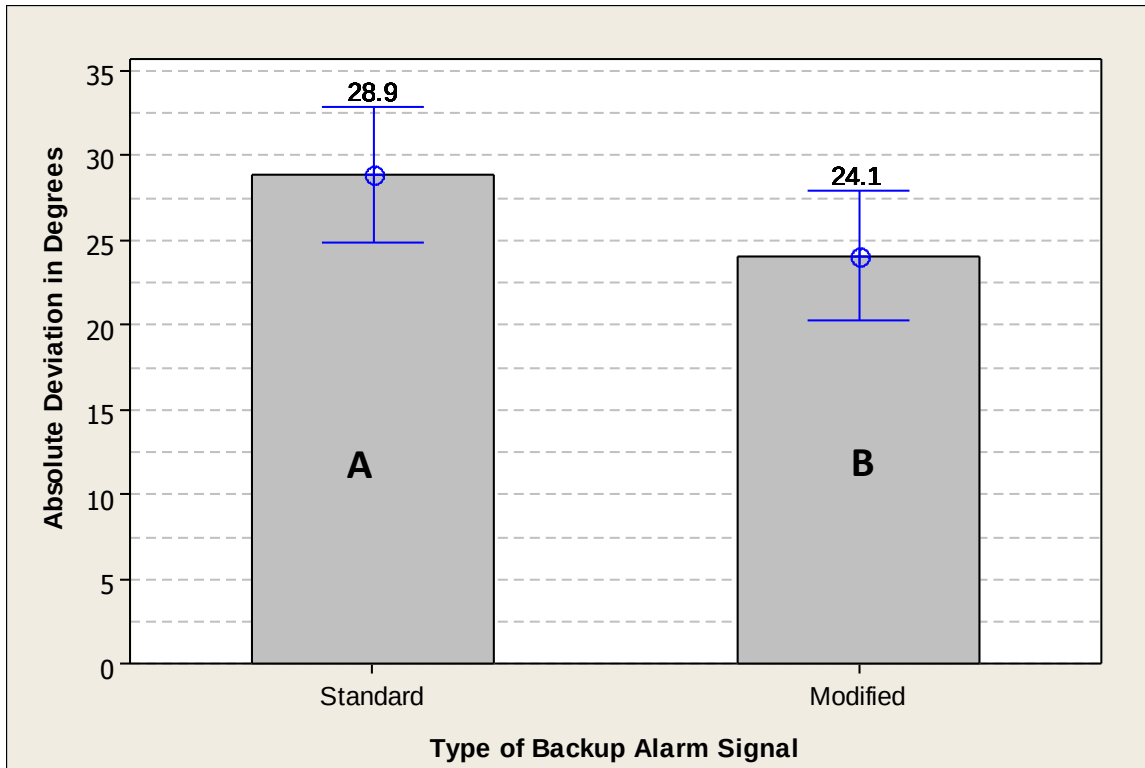


Figure 77. Main effect of backup alarm type on the *absolute deviation* in degrees from the backup alarm source, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$).

ANOVA (Table 23) revealed a significant interaction between *HPD* and *background noise level* with respect to absolute deviation in degrees from the backup alarm source, $F(7,77) = 7.2$, $p < 0.0001$. For analysis, the HPD interactions with background noise level were partitioned between background noise levels. In the 60 dBA background noise level, the means ranged from 3.4° for the unoccluded ear to 83.8° for the modified Bilsom diotic earmuff (see Figure 78). In the 90 dBA background noise level, the means ranged from 19.3° for the E-A-R HiFi™ earplug to 82.6° for the modified Bilsom Impact™ diotic earmuff (see Figure 79).

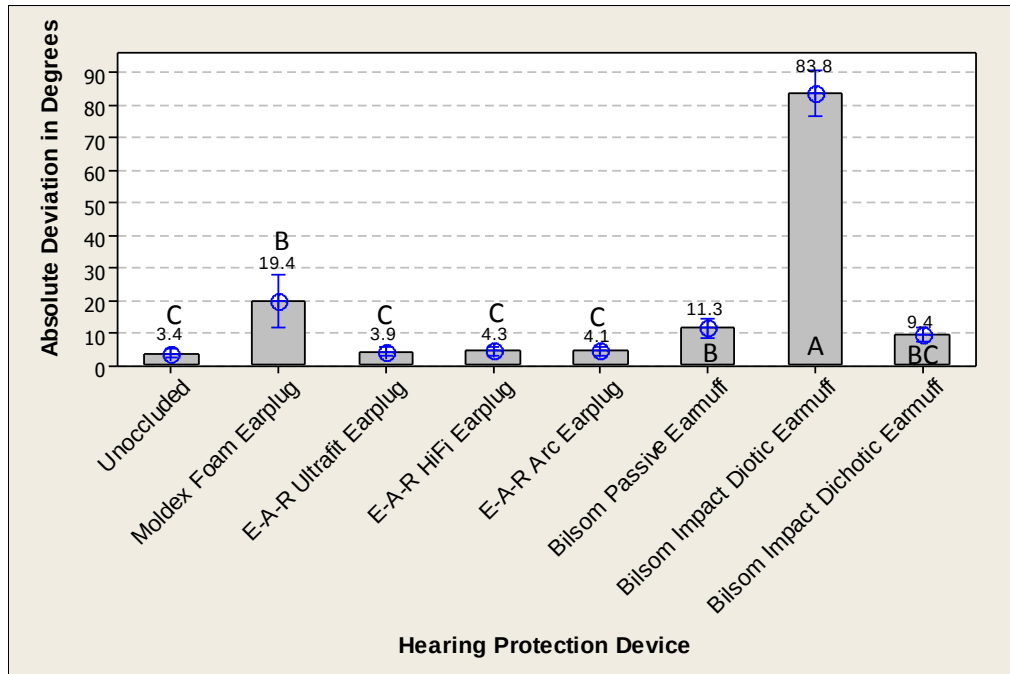


Figure 78. Effect of HPD on *absolute deviation in degrees* from the backup alarm in the 60 dBA background noise level, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

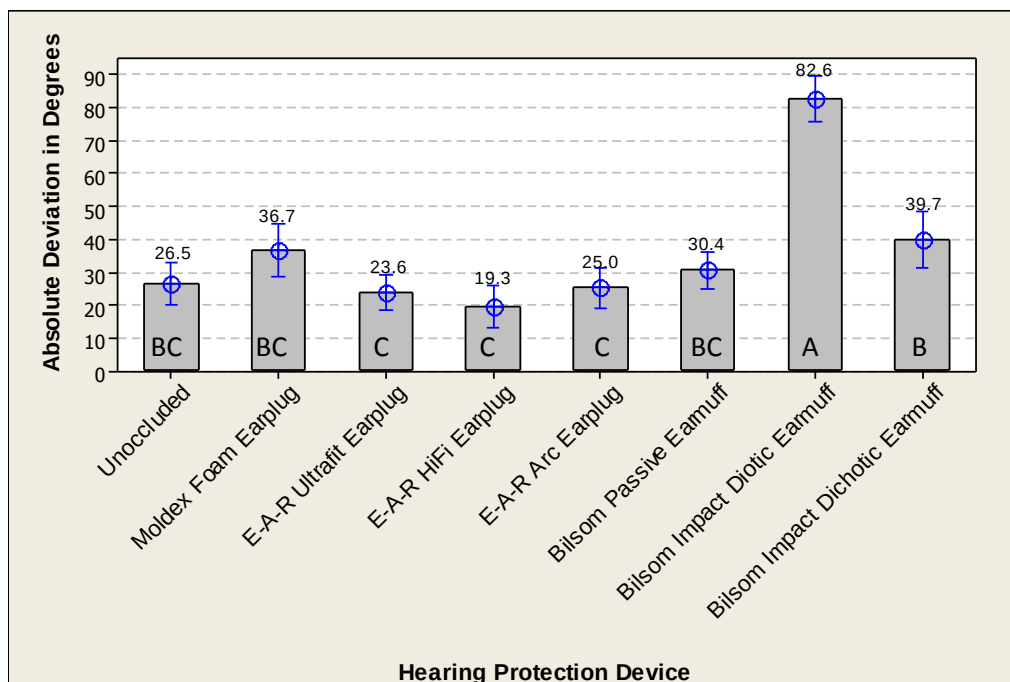


Figure 79. Effect of HPD on *absolute deviation in degrees* from the backup alarm in the 90 dBA background noise level, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

In 60 dBA background noise, the unoccluded ear resulted in a mean absolute deviation of 3.4°, the Moldex earplug 19.4°, the E-A-R Ultrafit™ 3.9°, the E-A-R HiFi™ 4.3°, the E-A-R Arc™ 4.1°, the Bilsom Lightning™ 11.3°, the modified Bilsom Impact™ diotic earmuff 83.8°, and the Bilsom Impact™ dichotic earmuff 9.4°. In the 90 dBA background noise condition, the unoccluded ear resulted in a mean absolute deviation of 26.5°, the Moldex earplug 36.7°, the E-A-R Ultrafit™ 23.6°, the E-A-R HiFi™ 19.3°, the E-A-R Arc™ 25°, the Bilsom Lightning™ 30.4°, the modified Bilsom diotic earmuff 82.6°, and the Bilsom Impact dichotic earmuff 39.7°.

Post hoc analysis using Tukey's test for the 60 dBA background noise condition indicated that the modified Bilsom diotic earmuff differed from all other HPD conditions with respect to absolute deviation in degrees from the enunciating backup alarm source. The Moldex foam earplug, the Bilsom Lightning™, and the Bilsom Impact™ dichotic earmuff did not differ with respect to this metric. When compared to the open ear, none of the E-A-R earplugs, nor the Bilsom Impact™ dichotic earmuff, differed in absolute deviation in degrees. Again, the result speak against the diotic technology for localization, in that listeners' localization decisions were off (on average) close to 90° from the actual backup alarm enunciation location. The higher-attenuating HPD conditions (by labeled NRR) appeared to result in difficulty for the listeners with respect to this metric, suggesting that the increased attenuation of three of the devices (the deep-insert foam Moldex earplug and the Bilsom Lightning™ earmuff resulted in increased absolute deviation in degrees with respect to localization of the backup alarm source when compared to the open ear, and to the lesser-attenuating E-A-R products.

Post hoc analysis using Tukey's test for the 90 dBA background noise condition indicated that the modified Bilsom diotic earmuff differed from all other HPD conditions with respect to absolute deviation in degrees from the backup alarm source. The Bilsom Impact™ dichotic earmuff differed from all three of the E-A-R products in that its absolute deviation performance was worse. No other HPD condition, except for the Bilsom Impact™ diotic earmuff, differed from the unoccluded ear with respect to this metric. The results again suggest that the diotic technology is inadvisable, in that localization decisions were off (on average) close to 90° from the actual backup alarm source.

ANOVA (Table 23) revealed a significant interaction of *HPD* and *backup alarm type* on absolute deviation in degrees from the backup alarm enunciation source, $F(7,77) = 3.3$, $p = 0.004$. For analysis, the HPD interactions with backup alarm type were partitioned between backup alarm types. In the standard backup alarm condition, the means ranged from 12.1° for the E-A-R HiFi™ earplug to 84.8° for the modified Bilsom diotic earmuff (see Figure 80). In the modified backup alarm condition, the means ranged from 11.4° for both the E-A-R Ultrafit™ and E-A-R HiFi™ earplugs, to 81.6° for the modified Bilsom diotic earmuff (see Figure 81). For the standard backup alarm, the unoccluded ear resulted in a mean absolute deviation of 17.2°, the Moldex earplug 33.3°, the E-A-R Ultrafit™ 16°, the E-A-R HiFi™ 12.1°, the E-A-R Arc™ 15.2°, the Bilsom Lightning™ 22.3°, the modified Bilsom diotic earmuff 84.8°, and the Bilsom Impact™ dichotic earmuff 29.9°. For the modified backup alarm condition, the unoccluded ear resulted in a mean absolute deviation of 12.7°, the Moldex earplug 22.9°, the E-A-R Ultrafit™ 11.4°, the E-A-R HiFi™ 11.4°, the E-A-R Arc™ 13.9°, the Bilsom Lightning™ 19.4°, the modified Bilsom diotic earmuff 81.6°, and the Bilsom Impact dichotic earmuff 19.2°.

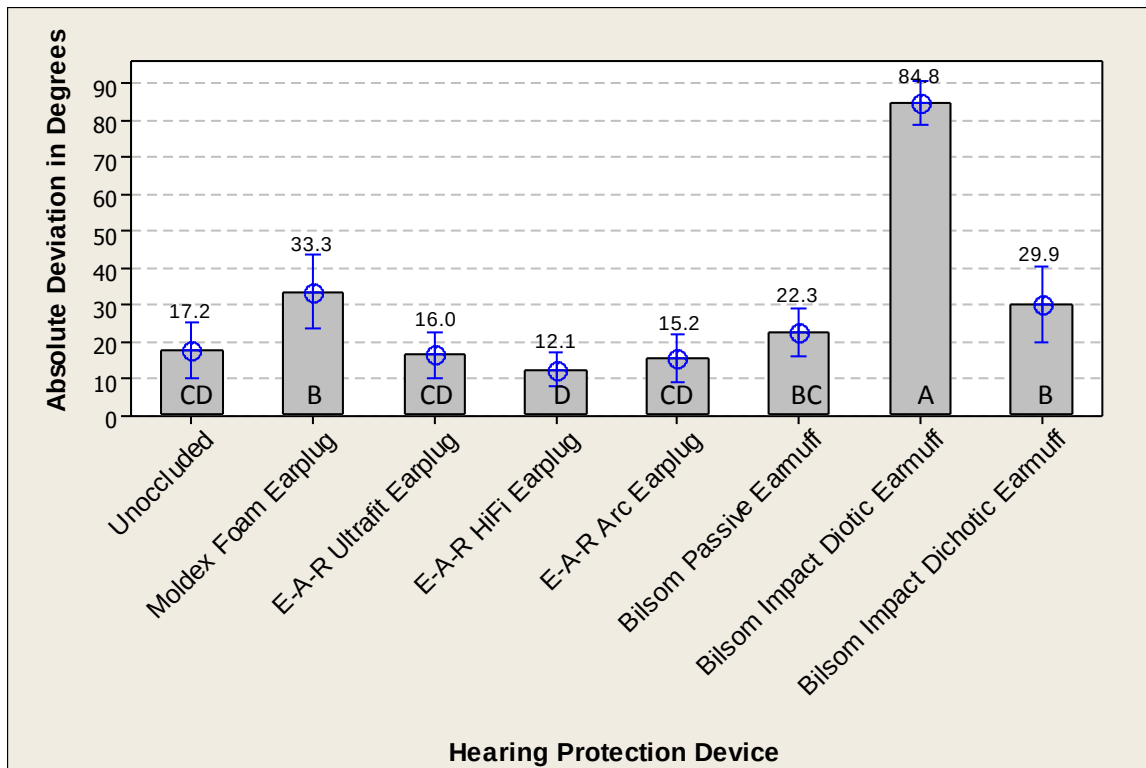


Figure 80. Effect of HPD on *absolute deviation in degrees* from the backup alarm in the *standard* backup alarm condition, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Post hoc analysis using Tukey's test in the standard backup alarm condition indicated that the modified Bilsom diotic earmuff differed from all other HPD conditions with respect to absolute deviation in degrees from the backup alarm source. The diotic technology of the modified Bilsom Impact™ presented difficulties for the listeners in being able to localize the backup alarm, in that localization decisions were off (on average) close to 90° from the actual backup alarm enunciation source. The Moldex foam earplug, the Bilsom Lightning™, and the Bilsom Impact™ dichotic earmuff did not differ with respect to this metric. No E-A-R product differed from the unoccluded ear with respect to absolute deviation in degrees, nor did the Bilsom Lightning™ earmuff. The E-A-R HiFi™ earplug differed from the Moldex earplug, the Bilsom Lightning™ earmuff, and the Bilsom Impact™ dichotic earmuff, in that localization performance was improved with it. Two of the higher-attenuating HPD conditions (by labeled NRR) appeared to result in difficulty for the listeners with respect to this metric, in that the deep-insert foam Moldex earplug and the Bilsom Impact™ dichotic earmuff resulted in increased absolute deviation in degrees with respect to localization of the backup alarm source when compared to the open ear, and to the lesser-attenuating E-A-R products. This contention must be tempered with the fact that the open ear did not differ from the (also) high-attenuating Bilsom Lightning™ earmuff, however.

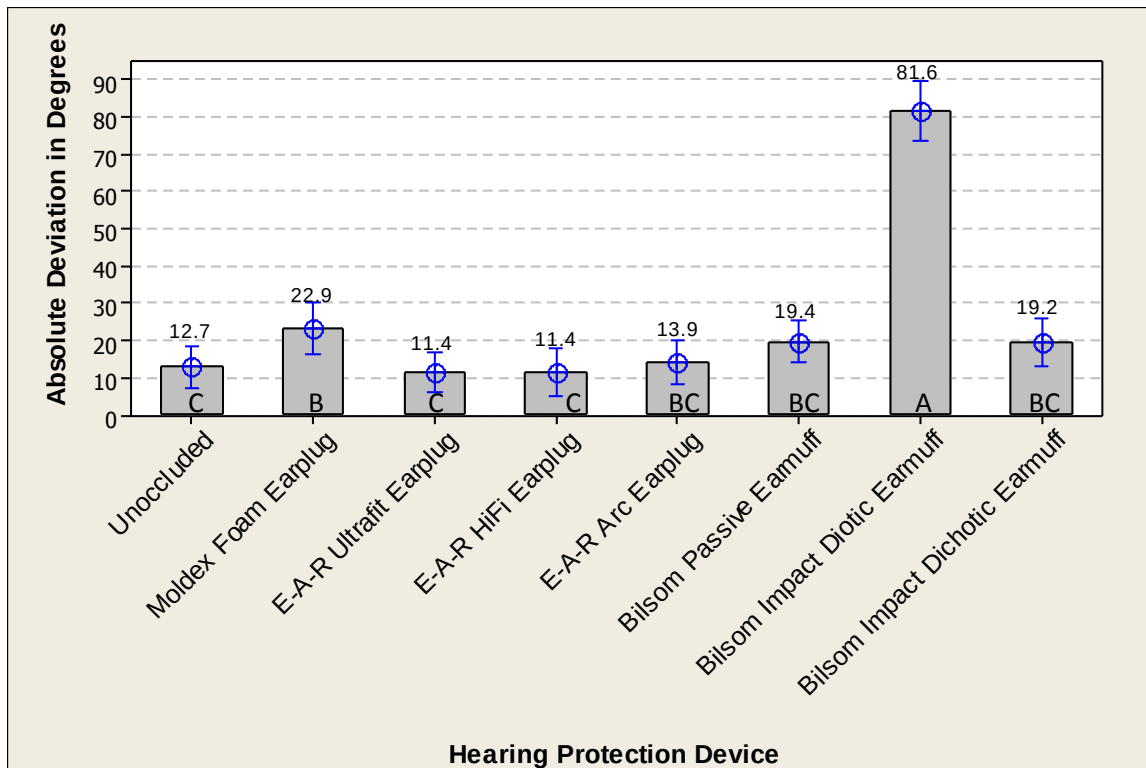


Figure 81. Effect of HPD on *absolute deviation in degrees* from the backup alarm in the *modified* backup alarm condition, with mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Similar to the standard backup alarm condition, post hoc analysis using Tukey's test in the modified backup alarm condition indicated that the modified Bilsom diotic earmuff differed from all other HPD conditions with respect to absolute deviation in degrees from the backup alarm source. The diotic technology of the modified Bilsom Impact™ presented difficulties for the listeners in being able to localize the backup alarm, in that localization decisions were off (on average) close to 90° from the actual backup alarm. Of the other HPD conditions, only the Moldex foam earplug differed from the open ear with respect to this metric. The modified backup alarm appeared to increase precision with respect to absolute deviation from the alarm's actual direction when compared to the standard backup alarm (and as reported previously for the main effect); this increased precision is notable when looking at the results across HPD condition as well, wherein there was less deviation between backup alarm types.

ANOVA (Table 23) revealed a significant interaction for absolute deviation in degrees from the backup alarm source between *backup alarm type* and *background noise level*, $F(1,11) = 11.2$, $p = 0.007$. In the 60 dBA background noise level, the mean absolute deviation in degrees for the standard backup alarm and the modified backup alarm was 18.1° and 16.8°, respectively. In the 90 dBA background noise level the mean right-left localization error for the standard backup alarm and the modified backup alarm was 39.6° and 31.3°, respectively. Post hoc analysis using Tukey's test indicated that the mean absolute deviation in degrees did not

differ between the two backup alarm types in the 90 dBA background noise condition, nor in the 60 dBA condition (see Figure 82).

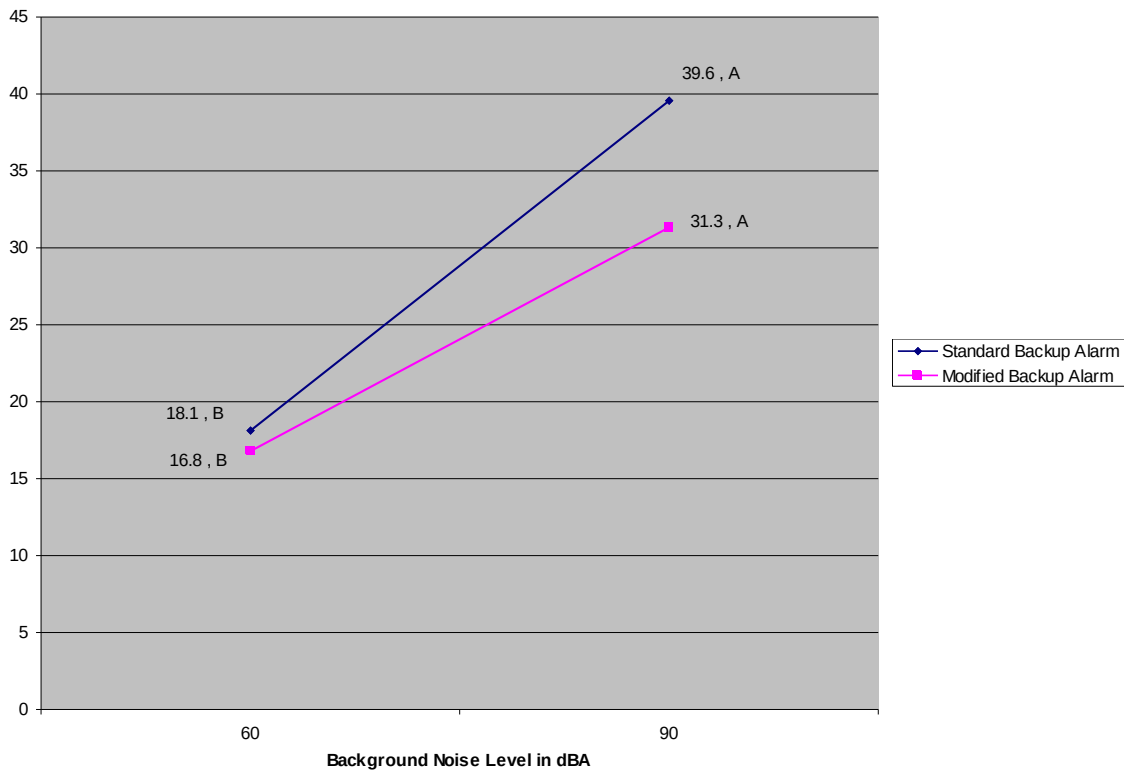


Figure 82. Interaction of backup alarm type and background noise level on *absolute deviation in degrees* from the backup alarm source. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Figure 82 shows that, as the background noise level increased from 60 dBA to 90 dBA, both backup alarms resulted in increased absolute deviation from the backup alarm's location. The results suggest that, as noise levels increase, the modified backup alarm does not provide an increased ability for listeners to localize the alarm in an absolute deviation sense, when compared to the standard backup alarm, which is unlike the results for both right-left and front-rear localization errors, where it did show an advantage. In other words, both the standard and the modified backup alarm resulted in similar responses as the background noise levels increased.

Conclusions: Backup Alarm Localization Study. Outlined next are the conclusions stemming from the backup alarm localization study.

Hearing protection device localization performance (main effects of HPD type).

Localization errors with respect to the dependent measures *percent correct*, *percent right-left errors*, *percent front-rear errors*, and *absolute deviation in degrees*, are first considered here in a collapsed fashion across backup alarm type and background noise level. Across all 4 dependent measures, the diotic earmuff, which presented the same signal to both ears, resulted

in marked decrements in localization ability, regardless of the dependent measure of localization, when compared to all other HPD conditions. This device consistently resulted in the poorest localization performance, suggesting that diotic technologies, as applied to earmuffs of similar design and passive attenuation to those of this research, are not recommended for construction workers who must maintain the ability to localize backup alarms from nearby vehicles.

On all of the dependent measures of *percent correct localization*, *percent right-left errors*, *percent front-rear errors*, and *absolute deviation in degrees*, all 6 of the HPDs, with the exception of the dichotic muff, performed equally as well as the unoccluded (open) ear, suggesting that universal-fit devices of these types may well provide reasonable localization of backup alarms while maintaining some level of noise attenuation, at least for normal hearing listeners as used in this experiment. There was clearly no localization benefit of the sound transmission dichotic earmuff over the other devices, nor any particular benefit of the amplitude-sensitive E-A-R Arc earplug or the E-A-R Hi-Fi earplug, both of which have relatively uniform and moderate attenuation. All of these “augmented” devices performed on a par with the two conventional passive earplugs and the conventional Bilsom earmuff.

These main effects results, which of course show equality across HPDs except for the deleterious localization effects of the diotic earmuff, must be tempered by their interaction results with the background noise level and backup alarm types.

With respect to the first hypothesis (i.e., that earplugs were expected to provide more accurate localization decisions when compared to earmuffs, the data generally do not support that hypothesis.

With respect to the second hypothesis (i.e., the diotic earmuff will result in the least accurate localization decisions), the data clearly support the hypothesis. As mentioned, the diotic technology that was custom-added to a Bilsom Impact™ earmuff consistently performed the poorest across all dependent metrics. The use of a single microphone/amplifier to feed both earcups of a sound transmission earmuff appears to be a very poor choice if localization is needed, as it is in construction.

With respect to the fifth hypothesis (i.e., localization accuracy when using the Moldex foam earplug would be improved when compared to the premolded earplugs (due to the possible adverse affect of the premolded earplugs’ handle on the spectral cues afforded by the inner portions of the pinnae), the data do not support the hypothesis. The Moldex earplug, at least in the main effect of HPD-type, performed equally well as the passive circumaural devices, and was indeed poorer at overall percent localization when compared to the premolded E-A-R models. It appears that the hypothesized ‘stem or handle’ effect of the premolded devices did not interfere with the ability for the listeners to localize through use of the spectral cues of the pinnae, including those of the concha/canal rim region.

Background noise levels. When localizing in the higher background noise level of 90 dBA, listeners experienced significantly greater difficulty in localizing the backup alarm signal as a percentage of correct responses (54.7%, collapsed across HPD and backup alarm type). In the lower background noise level of 60 dBA, participants were able to correctly localize the backup alarm signal 81.4% of the time. As such, when ambient workplace noise levels are high, more caution must be given to vehicular motions around ground crews, who likely cannot localize their backup alarms.

Of the errors made that were right-left (i.e., listener confusion as to whether the backup alarm was coming from the left or from the right), 5.4% of the errors occurred within the lower background noise level, while over twice as many (13.3%) occurred within the higher background noise level. Similarly, the percent of errors made that were front-rear in nature (i.e., listener confusion as to whether the backup alarm was coming from the front or from the rear), 7.2% of the errors occurred within the lower background noise level, while over twice as many (17.3%) occurred within the higher background noise level. Clearly, background noise levels, at least at the 90 dBA level investigated herein, wreak havoc with worker localization of backup alarms.

When localization errors were made, the absolute deviation in degrees (i.e., greater than 45°, see Figure 55) from the emanating backup alarm source was greater (by a factor of 2) in the higher background noise condition (36.5°) than in the lower background noise condition (17.5°).

Clearly, the noise levels evident at road construction sites—which represent a combination of both equipment noise (e.g., milling machines, rollers) and ambient noise (e.g., traffic passing by in an adjacent lane to the construction activity), can negatively affect the ability of workers to determine from where a backup alarm signal is sounding, and thus attend to an oncoming vehicle.

The significant HPD by Noise Level interaction did demonstrate, on a very limited basis, that certain HPDs (e.g., the E-A-R Ultrafit and Arc earplug on the percent front-back error measure), performed significantly better than others (e.g., the two electronic earmuffs) in the 90 dBA level. But these interactive effects of HPD-type were very isolated and restricted to basically two of the dependent measures (percent front-back error and absolute deviation in degrees). However, on the latter measure in 60 dBA noise, the high attenuation Moldex foam earplug did result in significantly poorer attenuation than all of the other earplugs and the open ear condition.

The data do tend to support the fourth hypothesis (i.e., that the higher background noise level would result in the least accurate localization decisions when compared to the lower background noise level). Clearly, the accuracy of localization decisions with respect to overall accuracy, accuracy between backup alarms coming from the left or from the right, accuracy between backup alarms coming from the front or from the rear, and accuracy as a function of absolute deviation from the backup alarm source vector, was better in the 60 dBA noise level when compared to the 90 dBA noise level.

Backup alarm type. The results demonstrate statistically significant improvements in localization performance for listeners when using the modified backup alarm when compared to the standard backup alarm (70% correct and 66% correct, respectively, when collapsed across HPD and background noise level). However, the magnitude of improvement (4%) is indeed rather small. As discussed, the rationale for the inclusion of the frequencies of 400 Hz and 4000 Hz as additions to the standard backup alarm frequency (i.e., 1250 Hz) was to foster listener utilization of Interaural Level Difference (ILD, the difference in sound intensity between the two ears) and Interaural Time Difference (ITD, the difference in sound arrival time between the two ears) in localizing the source of the signal in azimuth.

With respect to right-left errors, the modified backup alarm resulted in decreased errors (7.4%) when compared to the standard backup alarm (11.3%). As mentioned previously, the

ability of some of the HPDs tested to improve right-left localization performance suggests that their design (e.g., dichotic vs. diotic, those that did not block the pinnae) fostered the ability of listeners to utilize either ILD or ITD, and perhaps both. Again, there was a significant HPD by backup alarm type interaction, wherein there were no differences among HPDs or open ear conditions (except for the typically worse performance of the diotic muff) when presented with the modified backup alarm, but there were some differences among HPDs when presented with the standard backup alarm. Perhaps the modified backup alarm overcomes some of the localization-destroying characteristics of certain HPDs.

When localization errors were made, the absolute deviation in degrees from the backup alarm source was greater when listeners were presented with the standard backup alarm (28.9°) than when they were presented with the modified backup alarm (24.1°). While statistically significant, the difference in absolute deviation in degrees may not be practically significant (i.e., about 5°); given that vehicles with backup alarms are typically quite large in size, thus the advantage afforded may not one that is externally significant in operational road construction settings, at least on this one dependent measure.

While it was posited that the spectral cues in the modified signal may increase the performance of listeners with respect to front/rear localization, the results approached, but did not reach, significance ($p = 0.06$). There is some justification that, in safety-critical construction operations in which the ability to determine whether a backup alarm is coming from the front or from the rear, and especially when considering the modified alarm's advantage in overall percent correct and the improvement in right-left localization performance, such a marginal p -value (0.06) should be considered significant with respect to localization performance when comparing the modified backup alarm to the standard one.

The data therefore support the third hypothesis (i.e., the modified backup alarm signal would result in more accurate localization decisions when compared to the standard backup alarm signal). Based on the aforementioned results comparing localization performance between the standard and modified backup alarms, there appear to be sufficient advantages that can be realized for construction workers through the use of a backup alarm that incorporates the additional frequencies of 400 Hz and 4000 Hz, suggesting that the prevailing Standards with respect to backup alarm frequency content are in need of revision.

Interactions. The reported interaction of *HPD* and *background noise level* in percent correct localization suggests that the E-A-R earplug products were better able to maintain correct localization ability than could be realized with the deep-insert foam Moldex product in the lower noise (60 dBA) condition, and equivalent to the open ear's performance. Also, the fact that the circumaural products (with the exception of the diotic earmuff) resulted in localization ability on a par with the unoccluded ear and the E-A-R products, suggests that the (comparatively) high-NRR, deep-insert foam Moldex earplug negatively affected localization ability. In the higher noise (90 dBA) condition there were some advantages of the E-A-R earplugs (particularly the Hi-Fi device) but the differences were not as clear-cut as in the lower noise level. There was no discernable pattern that emerged when looking at the percent correct means across HPD condition other than the fact that, as mentioned, the diotic technology negatively affects localization ability.

The reported interaction of *HPD* and *backup alarm type* in percent correct localization indicated that, for the standard backup alarm, the Moldex foam earplug resulted in localization

performance on a par with the two non-diotic circumaural earmuffs, but poorer performance than the E-A-R earplugs and the open ear. The E-A-R products provided the highest percent correct localization ability, again on a par with the unoccluded ear, suggesting that their design fosters the ability to localize a standard backup alarm signal, while maintaining some level of hearing protection, more or less depending upon the specific product. For the modified backup alarm, all three of the E-A-R products did not differ from the unoccluded ear with respect to this metric, suggesting that their design also fosters the ability to localize a modified backup alarm signal while maintaining some level of hearing protection (via labeled NRR). Similar to the results in the standard backup alarm condition, the Moldex foam earplug resulted in localization performance on a par with the two non-diotic circumaural earmuffs, and poorer than the other earplugs and the open ear. Similar trends, though largely nonsignificant results, were obtained with the interaction of HPD with backup alarm type on the percent right-left localization errors.

The reported interaction in right-left localization errors between *background noise level* and *backup alarm type* indicated that, as the background noise level increased from 60 dBA to 90 dBA, the modified backup alarm resulted in right-left localization performance that did not change; however, the performance for the standard backup alarm did change (worsen) as the background noise level increased. These results suggest that, as the background noise levels increase, the modified backup alarm maintains an ability for listeners to better localize the alarm as compared to the standard backup alarm, possibly due to the hypothesized improvement in localization ability afforded through the additions of 400 Hz and 4000 Hz to the standard backup alarm signal. Thus, it appears that the ability to localize the modified backup alarm in the right-left dimension remains robust as noise levels increase.

The reported interaction in front-rear localization errors between *background noise level* and *backup alarm type* largely mirrored this effect wherein localization with the modified alarm remained about the same as noise level was increased.

With respect to the reported interaction in absolute deviation in degrees from the backup alarm source, as the background noise level increased from 60 dBA to 90 dBA, *both* the standard and the modified backup alarms resulted in increased absolute deviation from the backup alarm location. These absolute deviation results suggest that, as noise levels increase, the modified backup alarm does not provide an improved ability for listeners to localize the alarm when compared to the standard backup alarm, unlike the results for both right-left and front-rear localization errors.

Recapitulation and Overall Conclusions

As associated with each of the experiments covered above, conclusions specific to each experiment have already been presented in detail, along with supporting tables and figures. The intent of the ensuing section is to provide a recapitulation summary of the major outcomes and conclusions from this research project.

One goal of the exhaustive data collection efforts conducted in Phase I of this research effort, including job/task analysis, was to determine what trades/crafts/labor categories (carpenters, electricians, plumbers, laborers, crane operators, dozer operators, etc.) are represented at a wide range of construction sites (including small single-unit residential sites, large industrial sites, road construction, and commercial construction). This led to the system description and analysis, subject matter interviews, the dissemination of the hearing in construction questionnaire (Appendix A), and activity analyses; the sum total of these data indicated that the Research Team would focus efforts on road construction and, to a more limited extent, on other construction site types. Following the data collection, the Research Team visited many different construction sites that ranged from building construction (including earth-moving operations) to airport runway construction (including road milling and paving operations). At these site visits over 300 noise measurements were taken (i.e., min, max, Leq with 3 dB exchange rate, spectra) for approximately 50 different types of equipment (e.g., milling machines, dozers, cranes, trucks, chainsaws, drills, augers) and background noises (e.g., traffic noise, airport runway noise) for this study, all catalogued in Figure 3 and Table 3. The data gleaned indicated that many noise exposures to workers at road and other construction sites should be considered as potentially hazardous and that hearing protection was warranted in most jobs.

Many of the average (i.e., Leq) noise levels measured approached or exceeded OSHA general industry exposure “action” levels (i.e., 85 dBA TWA), and several of them exceeded OSHA’s general industry exposure “criterion” level. (It should be noted that the 1971 OSHA construction regulation consists only of the 90 dBA TWA “criterion” level, and that OSHA has never adopted an “action” level toward implementation of a full hearing conservation program for construction workers in the same vein as it did for general industry in 1983.) Road milling operations were measured to consistently produce maximum sound pressure levels in excess of 100 dBA (e.g., 103 dBA for a paving machine, 105 dBA for a high-frequency roller), and some non-road operations have produced similar levels (e.g., 101 dBA for a hydraulic excavator, 103 dBA for a bulldozer involved in earth-moving work), and average (Leq) values were also high, with many in the mid-90 dBA range. Disturbingly, the workers on and around pavement milling machines (and the equipment that supports its operations, such as Broche Brooms) were not seen to wear any hearing protection at any of the 14 infrastructure construction sites that were visited, which covers a sample of over 500 workers. The sound level measurements provided the Research Team with the information needed to focus further on specific jobs/tasks and operations toward worker noise dose, time-weighted average (TWA) values, and to target possible threshold shifts of exposed workers through pre- and post-workday audiograms. The resulting exposure data indicated a substantial noise dose for the operators of several different types/kinds of construction equipment (see Figure 10). For example, the noise dose for a paving machine operator was measured to be 570%, a value that exceeds the recommended dose quite dramatically. Clearly, the noise levels and exposures for operators in road and earth-

moving construction operations often meet and exceed safe limits. Continued exposure appears to lead to TTS (as evidenced by the audiometric data obtained on equipment operators in this research) which may ultimately progress into PTS, which itself leads to debilitating NIHL. While the workers' off-the-job exposures (e.g., many noisy hobbies and other vocations were reported) may also contribute to their NIHL, there is no question that the on-the-job construction exposures are, in many cases, hazardous to hearing. Furthermore, these noise conditions have a direct impact on construction workers' ability to detect and recognize operational signals such as backup alarms because of their masking effects. It is these conditions for which the evaluations and interventions conducted within the ensuing two experimental research Phases sought to address.

With the large amount of data collected across various construction sites with respect to their noise levels, spectra, noise dose, TWA values, and maximum and peak levels across various equipment in the initial Phase, the research team was then able to ascertain (quantify) the magnitude of the problems for construction workers in detecting the operational signals that they need to hear, with an eye toward increased operational safety. The goal of Phase II was to quantify the magnitude of the problems/impediments with respect to construction workers' ability to detect signals. To do so, the ISO 7731-2003 standard for the prediction of masked threshold for operational signals in the high-noise construction environment was used. This international standard specifies the physical principles of design, ergonomic requirements and the corresponding test methods for danger signals for public and work areas in the signal reception area, and provides guidelines for the design of these signals. The ISO 7731 standard states that any danger signal must be *clearly audible*, and the effective masked threshold must be distinctly exceeded, and includes masked threshold calculations between 500-2500 Hz specific to measurements taken. Through several applications of the calculations of that standard to actual noise measurements taken in Phase I, the backup alarms' frequency (and its harmonic) *were analytically found to not be reliably audible in the noise conditions*, which is not in keeping with the ISO Standard for Danger Signals (ISO 7731).

Based on the data emanating from Phase II, many instances were identified, particularly for the worker on the ground, wherein engineering controls are not feasible or effective; in such situations, there is a strong need for hearing protectors that cannot only protect workers' hearing, but which also provides some capacity to detect operational safety signals. Thus, various devices were obtained and analyzed for Phase III, which sought to determine/develop appropriate interventions to mitigate or eliminate the identified impediments to construction worker hearing. The commercially-available "communications-augmented" hearing protectors and headsets of all major HPD manufacturers were reviewed by the Research Team, and those devices which appeared to have the most promise for improving speech and signal detection in construction were procured for laboratory analysis. The electronic sound transmission devices were subjected to laboratory-based experimentation to determine their potential for improving workers' hearing in the bandwidth that encompasses critical speech and warning signal frequencies (i.e., 1000-4000 Hz). Those devices that appeared to be most promising in the measurements were then subjected to human factors experiments using human subjects to determine the detectability of operational signals, as well as their localization ability, within simulated construction noise.

Phase IV included three experiments (one field-based, and one laboratory-based) to assess performance of the identified interventions. The first human factors experiment in this research project, an outdoor (field-based) experiment on backup alarm detection (using the

ascending and descending method of limits) utilizing conventional passive hearing protection was conducted. This within-subjects factorial experiment sought to determine the point (i.e., linear distance) at which normal-hearing listeners could detect a backup alarm of the type used on construction-equipment in an outdoor, free-field condition with the type of hearing protection *now used in construction*, such as foam earplugs or heavy-duty passive, non-electronic (conventional) earmuffs. The primary objective of this research was to determine the linear distance at which normal-hearing listeners wearing an earmuff HPD could detect a construction vehicle's backup alarm operating in near free-field conditions in an outdoor field environment using the ascending and descending method of limits. Although the experiment was very basic and conducted on one HPD with normal listeners only, the results do provide data that may be useful for backup alarm manufacturers, standards committees, and construction safety officials toward reducing worksite fatalities caused by reversing vehicles, particularly in the realm of establishing work separation envelopes between workers and operating machinery. This study had a large degree of realism in that it evaluated backup alarm detection distances under field conditions and a high-attenuation earmuff as would be candidate hearing protection in severe construction noises; however, there are many other factors that also have bearing on the worker's ability to hear the alarm and avoid the vehicle which are in need of further study. Such factors include: the ambient noise of the equipment and other sources, the worker's hearing abilities, the attenuation of the HPD, the number of other (potentially confusing) backup alarms within earshot, and the worker's involvement with other activities which divert his/her attention.

The data from this human subjects experiment helped to determine *at what distance* HPD users could reliably hear the various backup alarms in outdoor worksite conditions and, as a result (based on the reversing speeds of various construction vehicles), how *much time* those HPD users would need to escape the vehicle's path and thus avoid a possible run-over incident. The normal-hearing listeners in this experiment performed the listening trials with a conventional earmuff-type HPD, and a high-attenuation one at that (Peltor H10A, NRR = 29). With the results, various options for interventions were thereafter evaluated with an eye towards balancing hearing protection with workplace conditions (i.e., the need to protect hearing while ensuring that backup alarms and other signals can be detected), and by suggesting what interventions may be suitable for construction workers who suffer from hearing loss. With this in mind, the overview now turns to a second experiment on backup alarm detection under conventional and augmented HPDs.

The second human factors experiment was aimed at empirically determining the effectiveness of the HPD interventions, and was a laboratory-based one, which further investigated the critical, and most fundamental task of backup alarm *detection*. The purpose of this study was, therefore, to evaluate the effectiveness of using up-to-date, commercially-available, assistive-listening HPDs of the sound-transmission type to augment signal detection (e.g., backup alarms of construction equipment), both of which are routine and necessary considerations at construction sites, and comparing their performance against existing, conventional HPDs of similar design and passive attenuation.

The primary objective of the second research study was to investigate if there was any advantage in using current sound-transmission earmuffs over conventional (passive) earmuffs, for both normal and non-normal hearers, in the detection of a backup alarm within the noise produced by certain construction equipment (road milling machine) that was measured to be of

very high noise output and operated in very dynamic situations which promote runover, as well as with pink noise at various sound pressure levels of 75, 85, 95, and 105 dBA.

The results indicated that the two sound transmission earmuffs tested did *not* offer an advantage over passive earmuffs with respect to the detection of a backup alarm signal within the 4 various levels of pink and milling machine noise. For the most part, the *passive* devices displayed a masked threshold advantage of (on average) 3 dBA over the sound transmission devices. This result can most likely be attributed to the fact that the two electronic earmuffs amplified both the background noise and the signal, therefore making it difficult for the listener to detect the signal, and also due to the fact that the electronic devices produced some earphone “hum” which may have served as masking source which affected detection of the signal.

Sound transmission earmuffs were expected to have lower masked threshold values (than passive HPDs) for both normal and non-normal hearers for noise levels below 85 dBA, and to have the same masked threshold values for noise levels above 85 dBA because they are designed to stop amplifying external sounds at approximately this level. However, the results produced different outcomes for both normal and non-normal hearers at most noise levels. According to the manufacturer of the Bilsom Impact™, the device has electronic filtering abilities that protect the ear from harmful background noise and amplify the sound the listener wants to hear; its amplification limiting levels are a “safe” 82 dBA. In congruence with the above, the manufacturers of the Peltor Tactical Pro™ (the other sound transmission device) also confirmed that the device offers protection from dangerous noise levels, while still amplifying safe sounds such as safety alarms. The built-in inhibitor in the device is claimed to restrain the sound amplification levels at a safe 82 dBA. The sound transmission devices offered no advantage over the passive devices in terms of masked threshold detectability for individuals with normal hearing. For normal hearing listeners, these results suggested that, contrary to the manufacturer’s indications, these devices were not able to distinguish ‘unwanted’ background noise from ‘the sound the listener wants to hear;’ in this case, the backup alarm. Instead, the devices amplified all sounds in the passband, regardless of whether or not they were safety-critical.

With respect to the limited sample (3) of non-normal hearing listeners, the results indicated that the sound transmission devices resulted in a *disadvantage* for hearing-impaired individuals in backup alarm masked threshold when compared to their counterpart, passive earmuffs. This, again, might be due to the fact that the sound transmission devices amplified both the signal and the background noise, therefore making it difficult to perceive the backup alarm. In the highest noise level tested (105 dBA), the sound transmission devices did not differ from the passive devices in backup alarm masked threshold, which suggests that whatever benefit received by the passive devices in lower noise levels disappeared in the highest tested noise level.

As anticipated, the background noise levels as tested in the second experiment (75 dBA, 85 dBA, 95 dBA, and 105 dBA) were found to directly affect the masked threshold values in a systematic manner—the higher the background noise, the higher the masked threshold value. Noise type (i.e., milling machine noise and pink noise), however, was not found to have a differential effect on masked threshold values. This result was somewhat surprising because, theoretically, one would expect upward spread of masking to occur in the higher levels of lower frequency noise presented by the milling machine noise. There were no differences in comfort

ratings for any of the earmuffs, indicating that no HPD had any advantage over the other in terms of comfort. However, this result should be tempered by the fact that participants completed the comfort rating scale based only on short duration in wearing the devices in controlled laboratory conditions. Likewise, no differences in detectability of the backup alarm signal were found between the earmuffs, indicating that no particular HPD (including the sound transmission type) was perceived as providing better backup alarm detection than any other HPD.

The third and final human factors experiment sought to investigate the critical task of backup alarm *localization* in the azimuth dimension using various hearing protection devices when compared to the open ear. Another component of this study was that of the backup alarm itself. Based on prior human factors research and known principles of auditory display design, the Research Team decided to ‘modify’ the current, standardized backup alarm signal’s frequency content in an effort to determine whether it would foster improved localization performance when compared to the standardized backup alarm. The modified backup alarm added frequencies (400 and 4000 Hz, in addition to the dominant standard alarm frequency of 1250 Hz and a harmonic at 2500 Hz) that may assist human localization ability via the addition of frequencies that exploit head shadow and binaural phase differences that are useful to the perception of localization. As in the previous detection study, varying levels of a masking noise were used (i.e., 60 dBA and 90 dBA) toward real-world applicability; that is, an attempt to recreate an ambient construction noise environment that would be found in the field, and which might affect the ability of construction workers to localize backup alarm signals.

With respect to the hearing protection device conditions tested, and across all dependent metrics, an intentionally modified Bilsom Impact™ earmuff was converted into a diotic device, which presented the *same* microphone signal to both ears, resulted in marked decrements in localization ability when compared to all other HPD conditions. This device consistently resulted in the poorest localization performance, suggesting that diotic technologies, as applied to earmuffs of similar design and passive attenuation, are not indicated for construction workers who must maintain the ability to localize backup alarms from enunciating vehicles. With respect to *percent correct* localization, all of the HPDs except for the diotic muff performed as well as the open ear, suggesting that universal-fit devices of these types may well result in the desirable qualities of backup alarm localization while maintaining some level of noise attenuation. On certain metrics of localization, the circumaural (non-diotic) earmuffs and the foam earplug tested performed similarly (and more poorly than the premolded earplugs; for the foam earplug, this result suggests that its deep-insert ear canal capability with respect to fit (when compared to the E-A-R earplugs, which are designed as ‘universal-fit’ with flanges), notwithstanding the relatively high NRR achieved through proper fit, may have adversely affected localization ability. All of the HPDs tested (with the exception of the diotic earmuff) resulted in the same localization performance as the open ear on the measures of right-left or front-rear localization.

Background noise level had a profound effect on localization performance. When localizing in the higher background noise level of 90 dBA, listeners experienced greater difficulty in localizing the backup alarm signal as a percentage of correct responses when compared to the lower background noise level of 60 dBA. Based on the results, the noise levels evident at road construction sites—which represent a combination of both equipment noise (e.g., milling

machines, rollers) and ambient noise (e.g., traffic passing by in an adjacent lane to the construction activity), can negatively affect the ability of workers to determine from where a backup alarm signal is emanating.

The results yielded statistically-significant, but relatively small magnitude, improvements in several metrics of localization performance for listeners when using the modified backup alarm as compared to the standard backup alarm. There do appear to be distinct localization advantages that can be realized for construction workers through the use of a backup alarm that incorporates the additional frequencies of 400 Hz and 4000 Hz, suggesting that (perhaps) the governing SAE and other Standards with respect to backup alarm frequency content need to be revised.

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3. NOISE AND VIBRATION CONTROL OF HAMMER DRILLS

(Burdisso, Johnson and Nieto) Start Date: 09/15/04 - End Date: 09/31/09

Abstract

Pneumatic percussive power tools are extensively used in the construction industry. They are one of the noisiest pieces of machinery, generating noise levels well above 110 dBA which are beyond the Permissible Exposure Limit (PEL) of 85 dBA set by the Occupational Safety and Health Administration (OSHA). In addition, the vibrations from these hand held power tools lead to hand-arm vibration (HAV) disorders such as pain, numbing, and blanching of the fingers commonly known as white finger. The main objective of this project was, thus, the development of noise and vibration control technologies for pneumatic tools. A chipping hammer was selected as the tool to demonstrate these technologies. However, the technologies can be translated to other tools. The approach taken was to first perform an in-depth vibration, acoustic, and fluid characterization of the tool. This effort provided valuable physical insight that was then used to develop noise and vibration control approaches. From the acoustic characterization, it was determined that the dominant noise source is the high pressure exhaust which was expected. More importantly, the fluid measurements indicated that the exhaust velocity was sonic over a small fraction of the operating cycle of the tool. This suggested that slowing the exhaust velocity and dissipating the energy at the peak exhaust velocities should lead to significant noise reductions. Experiments were performed using a commercially available small silencer that demonstrated a 10 dB overall noise reduction without any noticeable reduction in the tool performance.

A numerical model of the tool was developed that consisted of both the structural and fluid dynamics of the tool. The structural and fluid models were fully coupled and allowed to predict the tool behavior. The vibration and fluid characterizations provided the data to validate the accuracy of the developed model. The model showed good agreement with the experimental data. Using this numerical tool, a preliminary study of potential vibration control approaches was undertaken. The tool vibration is characterized by a sequence of large impulses with a periodicity given by the tool operating frequency, e.g. ~ 27 Hz. High acceleration levels are then present at the fundamental operating frequency and the harmonics within the 500 Hz range, e.g. 20 harmonics. The implication is that an effective vibration control device/method must reduce all these harmonics. In a preliminary investigation, the performance of conventional control methods was evaluated, e.g. isolation of the chisel from the tool, reduction of supply pressure, implementation of dynamic vibration absorbers, and so forth. Though these studies demonstrated some degree of success, they were not capable of reducing all the dominant harmonics. To this end, an impact vibration absorber was considered. This device is very simple and consists of a mass sliding within a cavity that dissipated energy through the collision of the mass with the cavity walls. An experimental investigation was undertaken to design proof-of-concept prototypes. The results demonstrated reduction of 63% percent of the impulses produced by the tool which implies a similar reduction of all the harmonics.

The simple technologies identified in this project have the potential to provide substantial noise and vibration reduction of pneumatic tools with minimal impact to the tool performance. The main recommendation is to test these concepts as integral part of the tool.

Section 1: Noise and Vibration Control of Hammer Drills

Highlights/Significant Findings

The key findings of the project were:

The in-depth tool characterization from the structural, acoustic, and fluid point of views is one of the main accomplishments. This effort provided valuable information critical for the validation of a numerical model and the investigation of noise and vibration control concepts. The structural characterization consisted of vibration measurements under multiple loads and extensive finite element modeling. The acoustic characterization consisted of sound power measurements and state-of-the-art noise source identification using phased arrays. Noise measurements were also performed with the tool in an actual working environment, e.g. breaking concrete blocks. The fluid characterization involved the measurement of the internal chamber dynamic pressures (using Kulite transducers) and mapping of the exhaust velocity fields (using hot wires).

From the previous characterization, the dominant noise sources are the two exhaust high pressure pulses. However, the hot wire measurements revealed that the exhaust velocity is sonic (due to choked flow) at least for a fraction of the time in the tool cycle. Thus, significant noise reduction could be achieved by mixing the two exhaust jets and slowing the flow. This was accomplished by fabricating a device that created a small cavity to mix the two jets and exhausted out through a single port with a porous silencer. The silencers were low cost commercially available off the shelf components. Noise reductions of over 10 dB were demonstrated with no degradation of the tool performance, assessed by monitoring the operating frequency.

The acoustic characterization under simulated operating conditions revealed that significant noise is radiated by the parts being broken by the chipping hammer. In the experiments performed, it was found that only half of the total acoustic energy was from the tool. Thus, noise reduction of the tool will not be sufficient to reduce the exposure to the operator. The development of a mechanical-fluid model of the chipping hammer tool was another accomplishment. This numerical model was validated using the fluid and vibration data from the tool characterization effort. The model was useful to screen a number of potential vibration control options.

The final significant finding was the demonstration of an effective vibration control approach using impact vibration absorbers (IVA). This device is a simple mass sliding inside a cavity. The vibration data clearly indicated that the acceleration spectrum was dominated by strong tones at the fundamental operating frequency (~27Hz) and the harmonics within the 0-500 Hz band. These tones are the results of the impact produced by the tool piton on the chisel and the rest of the tool's body. To reduce the hazard to the operator, it is critical that all of these tones be reduced. The implementation of IVAs for the vibration control of the chipping hammer was undertaken experimentally. A very extensive test matrix to assess the effect of materials, number of IVAs, and designs was investigated. The most important finding was that an array of six IVAs was capable of reducing the amplitude of the impacts by 63% which implies a reduction of the same factor for all the tones in the spectrum. The IVAs are small, inexpensive, and could be easily integrated into the tool design.

Translation of Findings

The research effort undertaken here revealed that relevant noise and vibration reduction of these types of tools can be achieved with practical devices. It is also very likely that a combination of control approaches will need to be implemented. However, reduction of the hazards to the tool operator lies on the implementation of these devices as an integral part of the tool by the manufactures. For a successful translation of the technologies, there must be mechanisms to bring together researchers, manufactures, and government agencies together such that the translation can be effectively accomplished. This effort must be spear headed by the government agencies responsible for the health of the construction workers. It is very unlikely that the industry will implement new control concepts, in particular in the current economical down turn.

Outcomes/Relevance/Impact

Noise measurements were carried out on the chipping hammer to determine the spectral characteristics, overall sound power level, and spatial source strength maps of the tool. To this end, an advanced 63 microphone phased array was used to successfully locate and identify the major sources of noise from this tool, e.g. acoustic pictures. Fluid measurements using hot wire were also performed on the exhaust and Kulite pressure sensors to measure the pressure in the upper and lower tool chambers. The fluid tests found that the velocity of the exhaust is approximately Mach 1.0 or greater. In addition to the laboratory measurements, noise data was also collected in the field under simulated operation conditions. The main conclusion was that the exhaust was the most dominant noise source at low frequency (≤ 1500 Hz) while tool vibration contributed to the mid to high frequency range. Noise control of the exhaust low frequency was targeted since earmuffs are less effective at low frequency. The approach for attenuation of this source was undertaken employing six commercial-off-the-shelf pneumatic silencers. Noise reduction ranged from 5.1 to 10.1 dB in the 0-1500 Hz frequency range. To assess the effect on the tool performance, the operating frequency of the tool was also monitored and found to be unaffected. Further noise reduction technologies were investigated by using particle impact noise absorbers and porous materials integrated into the conventional mufflers used in these tools. The noise reduction measured were again promising with attenuations ranging from 5 to 10 dB below 1250 Hz. Insignificant reductions were observed above 3150 Hz.

Another outcome of this project was the development of an experimental setup to measure the vibration from the chipping hammer. An experimental hand-arm model has been designed to have similar dynamic characteristics to those of a human hand-arm. This experimental setup addressed the issue of repeatability as measurements using human subjects suffers from variability between cases. It was found that the measured acceleration of the hand-arm rig was in the range of measured accelerations of the human subjects but with superior repeatability. This is critical for vibration reduction assessment.

A nonlinear numerical model of the chipping hammer was developed and validated for preliminary vibration control studies. Fundamentally, the numerical model was made up using a fluid flow and structural sub-models. Experiments were carried out to measure the handle response and exhaust jet velocities as well as pressure profiles. The results obtained from the numerical model were then validated using these experimental results. Finally, the model was

used to explore different vibration control techniques, in particular the low frequency vibration of the tool (~ 27 Hz and first few harmonics). The techniques investigated ranged from structural modification of the handle, vibration isolation, and using dynamic vibration absorbers (DVA). These studies showed poor (or at least not sufficient to justify fabrication and testing) performance of these technologies. An exhaustive literature review was then conducted for alternative control approaches. This study revealed that the most promising solution was an array of passive impact vibration absorbers (IVAs). To evaluate the performance of this IVA concept, several prototypes were designed and fabricated. These IVAs were then tested on the chipping hammer using an extensive test matrix (200 test configurations) to evaluate the effect of key IVA parameters, e.g. materials for sleeve and impact mass and IVA gaps. The test results identified bronze and tungsten as the best materials for the sleeve and impact mass, respectively. The vibration data showed that the peak acceleration was reduced by 63% with minimum increase in tool weight ($\leq 4\%$). Finally, modeling of the tool with the IVA was initiated and can be used to investigate the new IVA concept.

Section 2: Noise and Vibration Control of Hammer

SCIENTIFIC REPORT

Background

It is estimated that at least 420,000 US construction workers are potentially exposed to hazardous noise levels above 85 dBA. Rates of hearing loss among US construction workers easily exceed 20% for most construction activities. They are known to develop occupational hearing loss early in their careers, becoming substantially impaired by middle age. Noise has been regulated in U.S. industry under OSHA since the late 1960s. Initially the requirements were based on making the workplace safer by noise control of the sources. Concerns about the cost of effectively controlling hazardous noise and the lack of a process to measure the human effects of noise exposure resulted in a major revision to the rules with the adoption of the 1983 Hearing Conservation Amendment. The focus shifted from noise control and reduction to hearing conservation, i.e. implementation of hearing tests, training, and hearing protection. Abandoning the goal of quieting workplaces in favor of mandatory testing and ear protection has had a detrimental outcome. However, recent research has shown hearing protection devices usage rates in construction workers in the 9-49% range illustrating the difficulty of implementing effective hearing loss protection programs. Thus, a better strategy for reducing noise exposure is to eliminate or reduce noise source strength through the use of engineering noise control methods.

Recent investigations have provided a useful picture of the biggest sources of noise exposure as listed in Table 1.1. It is clear that pneumatic percussion drills are one of the main noise sources. The operation of pneumatic drills produces noise levels in the range of 110 to 120 dBA at the operator. These levels of noise are well beyond the Permissible Exposure Limit (PEL) of 85 dBA set by National Institute for Occupational Safety and Health (NIOSH) or the 90 dBA of the Occupational Safety and Health Administration (OSHA). These power tools are extensively used in construction, industrial, and mining sites. These compressed air operated tools are broadly classified according to their operation. Examples of these tools are chipping hammers, concrete breakers, rock drill, jackhammer, utility drills and many others. For the sake of illustration, Figure 1.1 shows some of these tools.

Table 1.1: Typical noise levels of construction equipment

Tool Name	Tool Drive Type	Minutes	Median dBA	SD dBA	Range dBA
Air compressor	pneumatic	255	96	11.2	70–114
Backhoe	gasoline	1908	86	6.0	70–108
Bulldozer	gasoline	494	89	8.2	70–104
Chipping gun	pneumatic	1151	93	13.1	70–120
Chopsaw	electric	631	80	8.6	70–106
Crane	electric	3059	78	7.7	70–110
Forklift	gasoline	3727	85	5.8	62–125
Hand hammer	mechanical	4443	85	8.0	56–110
Jackhammer	pneumatic	267	104	11.4	70–112
Lejeune gun	pneumatic	390	89	8.4	70–120
Truck	gasoline	970	78	8.0	70–123
Welding torch	other	1923	84	8.9	70–118

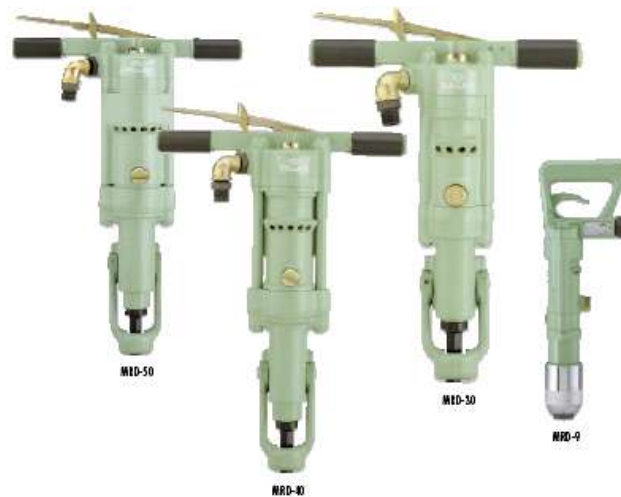


Figure 1.1: Typical pneumatic percussion drills.

The main noise source in pneumatic percussion is due to the discharge of high pressure air from the exhaust port. Mistakenly the exhaust noise is considered as a single source while in fact there are two components. One component is a series of discharge pulses at around 2000 cycles per minute that leads to a series of high intensity noise detonations. This noise component is physically located at the exhaust exit. The second component is the fast flow exit velocity acting like a subsonic jet. The noise in this case is produced by the turbulent mixing of the jet and the surrounding stationary flow and is located downstream of the exhaust exit port. In addition to the exhaust noise, there may be mechanical noise from the percussive tool components. One such noise source is the drill steel noise caused by the vibration generated by the impact between the drill piston and drill steel. The drill bit impacting against the rock or concrete is also a noise source. The rattling of the drill steel in the chuck or other components rattling within the drill are obvious noise generation mechanisms.

Hand held percussive tools are difficult to quiet due to several factors. The worker's ear is very close, e.g. within arm's length, to the noise source. Isolating the noise source is impractical with most portable hand tools because a sound proof enclosure restricts access to the tool. Muffling of the exhaust has been the preferred approach for noise attenuation. Most mufflers are made of rigid polyurethane (i.e. plastic) due to its ability to withstand the rough usage of a construction site. The muffler can also be an integral part of the machine.

The issue of human comfort when faced with machine interaction has acquired a lot of interest in the recent past. Particularly in a severe work environment like construction, human comfort is directly related to operator's health, work efficiency and work quality. Hand transmitted vibration (HTV) is one of the most common hazards faced by workers in the construction industry. A major source of HTV is the pneumatically driven impact hammers that leads to hand-arm vibration (HAV) disorders such as pain, numbing, and blanching of the fingers commonly known as white finger. A number of approaches have been developed over the years to reduce vibration typically anti-vibration gloves and handles.

Though noise and vibration control techniques have been developed, they are not sufficiently effective. Developing technology to mitigate these health hazards is still of paramount importance. This project focused on the development of practical control devices.

Project Specific Aims

Thus, there is still a paramount need to improve these machines. Therefore, the long term goal of this project is to improve the noise and vibration characteristics of pneumatic percussion tools. Thus, the specific aims of this project were:

1. To identify, characterize, and rank the dominant noise sources. For effective noise control approaches, properly identifying the noise sources is critical. The source identification process was accomplished using conventional noise measurements as well as state-of-the-art acoustic imaging methods using microphone phased array. This data was considered crucial in the design of noise control devices. It also served as the baseline case to evaluate control methods.

2. To develop and experimentally demonstrate noise control technologies. The goal was to use the noise characterization of the tool to develop effective noise control devices using lightweight, stiff, effective sound absorptive materials.

3. To characterize the vibration characteristics of a typical pneumatic tool. Though the vibration characteristics of percussive tools is well known, it is important to establish an experimental, repeatable baseline vibration spectrum to evaluate the performance of the control methods developed in this project.

4. To develop and experimentally demonstrate vibration control technologies: The goal was to develop advanced dynamic vibration absorbers to control the critical low frequency vibration components responsible for HAV disorders. To this end, advanced absorber configurations and materials were used to improve the vibration attenuation. We intend to design and develop advanced vibration absorbers by using:

Project Procedure

As described in the introduction, there are many types of pneumatic impact power tools. It was decided early in the project, to demonstrate noise and vibration control on one particular pneumatic tool to prove the viability of the methods. The pneumatic tool used in this work was the Atlas Copco TEX-317 pneumatic chipping hammer shown in Figure 2.1. The reason for choosing this tool was its relative small size and ease of use in the laboratory setting. The specifications of the hammer are net weight of 6.4 kg, length 387 mm, stroke 102 mm, air consumption 31.5 cfm, and a supply pressure ~ 90 psi.

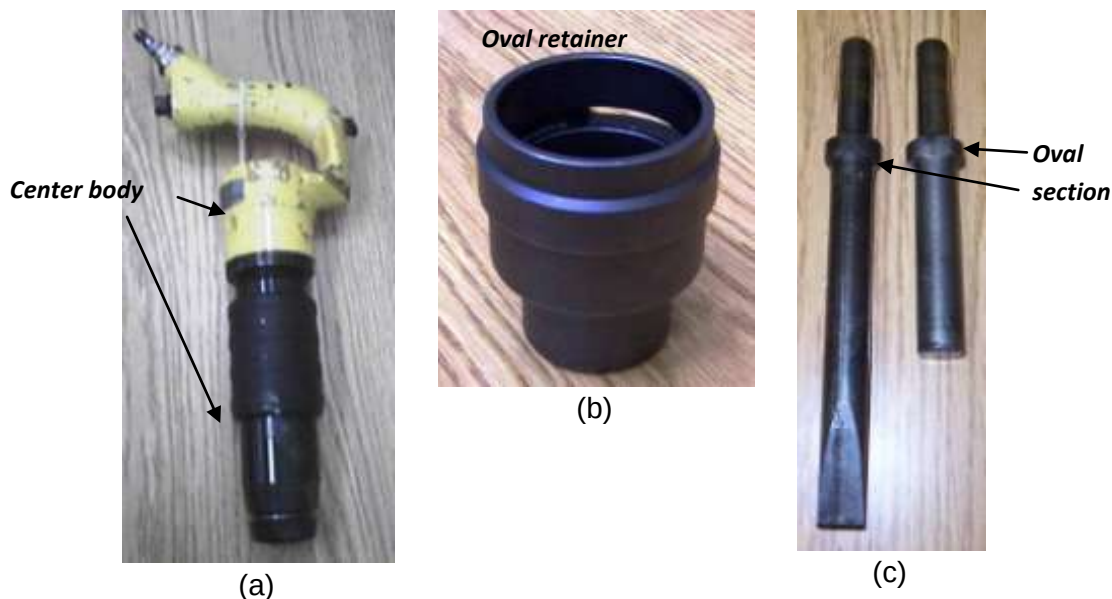


Figure 2.1: Chipping hammer used for the measurements: a) center body of the tool with the exhaust deflector attached b) the oval retainer and c) the long and short chisels.

Pneumatic tools by definition operate via the constant supply of compressed air. A pneumatic hammer has the capability to deliver a large number of impulses in rapid succession to a surface intended for demolition. The mechanism which delivers the impact is a piston contained in the center chamber of the tool. The piston strikes the top end of the impact tool (chisels) inserted into the end of the hammer. The piston doesn't strike the upper part of the tool. Various kinds of chisels can be inserted so that the tool can be used as more than merely a hammer; it can be used as a pick, concrete breaker, a digging tool, and so forth.

The tool consists of three major physical components: the center body, chisel, and oval retainer. The chisel is the generic component that is used to transfer the force from the internal piston to the surface intended to be struck. The tip of the chisel often is shaped in a way that allows for maximum breaking potential and penetration. For this project, two variations of the chisel were used. The first variation, referred to as the short chisel, does not have an angled tip and the chisel is 16.3 cm in length. The second variation, referred to as the long chisel, has an angled tip and a length of 28.8 cm. The oval retainer is the component of the tool which holds the chisel in place, e.g. keeps the chisel from being launched away from the tool when the tool is operating. The center body is the main component of the tool.

The center body contains the main working parts of the tool such as the piston, inlet valve, and diaphragm valve. Figure 2.1a shows a closer view of the center body. The center body itself is the shell which holds all these components. The center body is a hardened steel shell where the inside of the shell is the cylinder in which the piston operates. The center body shell also contains some major operating components of the tool. The center body has exhaust ports which allow the pressure in the upper and lower chambers to exhaust at the appropriate times during the operating cycle. For this chipping hammer, there are two levels of exhaust ports: upper and lower level exhausts. There are six exhaust ports per level making a total of twelve exhaust ports. The center body is covered by an exhaust deflector made of rubber as shown in Figure 2.2. This deflector has one hole per level. It was observed that the space between the exhaust deflector and the tool is filled with air during operation. The air that is in this area is not only exhausted out of the two holes in the deflector but also exhausted from the top and bottom of the exhaust deflector. It was also observed that the deflector rotates during operation so that the deflector can either cover all of the twelve exhaust ports or allow two of the ports to be open to atmosphere. The unpredictability of the deflector position caused concerns regarding repeatability of noise measurements. Therefore, the deflector was fixed so that two of the ports would be exposed at all times during measurements. Otherwise the exhaust deflector was removed from the center body of the tool. A detailed description of the operation of the tool is described in the Appendix.

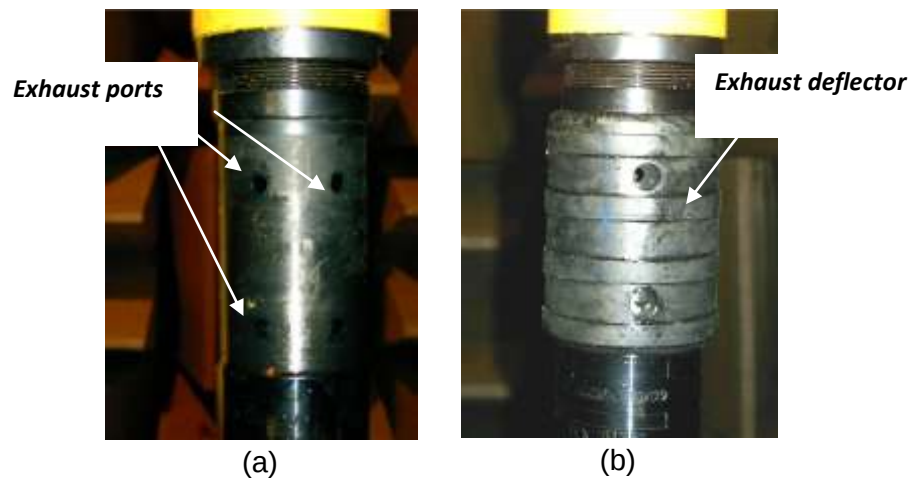


Figure 2.2: Center body of the tool a) without and b) with the exhaust deflector.

Effective noise and vibration control techniques are obtained when the source mechanisms are uncovered and understood. They must be quantified to then assess the effectiveness of the control devices. To this end, the experiments must be performed in a controllable and repeatable form. Based on these premises, the approach taken in this project to reduce the noise and vibration of the chipping hammer was to divide the research in phases. Each phase was intended to accomplish specific objectives and support the work on subsequent ones. These phases are briefly described here:

Phase I: Development of Hand-arm Test Rig: In this phase, a test rig was developed to mimic the dynamics of the tool operator, e.g. dynamics of the hand-arm. This rig was primarily intended to perform accurate and repeatable vibration measurements.

Phase II: Acoustics Characterization: In this effort, the acoustics of the chipping hammer was experimentally characterized. This involved determining the noise levels of the unloaded and loaded tool and the identification of the dominant noise sources and associated physical mechanisms.

Phase III: Vibrations Characterization: Analogous to the acoustic characterization, vibration measurements of the tool in the loaded condition with multiple preloads were performed. In addition to these experiments, extensive numerical model of the various tool components using the Finite Element method were also performed. The models were validated experimentally using modal hammer test data.

Phase IV: Fluid Characterization: The fluid characterization consisted of flow measurements of the loaded tool. The data recorded consisted of hot-wire measurements to map the exhaust flow field and the total internal pressure in the tool. This data was used to validate a structural/fluid numerical model of the tool developed in Phase V.

Phase V: Numerical Model of Tool: A numerical model of the tool was developed that included the dynamics of the mechanical component (structural model) and the internal pressure/exhaust flow (fluid model) that drives the tool. These models are fully coupled and was validated using the vibration and fluid characterizations described previously. The model was used for preliminary vibration control studies.

Phase VI: Noise Control of the Discharge Pulse: The information from the acoustic and fluid characterizations provided insight into the dominant noise source, e.g. the exhaust. As expected, it was found to be the dominant source. More importantly, the hot wire measurements showed that the jet was sonic (flow velocity equal to sound speed) at least for a small fraction of time in the tool cycle. Thus, the main approach for noise control was to slow the exhaust by creating a settling cavity and using commercially available silencers to diffuse the jet. The degradation of the tool performance due to these devices was also determined.

Phase VI: Vibration Control: In this phase, vibration control devices were investigated. The initial step was to use the numerical model to assess the feasibility of various control concepts. The most promising approach was the use of impact vibration absorbers since they provided reduction of all frequency components of the vibration.

Phase VII: Modeling of Impact Vibration Absorber: This last phase was undertaken to develop a model of the impact vibration absorber that can be incorporated to the tool models. This model of the IVA is unique in the sense that provides a method to model the impact under any type of input unlike what is found in the literature that is valid for harmonic inputs only. This model can be used in the future to optimize the IVAs for each application.

Overview of Main Results

In this section, the most important results from the research phases described in section 2.3 are presented.

Phase I: Development of Hand-arm Test Rig

A human hand is very complex biological system consisting of number of different elements. The layers of skin, nervous system, muscles and bones are found to be the most susceptible parts to the HTV. In the past, a large amount of research has been carried out by many investigators to measure the acceleration levels of the pneumatic impact hammers. They also took a number of human subjects' tests. However the problem with the human test is the repeatability of the results given the nonlinear nature of the human hand-arm system. The response of the tool depends on various factors such as grip force, push force, position of the hand-arm etc. while the operator is holding the tool. The standard ISO 8662-2 defines the procedure for the human tests. As per the standards, the tests should include three skilled operators. Each operator should perform five test runs on the energy absorber. Each test should be carried not less than 8 seconds. It is clear that the whole procedure to carry out the human test is cumbersome and takes lot of time. Moreover, it was found from previous research that the vibration responses of the impact hammers do vary with the operators.

The principal objective of this part of the work was to address these issues. Therefore it was decided to develop, build, and test an experimental rig which could simulate the average dynamics of the hand-arm system while operating the hammer drill. The rig could be used to carry out the vibration tests and measure the vibration levels generated by the tools. Also, the rig should respond in the same way for the different preload conditions as that of the human subjects. However, the rig performance needs to be dependable in terms of the repeatability of the results. Consequently, a mechanical rig was designed and built. The impact hammer tool was mounted on the rig and extensive vibration tests were carried out to validate the performance of the rig. The rig was tested for different preload conditions. Similar tests were carried out on three human subjects. The response of the tool for the rig was compared to that for human subjects for validation purposes.

The experimentally simulated hand-arm rig along with the tool mount and accelerometer mounting position are shown in Figure 2.3a, b and c, respectively. The experimental rig was designed to simulate the hand arm dynamics as discussed previously. The experimental simulated hand-arm rig consisted of a hollow and rectangular cross-sectional aluminum beam. The hollow portion of the beam was filled with lead balls to add mass and damping to the system without adding stiffness. Viscous glue was added to the balls to keep them well coupled with the fiber glass beam. In addition, the balls added damping to model since the hand-arm system is heavily damped. The beam was mounted using pivot joints between two vertical extruded aluminum beams (effectively a simply-supported configuration). A simple U-shaped clamp was used to mount the tool to the experimental rig as can be seen from Figure 2.3b. A rubber grip was placed between the tool and the U-shaped clamp to simulate the interface between the tool and the palm. An adjustment slot in the pivots allows a variable preload to be applied. An accelerometer was mounted on the tool in order to measure the vibration in the direction of the axis of drilling operation another accelerometer was mounted on the horizontal beam to measure the beam response. An energy dissipater, into which the tool is driven, was

manufactured as described in the ISO 8662-2 standard. The dissipater was filled with rubber and steel balls. Both the dissipater and the vertical beam were mounted firmly on the floating floor in the lab.

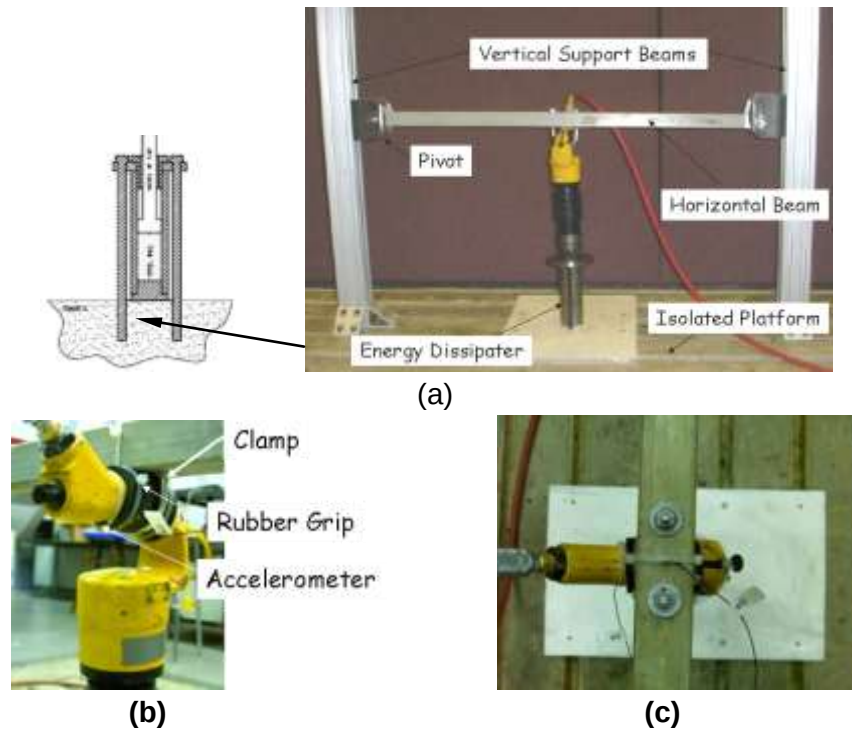


Figure 2.3: Experimental rig a) front view, b) tool mount, and c) top view.

Various experiments have been carried out using human subjects and the experimental rig in order to validate the experimental approach. They are: tool in free-free condition, human subjects with preload, and experimental rig with preload. A summary description of the experimental tests and results are presented.

The testing of the tool in free-free condition was performed to know the absolute vibration levels generated by the impact hammer while in operation. With the tool suspended from the top by means of a rope the compressed air of 90 psi was allowed to drive the impact hammer in a free-free (unloaded) condition. The accelerometer was mounted at the handle of the tool in the Z-direction. Three tests were carried out with three different chisels in order to understand the effect of the chisels on the response of the tool. Two of the chisels were provided by the tool manufacturer with the tool whereas the third chisel was manufactured as per ISO 8662-2. The response of the tool for the ISO 8662-2 chisel was the same as that for the other two chisels. As a result the ISO-8662-2 chisel could be used for the further tests. Figure 2.4a shows the auto-spectrum for the hammer at the free-free (unloaded) condition. The acceleration spectrum is dominated by densely packed peaks consisting of the harmonics of the blow frequency of the tool with a background broadband acceleration. The figure reveals extremely high acceleration levels in the low frequency range from 0-800 Hz. Also the handle

resonance occurs at 520 Hz and this underlying resonance can also be seen in the figure. The narrowband auto-spectrum was converted to 1/3-octave band auto-spectrum as shown in Figure 2.4b.

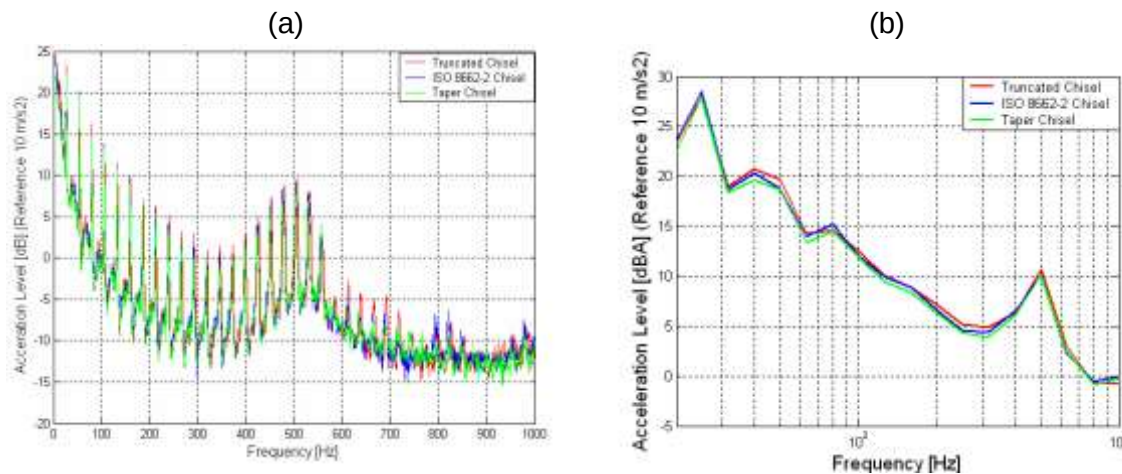


Figure 2.4: a) Narrowband and b) 1/3 Octave band acceleration auto-spectrum of the tool handle for free-free boundary conditions.

The vibration measurements were also performed with three different human subjects (VAL graduate students) as shown in Figure 2.5. These tests were carried out in order to understand the basic nature of the vibration levels when a human is operating the hammer and later to validate the experimental rig performance. The subjects were asked to hold the hammer while applying specified preloads. The digital weighing scale was used for maintaining a constant preload on the hammer throughout the test. Tests were run for almost one minute continuously. These tests were repeated three times to check the repeatability of the human subjects. Each of the test sets was carried out on three consecutive days. Figure 2.6 shows the typical auto-spectrum of the acceleration of the tool-handle during the three human tests for the 200N preload case.



Figure 2.5: Human vibration tests.

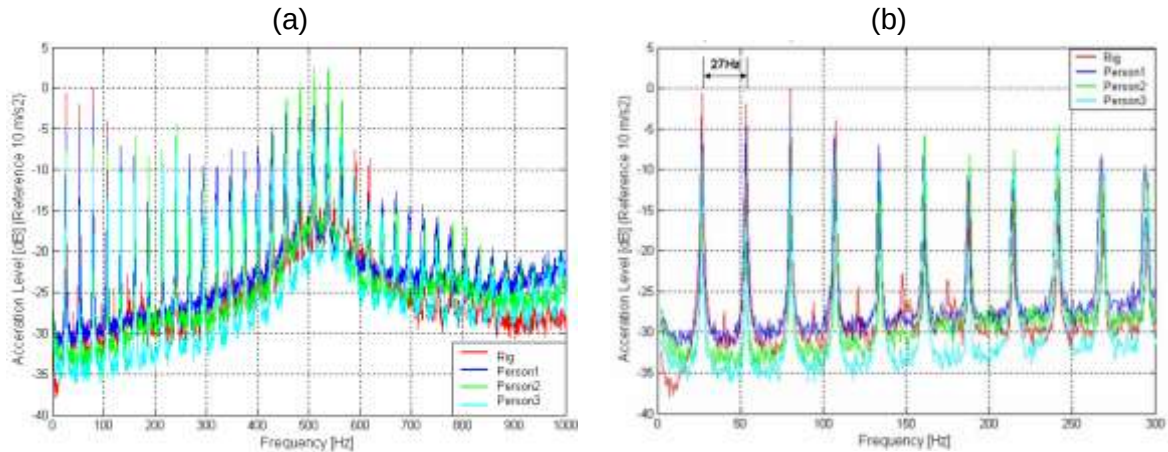


Figure 2.6: a) Narrowband acceleration auto-spectrum of the tool-handle for rig and human subjects and b) zoom in 0-300 Hz.

The tool was also tested with the experimental rig to simulate the hand-arm system, e.g. replaces the operator. The response using the experimental rig is also plotted in Figure 2.6. It can be observed that matches very well with that of the human subjects for the case shown.

Comparison between the Free-Free and Loaded Test: Figure 2.7 demonstrates the comparison between the free-free and loaded test for the human subjects. There is a drastic drop in the vibration levels in the lower frequency range 0-300 Hz. This may be due to a combination of two factors. Application of the feed force by the subjects in the Z-direction introduces mechanical impedance which tends to suppress the vibration levels. Secondly, there is large energy absorption in the low frequency range area. The vibration levels drop approximately 20dB. Interestingly, there has been comparatively less energy absorption in the high frequency range 300-1000 Hz. The vibration levels drop about 5 dB. This is also in line with the previously published research in this area according to which the maximum damage to hands happens in the low frequency.

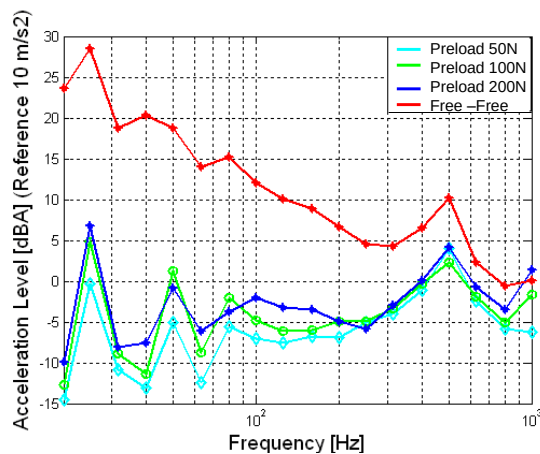


Figure 2.7: Comparison of 1/3 Octave band acceleration auto-spectrum of tool handle for free-free boundary conditions versus human tests

Validation of the Experimental Rig: The narrowband auto-spectrum of the tool was converted into 1/3-octave band auto-spectrum as shown in Figure 2.8. The data shows that there is some variation between the responses of tool for different people for the same preload and the tool response for the experimental rig lies very close to the range of tool response for the human subjects. There is a high frequency peak in the 500 Hz band and this corresponds to the resonance of the tool handle measured at 520Hz. The result shows three distinctive peaks appear in the 0- 200Hz frequency range. The first peak at 25 Hz corresponds to the impact frequency (~27 Hz) of the tool and the first and second harmonic of the blow frequency appears subsequently. The comparison is 2-3 higher at low frequencies and around 5 dB lower at high frequency.

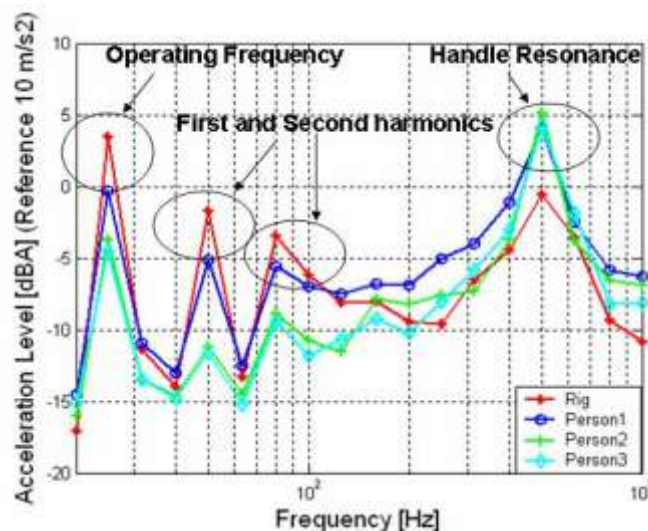


Figure 2.8: Comparison of 1/3 octave band acceleration auto-spectrum of the tool-handle for human subject versus rig at 200N.

Repeatability of the Experimentally Simulated Hand-Arm Rig and Human Test: Repeatability is a measure of reliability of the results and is very important aspect in the experimental tests. In order to investigate repeatability, two different tests were conducted for both the experimentally simulated hand-arm rig and three human subjects for each preload on different days. As an example, Figure 2.9a shows the measured accelerations of the tool for the simulated rig for the two different tests at 50N preload. The tool response for the simulated rig is comparatively consistent, particularly in the low frequency region from the 0 to 300 Hz. After 300 Hz, the response of the simulated rig becomes slightly uncertain. The maximum variation in the vibration level is 3 dB. Figures 2.9b, c, and d also show the test results for the three 50N preload cases for three human subjects. While the repeatability for persons 1 and 2 appears to be good for different tests, the repeatability for the person 3 for the different tests seems poor. There are many factors which could contribute to this variation such as changes in the grip/push force and hand-arm position etc. Overall, it appears that there is some degree of variation in the tool response for human tests results as well as the tool response for the simulated rig results.

Based on these results, it was determined that the experimental rig mimics very well the effect of operator on the vibration of the tool. In addition, it provides a system with good repeatability. This experimental rig was used in the rest of the research effort.

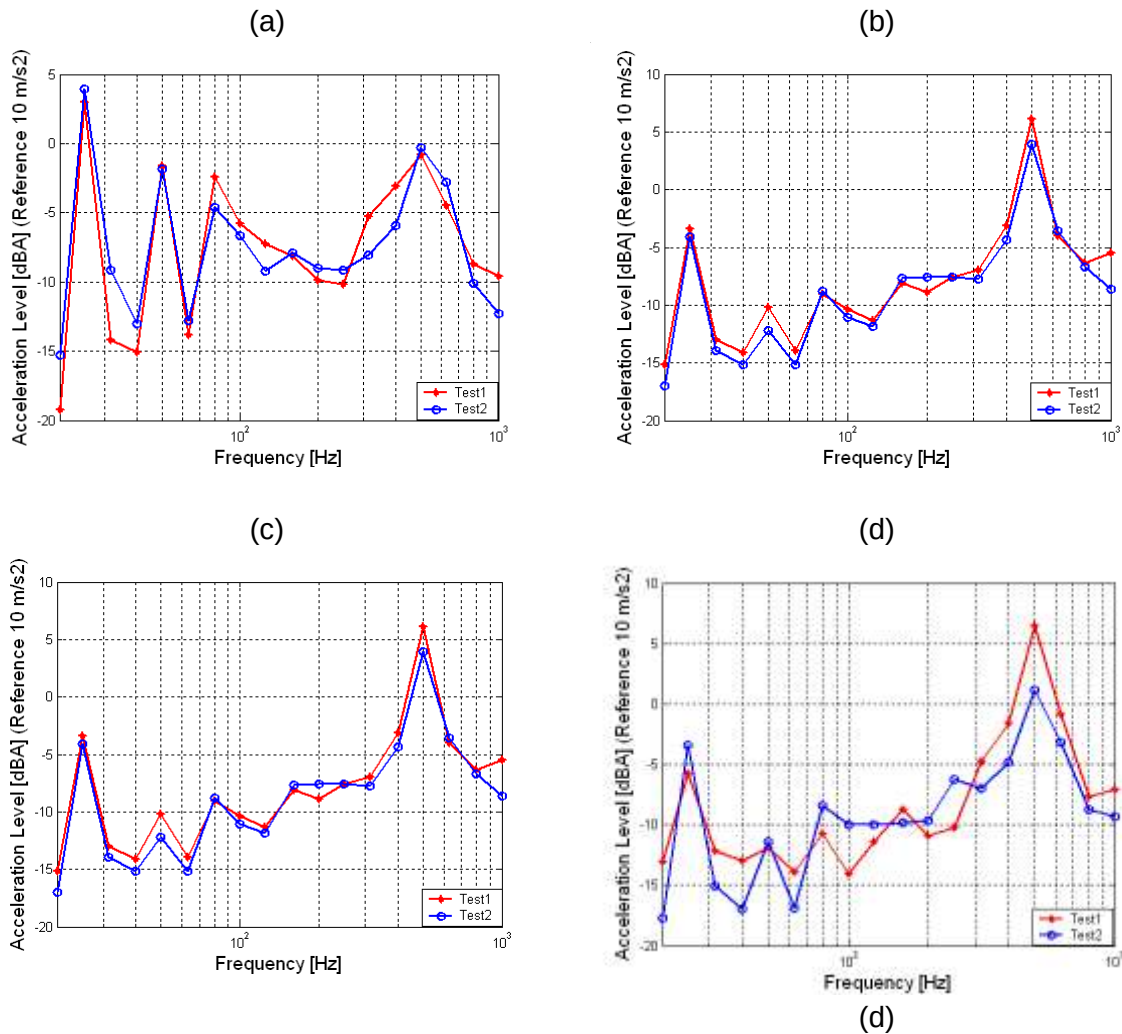


Figure 2.9 : Repeatability of acceleration auto-spectrum results for two different tests a) experimental rig tests, b) person 1 tests, c) person 2 tests and d) person 3 tests (for two different days) at preload 50N.

Phase II: Acoustics Characterization

Full acoustic characterization involved measuring the sound power spectrum of the tool, the directivity of the tool, and identifying individual sources of noise.

Sound Power Measurements of Unloaded Tool:

Depending on the operator and the particular task, it is likely that the tool will be used in an unloaded condition for some amount of time. This makes the unloaded configuration an important test case to characterize, e.g. determine the sound power of the tool. To measure the

sound power of the pneumatic tool, sound pressure levels over a spherical surface centered at the tool were measured. The experimental setup is shown in Figure 2.10. The noise measurements were carried out in a fully anechoic chamber with a cut-off frequency of 100 Hz. The chipping hammer was hung from the anechoic chamber's ceiling using a rope while a conventional array of sixteen far-field microphones was used to determine the radiated sound power and radiation directivity as a function of frequency. The setup used for this test consisted of an aluminum ring with a radius of 1.08m (3.5ft) that was covered with acoustic foam to minimize reflections. The ring was attached to two supports such that the tool was positioned at the center of the ring. Moreover, the supports were designed such as to allow the ring to be rotated to any position. The microphones were evenly mounted along half the ring from one support to the other, i.e. on a semi-circumference. By making multiple measurements with the ring/microphones rotated to different positions, the sound field on a spherical surface centered on the tool was obtained.

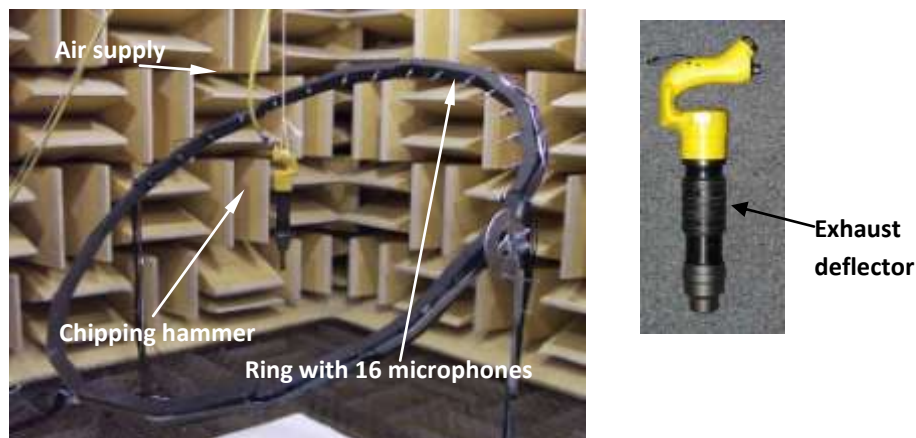


Figure 2.10: The experimental setup for the unloaded sound power level measurements.

For the sound power measurements of the unloaded tool, there were multiple configurations measured. For the first configuration, the tool was operated at 90 psi with the short chisel and no exhaust deflector. The A-weighted sound power spectrum was computed and is shown in Figure 2.11. The spectrum shows two distinct characteristics. At frequencies below 1500 Hz, the noise spectrum is characterized by a series of tones with a fundamental frequency of 27.5 Hz. This noise source is clearly due to the exhaust pulsation associated to the operation of the tool. For ease of visualization, the low frequency portion of the spectrum is enlarged and shown in Figure 2.12 where the fundamental frequency and harmonics are easily identified. The high frequency part of the noise spectrum above 1500 Hz shows the presence of many resonance peaks 5-10 dB above the broadband component. The peaks are associated with the mechanical resonances of several of the tool's components indicated in the spectrum. The repeatability in the measurements was ± 1 dB with the exhaust deflector removed.

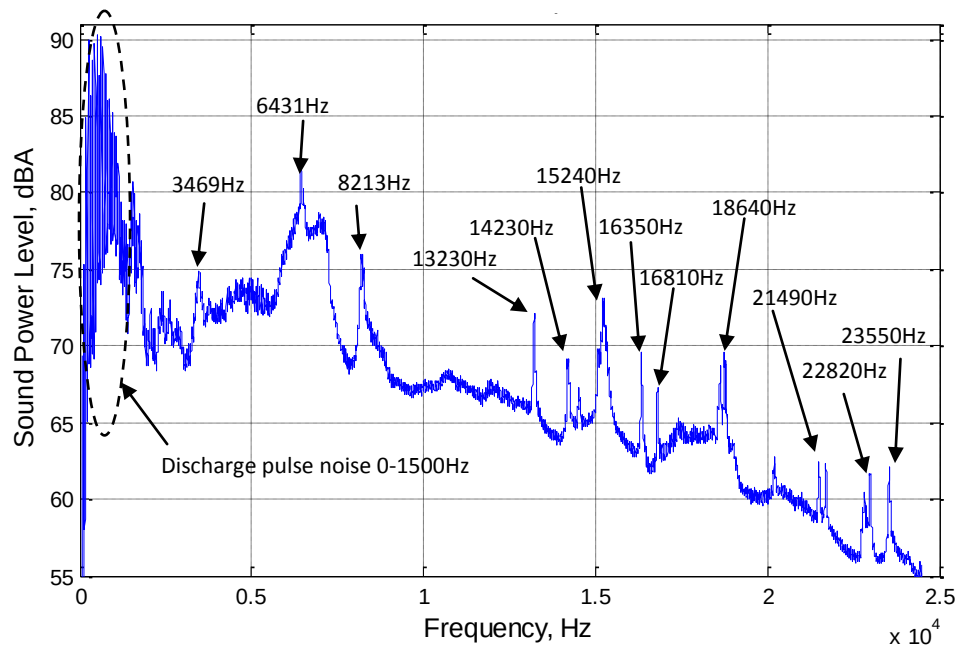


Figure 2.11: Sound power spectrum of the chipping hammer in free condition working at 90psi.

The Overall Sound Power Level is 111.0-dBA (spectral resolution 3.125 Hz).

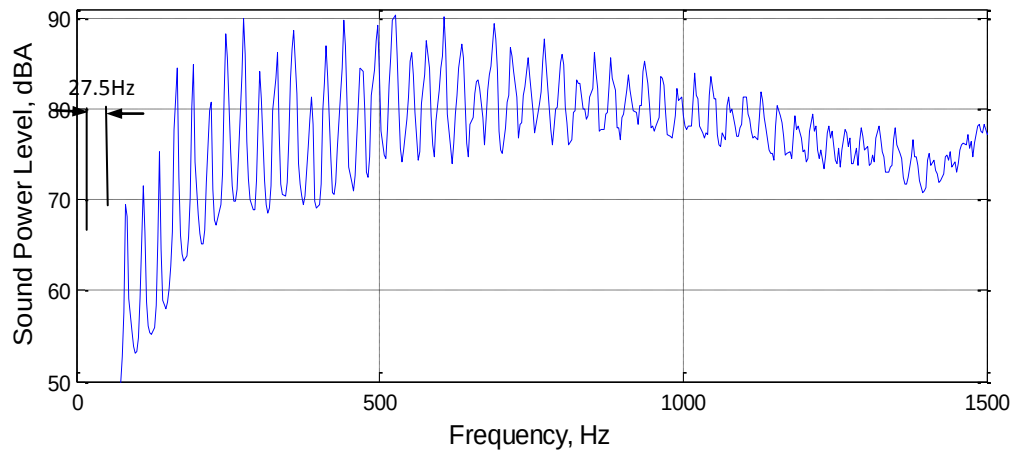


Figure 2.12: Sound power spectrum of the chipping hammer in free condition working at 90 psi in the range of 0-1500Hz. The Overall Sound Power Level is 107.0 dBA.

For the measurements of the second configuration, the tool was operated at 90psi with the short chisel and exhaust deflector. The only difference between the first configuration and the second configuration is the addition of the exhaust deflector. The total sound power level for the second configuration is 109.2 dBA that it is only slightly lower than the 111.0 dBA of the first configuration. To better show the effect of the exhaust deflector, Figure 2.13 shows the two spectrums plotted on the same graph. From the plot, it can be shown that the low frequency and high frequency broadband components of the noise are affected. The low frequency of the second configuration is somewhat lower than the first configuration e.g. reducing the peaks by

approximately 2-3 dBA. The main conclusion is that the exhaust deflector reduces the sound power only marginally, e.g. 1.8 dB and thus it is not an effective control device.

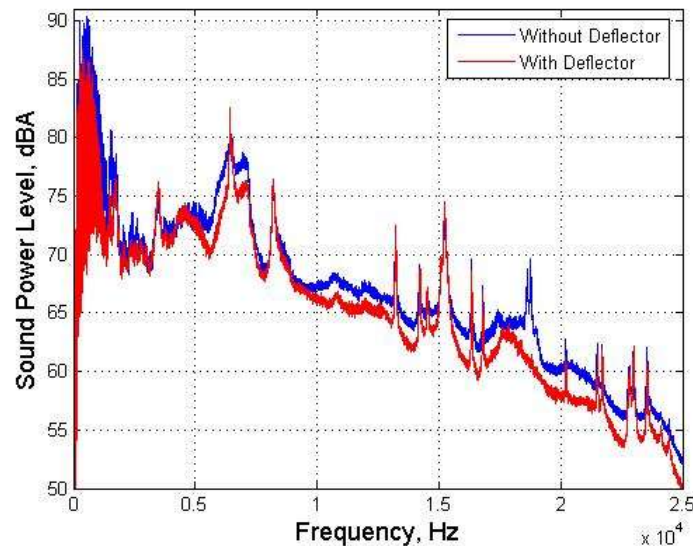


Figure 2.13: Sound power spectra of the tool operating with and without the exhaust deflector.

The third configuration consisted of the tool operating at 90 psi supply pressure with the exhaust deflector and the long chisel. The only difference between the second and third configuration setup is the change in chisel type. Figure 2.14 compares these two configurations. The overall sound power level was found to be nearly the same at 109.2 and 109.3 dBA. Therefore, the chisel has no specific contribution to the overall sound power level of the tool. However, investigation into the narrow band power spectra of both the second and third configuration shows that variation of the chisel causes resonance peaks to shift in the spectrum. For example, the long chisel produces a resonance peak at 12640 Hz and the short chisel produces a peak at 15230 Hz. The cause of these peaks is explained by the existence of a resonance of the short chisel at 15227 Hz found through the mechanical analysis of the tool. Other resonances remain unaffected by the chisel such as the peaks at 6425 and 14220 Hz because they are associated to other components of the tool.

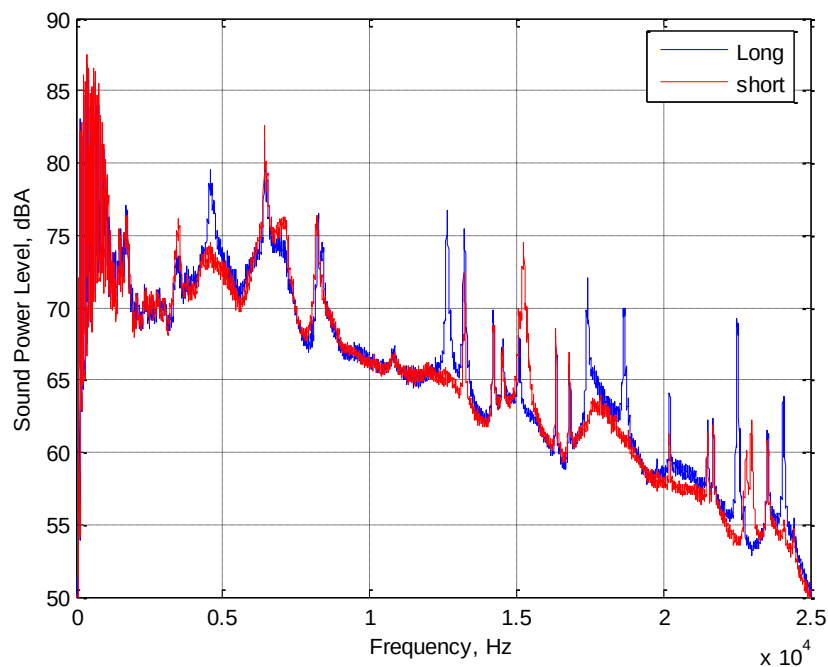


Figure 2.14: Comparison of the power spectrums of the chipping hammer with the long and short chisel.

Since it is important to establish the effect of the supply pressure on the radiated noise, the noise results for the tool operated at 80 psi is described and compared to the configuration where the tool is operated at 90 psi. Figure 2.15 shows the two spectra of the tool operating at 90 and 80 psi. This comparison yielded interesting results. The high frequency broadband noise components were reduced by approximately 2 dB. On the other hand, the amplitude of most the resonance peaks in the high frequency region seems to remain unaffected or only slightly reduced, e.g. resonance peak at 14230 Hz was reduced by 2 dB. The low frequency region of the spectra does not exhibit any abnormalities and is not shown here. The overall sound power level was reduced by the smaller supply pressure, e.g. overall sound power reduced from 109.2 dBA (for 90 psi) to 108.0 dBA (for 80 psi). The sound power level in the low frequency region changes by only 1.0 dBA because of the supply pressure and the high frequency region is slightly affected with a reduction of 1.2 dB when the supply pressure is dropped by 10 psi. It is also noted that the operating frequency of the chipping hammer is also affected by the supply pressure. The tool operates at 27.5 Hz (1650 RPM) for 90 psi and is reduced to approximately 25 Hz (1500 RPM) when the supply pressure is 80 psi. However, it is speculated that the reduction in supply pressure leads to a reduction in chipping capabilities/efficiency of the tool. Therefore, the small attenuation in noise by reducing the supply pressure is not a viable noise control approach.

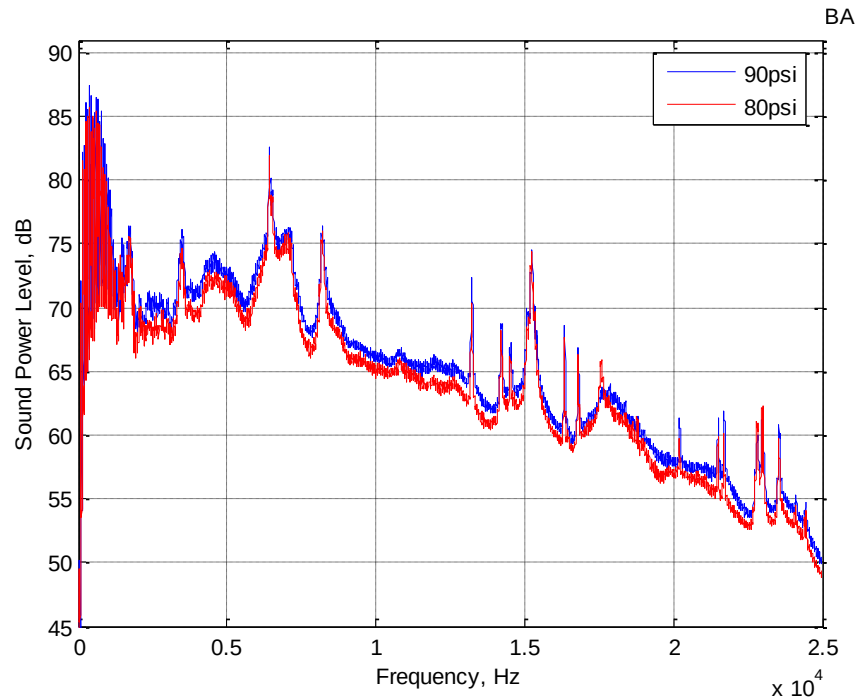


Figure 2.15: Comparison of the chipping hammer operated with the short chisel at 90 and 80 psi.

The far-field measurements were also used to find the directivity of the chipping hammer. Inspection of the directivity results revealed to be basically uniform for the total sound pressure level. Since the user is so close to the chipping hammer and because the chipping hammer's normal operating conditions involve close proximity to reflective surfaces, it was determined that the directivity of the chipping hammer is not an important metric worthy of evaluating.

Sound Power Measurements of Loaded tool

Since the tool will be operated in a loaded condition, it is important to gain some insight into the radiated noise under this condition. However, it must be noted that the loaded configuration is significantly more difficult to define and setup since it depends on the operator and how it uses the tool, the type of task performed, and so forth. This section will discuss the measurements performed to determine the sound power of the chipping hammer in the loaded configuration.

A picture of the experimental setup is shown in Figure 2.16. The experimental setup for this measurement consisted of eight microphones placed on the circumference of an eight foot diameter circle that encompassed the tool which was operating in the center. The microphones signals were recorded using a Sony PC208a DAT recorder at a sampling frequency of 12000 Hz. The area in which the measurements were performed was in a field near the Virginia Tech campus. For the tool to be loaded, an impact surface was prepared. For these experiments, the impact surface was a three foot square block of concrete which was approximately two inches thick. This concrete block was assumed to be representative of a typical impact surface found in the construction industry. After every loaded test, the broken concrete block was

removed from the testing area and a new concrete block was replaced in the original location. For the unloaded test, the tool was merely held a few inches from the surface so that all reflections from the concrete block or the grass remained constant between configurations.

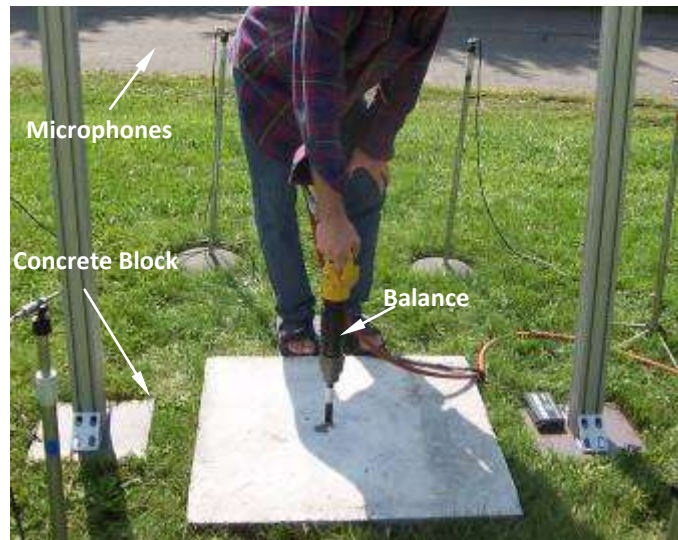


Figure 2.16: Experimental setup for loaded tests is shown. Subject is applying 100N force through the chipping hammer into the 3'x3' concrete block. The radiated acoustics is measured by 8 surrounding microphones.

Both loaded and unloaded tests were performed for direct comparison. For the unloaded case, the tool was held by a human operator two inches from the surface of the concrete block. For the loaded case, the chipping hammer was forced into the concrete block with 100N of average force. The applied force was measured with a scale under the operator's feet. The operator would weigh himself before contact with the surface and then weigh himself during the measurement.

The time signals from eight microphones were recorded and a sample of one of the microphone signals is shown in Figure 2.17. In the microphone signals, there are two clear sections that correspond to the level of impact. These two sections represent the initial stage where the chisel makes contact with the surface and the second stage where the block has begun to break apart or disintegrate. The two sections are highlighted and are labeled in the figure as "impact" and "disintegrate". The best estimate of the sound created from the chipping hammer in its loaded condition is the initial "impact" region highlighted in Figure 2.17.

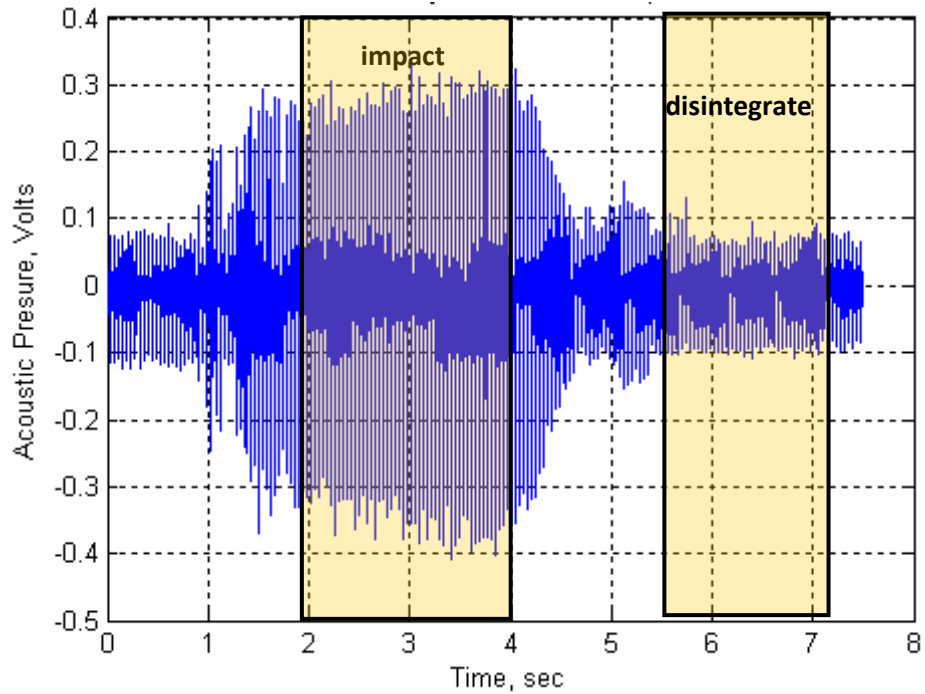


Figure 2.17: Time history of one field microphone for a loaded case.

The average sound pressure level for the loaded case in the “impact” region and the sound pressure level for the unloaded case have been calculated and the comparison plot shown in Figure 2.18. The overall sound pressure level of the loaded case is 12 dBA higher than the unloaded case. It was determined that most of the noise in the loaded condition, when the tool first impacts and breaks the concrete block, was most likely produced by the concrete block. This result implies that the operator noise exposure will be highly dependent on the actual surface intended to be broken, thus making acoustic characterization very difficult to quantify reliably. It also suggests that noise control of the tool might not be that beneficial.

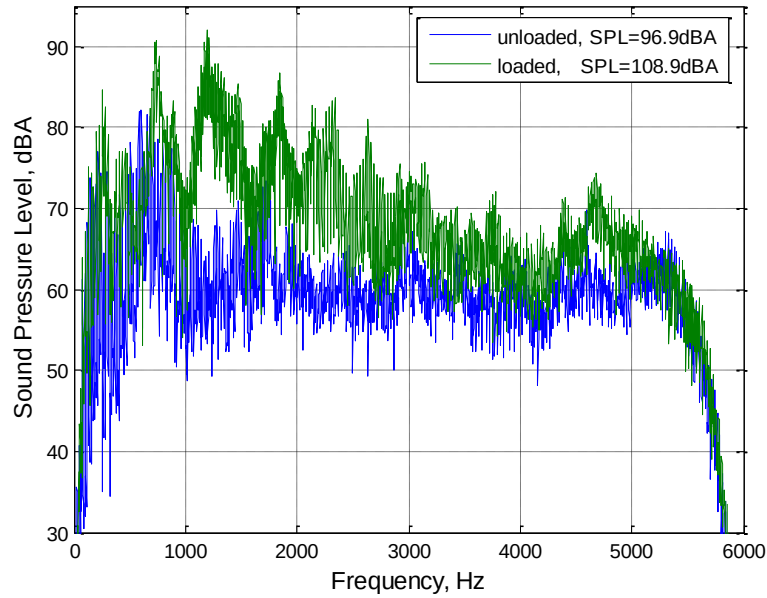


Figure 2.18: Average sound pressure level for the unloaded and loaded (initial impact region) cases.

Noise Source Acoustic Mapping

As part of the acoustic characterization, microphone phased array measurements were performed to identify the noise sources. A microphone phased array is used with special post processing techniques to create acoustic maps or pictures. Figure 2.19 shows the experimental setup for this test. It consisted of mounting the microphone phased array inside the anechoic chamber at a distance of 3.3m (10.8 ft) from the tool. The phased array panel had 63 microphones and a diameter of 1.524 m (5 ft). The microphones were arranged in a 6-arm spiral equal-aperture-area pattern that provided acceptable resolution, i.e. spot size, at the lowest frequency of interest and good side lobe control at the highest frequency of interest. The tool was measured in one configuration which was defined as the tool being operated at 90 psi supply pressure, no exhaust deflector, and the long chisel.

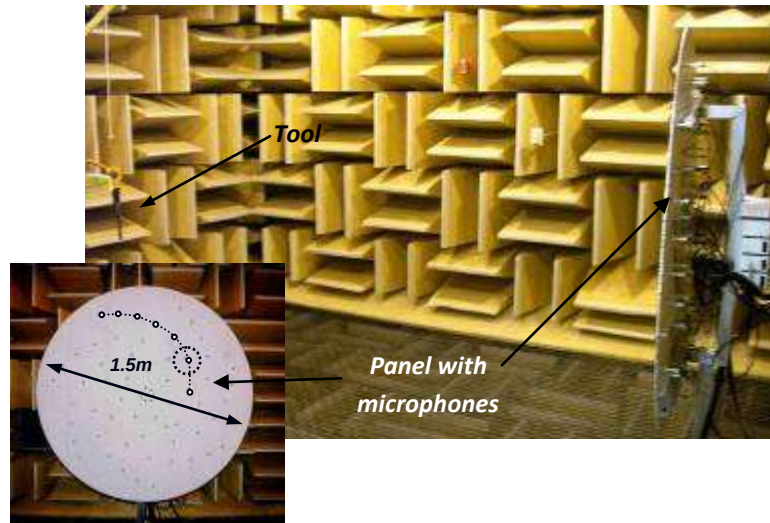


Figure 2.19: Setup for the Microphone Phased Array measurements.

The acoustic images were generated for the complete frequency spectrum in $1/12^{\text{th}}$ octave bands, i.e. total of 79 acoustic images. In addition to the $1/12^{\text{th}}$ octave band maps, the same data was beam-formed at the peak frequencies associated to the component resonances. A uniform scanning grid was used that completely enclosed the tool. The grid resolution was 1.27 cm. An acoustic image created for the 8391 Hz band is shown in Figure 2.20a. It is shown that the main noise source for this frequency is the oval retainer interacting with the chisel. As can be seen in the plot, the main lobe is centered on the main interaction location between these two components. Another acoustic image created for the 16800 Hz band is presented in Figure 2.20b. It is shown that the main source in this band is the oval retainer. The main lobe in this case is located directly on the edge of the oval retainer suggesting that the oval retainer is vibrating and radiating sound.

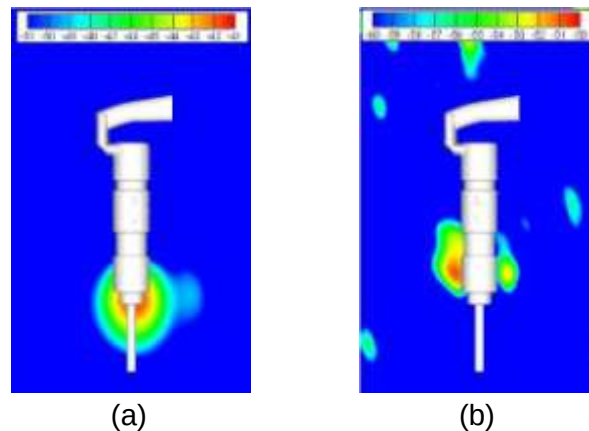


Figure 2.20: a) Beam-forming map at 8391 Hz of the chipping hammer showing a noise source at the interaction between the oval retainer and chisel. b) Beam-forming map at 16800 Hz of the chipping hammer showing a noise source at the oval retainer.

The acoustic maps were also related to other information to gain a better understanding of the tool noise emission. To illustrate this approach, Figure 2.21 shows the acoustic maps and the corresponding finite element results of individual component. For example, in Figure 2.21a the acoustic map shows that the likely noise source for the resonance at 6431 Hz is the center body. However, an analysis of the modal hammer measurements and FE model show that there isn't a natural frequency of the center body near this frequency. However, there was a natural frequency of the oval retainer at 6462 Hz found from the modal hammer measurements. Thus, it was determined that the oval retainer is the source of the peak at 6431 Hz. The mode shape causing this peak was found from the FE model and is shown in Figure 4.21b. The rest of the figure shows additional examples.

Using the procedure described previously, each peak in the sound power spectrum was investigated in order to reveal the noise generation mechanisms of the tool. In this manner, the noise mechanisms causing the peaks of the sound power spectrum were uncovered.

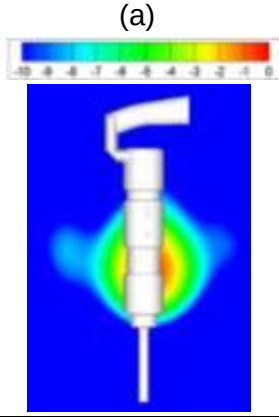
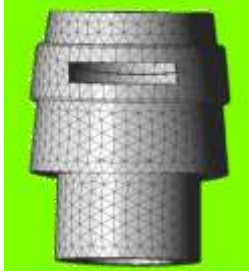
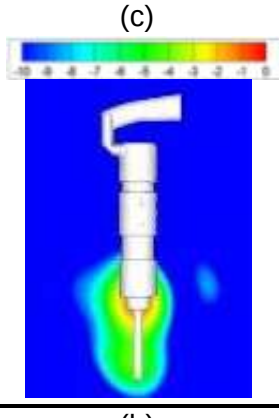
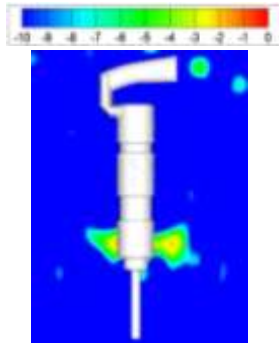
Resonance frequency and level	Beam-forming plot	Noise sources (FEM mode shapes and experimental resonant frequencies if available)
Frequency, 6431Hz Sound Power Level 83dBA	(a) 	(b) Oval Retainer FEM Mode shape at 5532 Hz Hammer resonant frequency – 6462 Hz 
Frequency 8230 Hz Sound Power Level 78.5dBA	(c) 	(d) Long Chisel FEM Mode shape at 8280 Hz Hammer resonant frequency – unavailable  Source at 8230Hz E) Long Chisel FEM Mode shape at 8541 Hz Hammer resonant frequency – unavailable  Source at 8391Hz
Frequency 16350Hz Sound power level 68.6dBA	(h) 	(i) Oval Retainer FEM Mode shape at 16178 Hz Hammer resonant frequency – 16350 Hz 

Figure 2.21: Beam-forming maps of chipping hammer at 6500, 8230, 12600, and 16350 Hz. Figure also shows the mode shape of the mechanical component responsible for the noise at these frequencies.

Phase III: Vibrations Characterization

This section focuses on the vibration characterization of the pneumatic tool. It consisted in the development of Finite Element models, modal hammer tests, and the correlation of these

results. The main intent of the Finite Element models is to gain some insight into the mode shapes of the tools and to be able to guide in the identification of the mechanical noise sources. The results found from this mechanical analysis were used later in the project to aid in the characterization of the chipping hammer. Specifically, the resonance frequencies found from both the modal hammer measurements and the Finite Element analysis were used in combination with the phased array measurements to spatially locate the sources of the peaks found in the sound power spectrum.

Modal Characterization

The mechanical resonances of the chisel, oval retainer, and the partially assembled center body of the tool were characterized. These components are important form the mechanism of transmission of the impact force from the tool to the impact surface and the operator. To determine the modal properties of these components, Finite Element models were developed to determine mode shapes and natural frequencies. In addition, modal hammer testing was also performed on these parts. The modal hammer measurements were used to verify the Finite Element models and independently characterize the mechanical components of the tool

Finite Element models were developed for the center body, oval retainer, long and short chisels. Here only the center hardened shell of the center body was modeled as a hollow shell made of steel. Drawings of these components are shown in Figure 2.22.

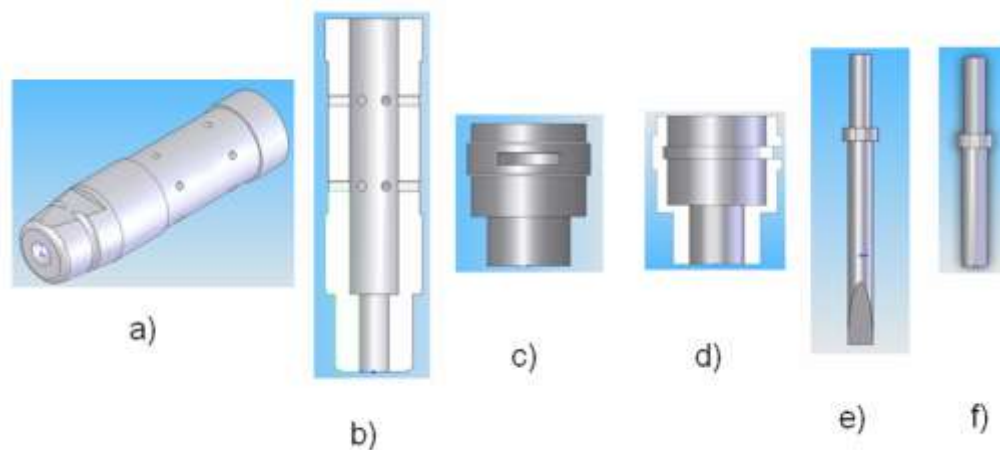


Figure 2.22: Finite element models of A) B) center body, C) D) oval retainer, E) long chisel, and F) short chisel.

The Finite Element models produced many different mode shapes for each component, e.g. these are modally rich components. However, only a limited number of the modes are discussed here.

To corroborate the Finite Element data and gain a better understanding for the mechanical noise generation, modal hammer measurements of the short chisel, oval retainer, and center body shell were performed. For modal hammer measurements, an impulse is input into the system and the response of the system is measured. To apply the impulse to the system a “modal hammer” was used. The force transducer measures the impulse which is imparted to the system. Because the tip of the hammer is not perfectly hard, the impulse is not

perfect either. The tip acts as a low pass filter where the softer the tip, the lower the corner frequency of the low pass filter. For the measurements presented here, the modal hammer was equipped with a metal tip, thus allowing for a relatively high corner frequency for the input signal. The response of the system was measured with a single accelerometer since only the natural frequencies were desired from these tests. The experimental setup of the modal hammer tests consisted of suspending each component by a small elastic “bunji” cord or string as shown in Figure 2.23. This method of suspension allows for the assumption that the measured component is in a free-free boundary condition. This setup is the easiest and most common method of measuring transfer functions of mechanical components. Multiple accelerometer and impact locations were tested. From all these results and estimate of the resonances were obtained.

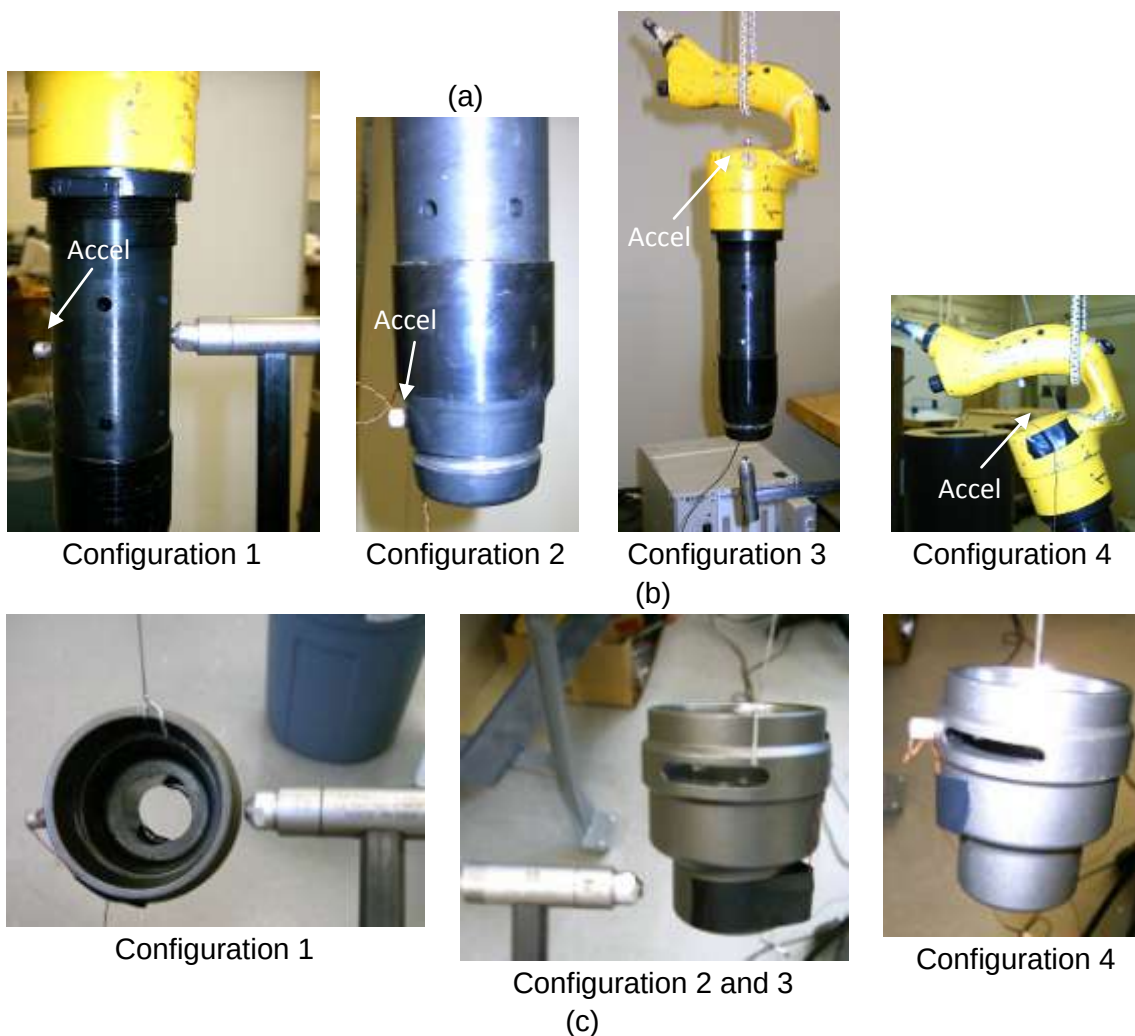




Figure2.23: Modal hammer testing a) tool center body, b) oval retainer and c) chisels.

The measured resonant frequencies for the components tested are presented in Table 2.1. These estimated natural frequencies were obtained as the average of multiple test configurations. It can be seen that the lowest resonance found for the center body is relatively low at 542 Hz which corresponds to the handle fundamental resonance. Contrary to the center body, the oval retainer has much higher resonant frequencies. This is caused by the physical dimensions of the component being smaller than the center body. It should be noted that these results make logical sense as well. The oval retainer seems to have “sets” of natural frequencies: 6413 and 6478 Hz, 12820 and 12870 Hz, and so forth. These sets of frequencies arise from the asymmetry of the oval retainer. These resonance frequencies are likely associated with radial “breathing” modes of the oval retainer. Because the oval retainer is not completely symmetrical, one direction will be stiffer than the other orthogonal direction, thus causing a rise in natural frequency for the stiffer dimension. The next higher set of natural frequencies (12820 and 12870 Hz) would be the second radial “breathing” mode of the oval retainer. Although some of the resonant frequencies for the short chisel are relatively low, it can be shown that most of them are much higher than all the other components tested.

Table 2.1: The natural frequencies in Hz of the center body, oval retainer, and chisels found from modal hammer measurements

Mode	Center Body	Oval Retainer	Short Chisel
1	542	6413	3283
2	820	6478	3310
3	1084	12820	4871
4	1145	12870	6582
5	1626	12910	6611
6	1738	12970	8174
7	2051	13223	9887
8	2168	14205	9918
9	2773	14493	11473
10	3374	15090	13197
11	3586	16343	13233
12	7405	16810	14777

It is noted that the results found from the modal hammer testing make logical sense for the short chisel. For example, the natural frequencies for the short chisel have a pair of mode shapes near 3300Hz. It can be shown that these two natural frequencies correspond to the first bending mode of the chisel. However, since the chisel is not perfectly symmetric, the bending mode in one direction has a slightly higher natural frequency than the other. The lack of symmetry is caused by the oval section. Because the oval section is longer in one dimension than the other, then it is stiffer in that direction, thus making the natural frequency slightly higher. This is the explanation for the existence of the 3308 Hz natural frequency.

Finite Element vs Hammer Test Results

The natural frequencies found from the Finite Element models are presented in Table 2.2. Selected mode shapes are also illustrated in Figure 2.24.

Table 2.2: Natural frequencies found from Finite Element model.

Center body	Oval Retainer	Short Chisel
Natural frequency (Hz)	Natural frequency (Hz)	Natural frequency (Hz)
960	5510	3194
961	5532	3219
3845	12918	7921
4832	13452	7934
4836	13975	10265
5945	14012	14801
10819	14341	14803
10915	14656	16014
12629	16178	16943
16691	16821	22026
17029	17602	22121
17161	18577	
17166	18958	
18782	19600	
19182	20838	
19467	21709	
19468	22335	
21952	22839	

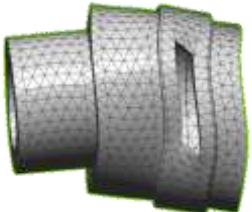
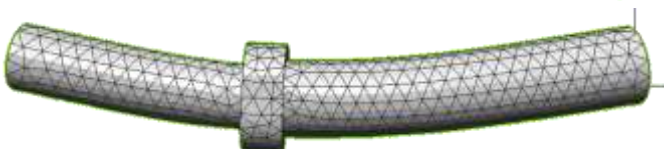
Natural Frequency, Hz	Mode Type	Mode shape
4832Hz	Bending	
4836Hz	Bending	
13452Hz		
3194Hz	Bending	
3219Hz	Bending	
4629Hz	Bending	
4671Hz	Bending	

Figure 2.24: Selected mode shapes calculated from FE model of center body, oval retainer, short chisel, and long chisel.

A comparison between the resonant frequencies found from the modal hammer tests and the natural frequencies found from the Finite Element model were also carried out and the results shown in Table 2.3. It is shown that the natural frequencies of the center body do not match well with the Finite Element natural frequencies. The poor agreement is expected because of the different boundary conditions imposed on the center body in the two different analyses performed, such as the free-free boundary condition in modal hammer testing and the

clamped-free boundary condition in the Finite Element model. It is also noted that there are many complicated sub-components not included in the simplified Finite Element model. On the other hand, for the oval retainer and short chisel, the natural frequencies found experimentally match within 3% with the calculated natural frequencies.

Table 2.3: Comparison of the natural frequencies found from the modal hammer tests versus the natural frequencies found from the Finite Element models.

Center Body		Oval Retainer		Short Chisel	
Natural Frequencies		Natural Frequencies		Natural Frequencies	
Experimental (Hz)	FEM (Hz)	Experimental (Hz)	FEM (Hz)	Experimental (Hz)	FEM (Hz)
542			5510	3284	3194
820			5532	3308	3219
	960	6411		4858	
	961	6462		6594	
1084		12820	12918	6619	
1145		12870		8174	7921
1626		12920			7934
1733		12970		9913	
2046		13230	13452	9929	
2168			13975		10265
2773		14200	14012	11470	
3313		14500	14341	13250	
3586			14656	13270	
	3845	15090		14780	14801
	4832	16350	16178		14803
	4836	16810	16821	15230	
	5945		17602		16014
7405		18480	18577	16530	
	10819		18958	16550	
	10915	19810	19600		16943
	12629		20838	18100	
	16691		21709	19860	
	17029		22335		22026
	17161		22839		22121
	17166		23487		
	18782		23655		
	19182		24683		
	19467		24925		
	19468				

It is also shown that there are some differences between the measured and predicted natural frequencies of the oval retainer and chisel. The minor discrepancies can be explained by the fact that in modal hammer testing, it is difficult to find a measurement location or input

location that can measure or excite all the modes of the structure. On the other hand, the most likely cause of the disagreement between experimental and numerical models is that the material properties and dimensions of the Finite Element model do not accurately represent the physical model. Note that the Finite Element models were developed from a few measurements of the tool, i.e. no detail drawings were available for the tool. Because the oval retainer and short chisel are relatively simple physical components, the numerical model is more representative of the actual structure. However, the center body is a very complicated structure, thus it is believed that the Finite Element model of this component was unable to predict accurately the natural frequencies of the physical model.

Phase IV: Fluid Characterization

The fluid measurements of the tool were performed to investigate the characteristics of the exhaust air flow. The reason for performing these types of tests is because high speed jets can cause high energy noise detonations. The noise detonations are caused by the physical flow of air away from the tool which can act as a monopole radiator of sound. The flow itself mixes with the ambient stationary surrounding air creating broadband noise. To determine if these are important noise sources in pneumatic tools, hot film anemometry was used to determine the velocity of the exhaust streams while pressure transducers were used to measure the pressure in the upper and lower chambers. The pressures in the upper and lower chambers were also useful to determine the operation chronology of the tool.

Two experiments were performed to characterize the fluid part of the tool. The first experimental setup can be seen in Figure 2.25a showing the Atlas Copco TEX317 tool mounted in the hand-arm rig. The rig was used to steady the tool during operation so that the transducers could record accurate measurements. Also used in the experimental setup was an energy dissipater built using ISO 8662-2 standard and was used to absorb the impact and maintain repeatability between tests.

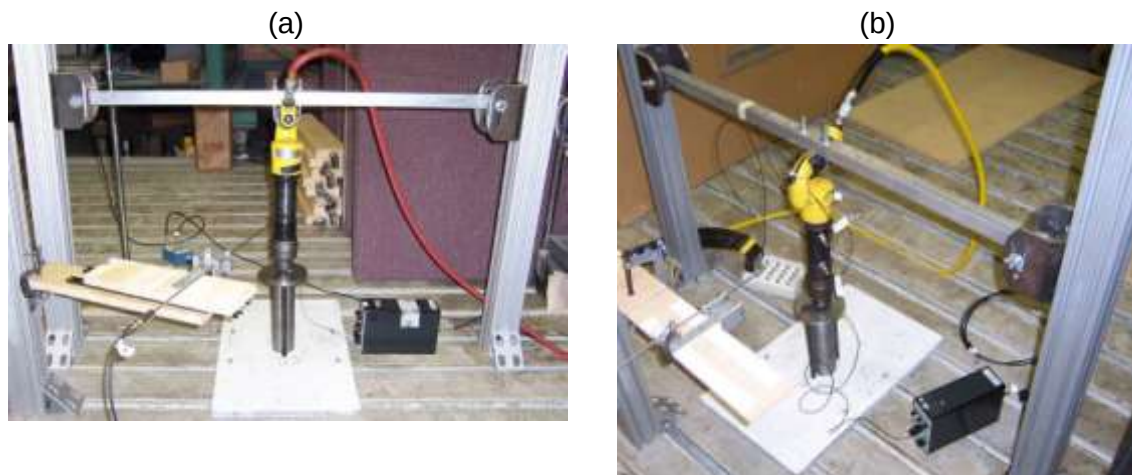


Figure 2.25: Experimental setup for a) first and b) second hot film anemometer measurements.

The transducers for the first experimental setup included a hot film anemometer and one accelerometer. The hot film was used to measure the velocity of the exhaust at multiple spatial

locations. Hot film anemometry takes advantage of heat transfer properties of the wire used at the tip of the hot film probe. For this experiment, a constant temperature anemometer (CTA) was used. For CTA, the wire is exposed to flow while the flow carries away energy. Energy is then supplied to the wire to maintain the temperature. The amount of energy required to maintain the temperature can be measured and is related to the velocity of the flow. To maintain the temperature of the probe and measure the energy supplied, a DANTEC type 55M01 power supply was used. The output from the power supply was not linear and therefore calibration is required. To calibrate the hot film probe, a TSI calibrator model 1125 was used.

For the measurements performed for the first experiment, the hot film probe was placed horizontal to the ground and perpendicular to the tool and was always parallel to the exhaust flow. Measurement points were taken at four radial positions as well as 11 to 16 angular or tangential positions for the two different exhaust ports (upper and lower ports). Spatial measurement location error was $\pm 0.1\text{mm}$. The velocity was also assumed to be symmetric across the horizontal and vertical axis of the exhaust port; consequently, measurements were taken in the horizontal plane only and not in the vertical direction. The velocity was also assumed to be identical for all the ports on the same level. Thus, a single port was measured per level.

Since only one hot film anemometer was available at the time of testing, a method of aligning the two measurements in the time domain was needed. Since the chisel is impacted at the same point in every cycle, an accelerometer was affixed to the chisel in the horizontal direction which shows the exact time of impact between the internal piston and chisel. The accelerometer signal was used to align the upper and lower port velocity time histories. The measurements yield a velocity profile in the two dimensional spatial domain. For this experiment, measurements were made at the supply pressure of 90 psi.

The second experimental setup can be seen in Figure 2.25b. For the second experimental setup, the instrumentation used included the same hot film probe, two pressure transducers and one accelerometer affixed to the handle. The main difference between the first and second experimental setup is the use of the pressure transducers in the upper and lower chambers. The center body of the tool was machined to allow the pressure transducers to be affixed to the tool during operation. A diagram and picture showing the locations of the pressure transducers are shown in Figure 2.26. The pressure transducers were used to provide accurate data consisting of the instantaneous pressure in the respective chambers. For the second fluid flow experiment, the exhaust jet velocity was not measured in such detail in the spatial domain as the first fluid analysis experiment was. In this second experiment, the exhaust velocity was measured at 3 mm from the surface of the tool in the radial direction and at three tangential positions at the one radial position. Thus, spatial velocity measurements exist only at three locations for each configuration. For this experiment, measurements were made at three supplied pressures, e.g. 90, 80, and 60 psi, respectively.

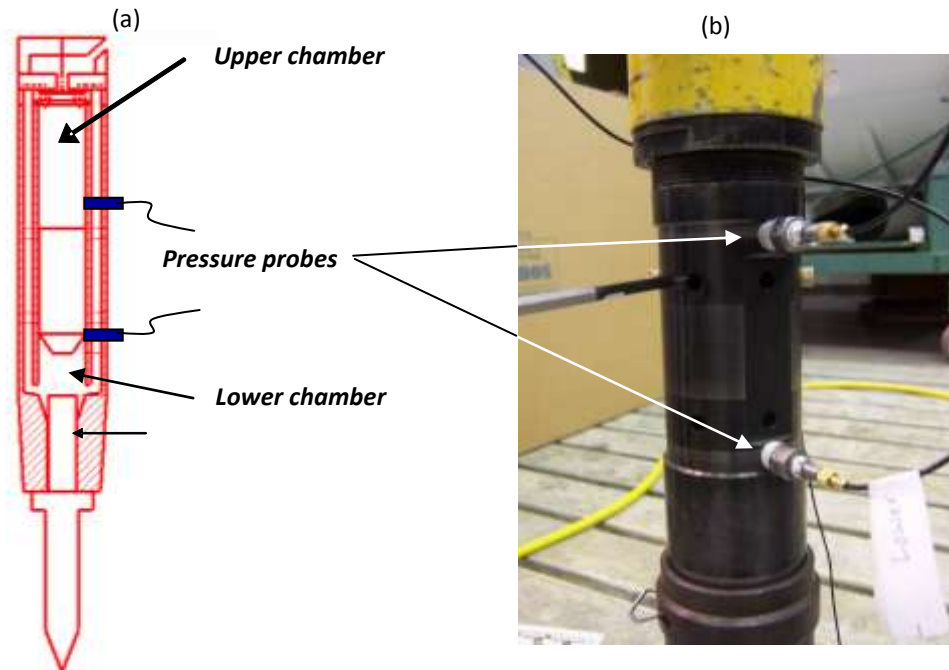


Figure 2.26: Placement of pressure probes for the second fluid analysis experimental setup is shown.

The exhaust velocities time histories for both upper and lower ports are shown in Figure 2.27. For the time histories shown, the probe was placed 5 mm from the surface of the tool along the center line of the exhaust port. For the three operating cycles shown in the figure, it can be shown that the low port has lower peak velocities. The velocities for each measurement point in space were averaged with respect to time to reveal the location of the bulk of the flow and to reveal the mixing regions of the exhaust flow. The mixing regions are important because it is hypothesized that quadrupoles develop in this region which radiate broadband jet noise. To determine the location of the mixing region, the average velocity was computed at each measurement point and the spatial distribution of average velocities for the upper port can be seen in Figure 2.28. An interesting result is that the flow area does not expand greatly. This is important when considering the potential shock wave that is caused by supersonic flow that may be present in the exhaust. Because supersonic flow requires a converging-diverging nozzle, the flow cross-sectional area would have to increase after the choke point to reach supersonic speeds. Analysis of the data reveals that the flow does not expand greatly thus implying that the flow does not likely exceed Mach 1.0.

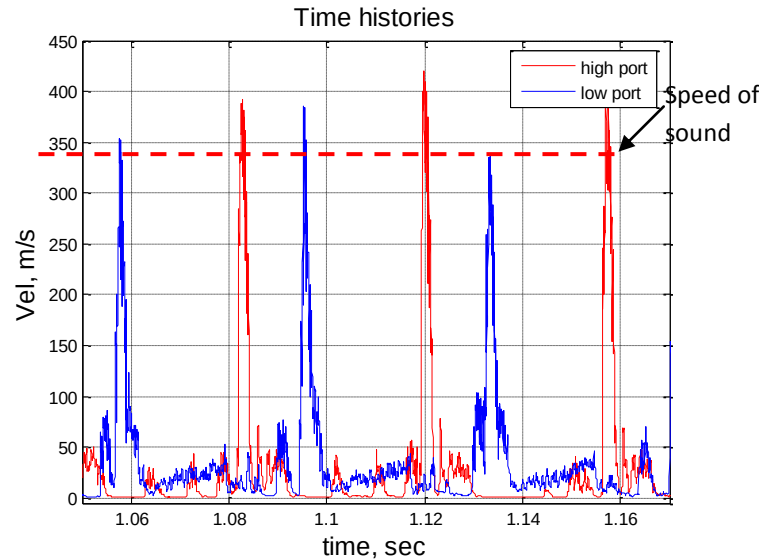


Figure 2.27: The velocities of the upper and lower exhaust ports over three operating cycles of the tool.

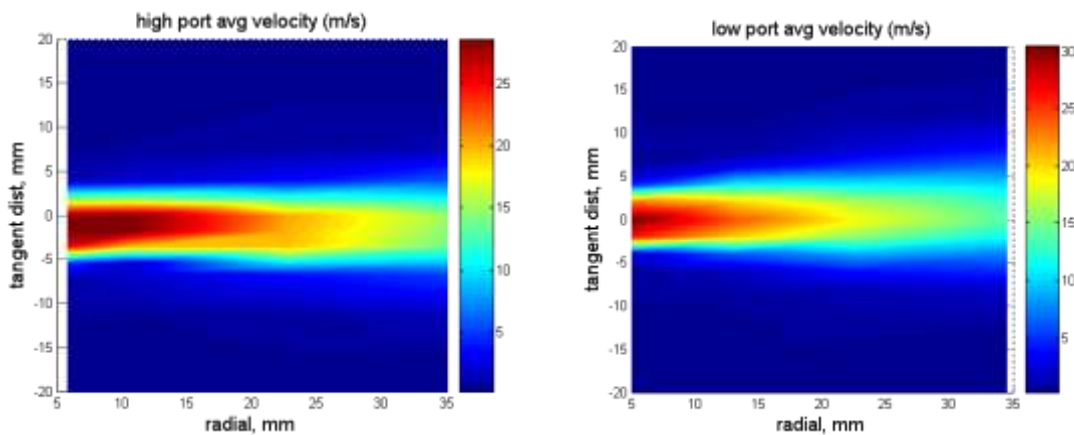


Figure 2.28: The time averaged velocities for the multiple spatial measurement positions shows the spatial distribution of the average velocities for the a) high and b) low port.

The results from the second experiment yielded the pressure in the respective chambers and how they related to the exhausted jet velocity. The pressure from three representative cycles can be seen in Figure 2.29. The supply pressure for this experiment was 90 psi. It is noted that the pressure transducers were covered during part of the operating cycle. During this part of the cycle, the pressures that were recorded are assumed to be inaccurate and were thus removed. The values shown in the plot are interpolated between the two known pressures and are shown with dashed lines. The exhaust velocities from the same three cycles can be seen in Figure 3.30. It must also be noted that the velocities reported in this case are well above Mach 1.0. The velocities that are shown have been extrapolated using King's law, which is reasonable to an extent. However, it is believed that extrapolation into the supersonic region is not completely accurate since the hot film was calibrated to a maximum velocity of 170 m/s.

However, it can be concluded that the jet velocities are very high and likely supersonic for a short period of time, in particular for the high ports.

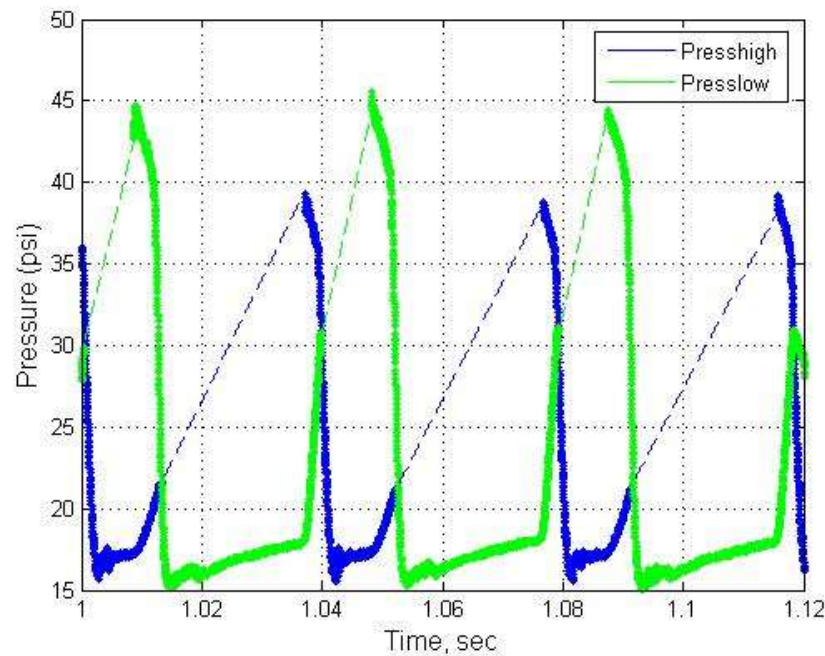


Figure 2.29: The pressures in the upper and lower chambers are plotted. The dotted lines indicate the time period where the pressure transducer was covered by the piston. The dotted lines are a linear interpolation between the two known points.

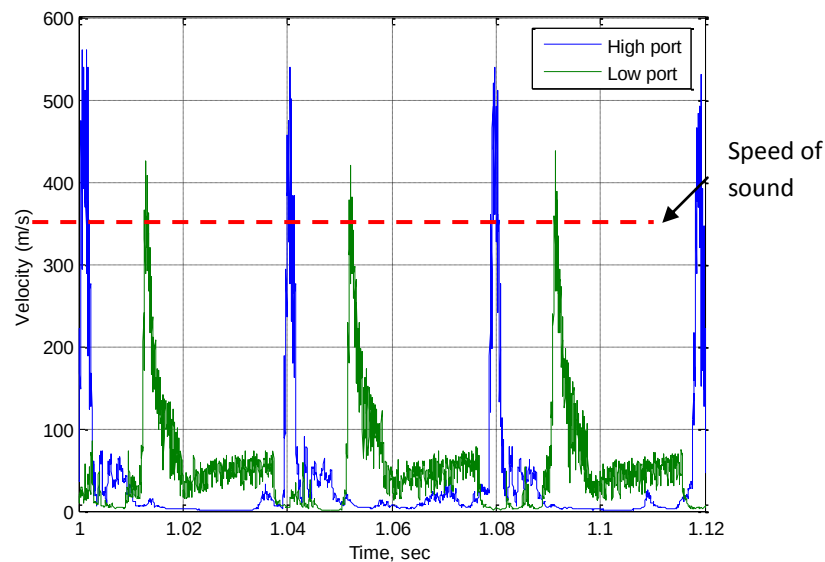


Figure 3.30: The velocity of the upper and lower exhaust ports.

The velocities found from the second experiment show similar results to those found from the first experiment. The velocity from the high port is always higher than the velocity from the low port. Upon analysis of Figure 2.29, it seems that the lower chamber has a higher

pressure which would imply that the lower port would have the higher velocity. However, since the pressure transducers were physically covered during part of the operating cycle, it is believed that the upper chamber actually has the higher pressures, thus creating the higher velocities seen in the exhaust. Also, the velocities from both high and low ports show that they are supersonic. However, the confidence in these supersonic velocities is low. As stated in the discussion earlier, for supersonic flow to be present, there must be a converging-diverging nozzle. Since a converging diverging nozzle does not seem to be present, the highest velocity of the flow should be Mach 1.0. However, it is noted that if supersonic flow is present, by definition supersonic flow must contain shock waves to rectify the pressure difference. It is well known in the acoustics industry that shock waves are a significant noise source and therefore could be very significant in the source identification of pneumatic tools.

The fluid measurements performed were utilized later in the project for the noise control and modeling of the tool. It is known that the high speed jet mixing can cause loud levels of broadband noise. It is noted that this chapter was not able to definitively prove this assertion. However, experiments discussed will show that the addition of mufflers will reduce low frequency exhaust pulses and the high frequency broadband noise, thus proving that the high speed exhaust is the cause of these noise sources.

Phase V: Numerical Model of Tool

A novel nonlinear numerical model for the pneumatic impact hammer was developed. The model was validated using the experimental data obtained in the previous sections, e.g. exhaust jet flow rate, the chamber pressures, and handle vibration. The objectives behind the numerical model of the pneumatic impact hammer were to simulate the physical aspects that drive the hammer, to devise best possible vibration control techniques as well as to avoid the need for extensive laboratory experiments testing. It can also predict the displacement, velocity and acceleration of each component of the tool as well as the exhaust jet velocity profiles and their levels.

The pneumatic impact hammer has many structural components such as center body, piston, and so forth. Vibrations in the impact hammer are mainly generated by the impacts between the chisel and the piston and reaction forces as the piston is accelerated. These repetitive impacts then propagate through the interconnected structural components exciting system resonances. Therefore, in order to calculate the vibration levels, the components of the impact hammer must be considered in a structural dynamic model. The piston inside the impact hammer is forced by pressurized air in order to model this forcing a fluid flow model is developed. The fluid flow model is based on the assumption of isentropic fluid flow through a bleed orifice⁰. Therefore these impact hammers can be fundamentally divided into two sub-models 1) a structural dynamic model and 2) a fluid flow model. Therefore, it is important to mathematically formulate both parts and then couple the models together. These models are briefly described here.

Structural Model

The structural model consists of a lumped mass parameter model and impact model. The modeling of impact is nonlinear in nature and therefore requires a time domain numerical

integration approach. The lumped parameter and the impact models are explained in detail in the following subsections.

The dynamic model used here consists of the center body, the chisel, the piston and the handle as shown in Figure 2.31. Importantly, the model takes into account the interaction between the chisel and the ground as well as interaction between the handle and the operator's hand. All these components are modeled as lumped masses connected to each other through springs and dampers⁰. Physically the piston is not connected to any of the other component during its entire cycle except when it impacts the chisel for a fraction of a second. Therefore, the impact between the piston and chisel is modeled as a nonlinear spring. Likewise, there is also a nonlinear spring at the top of the chamber which restricts the piston going beyond the maximum specified stroke. The contact between the chisel and center body is also modeled in this way. A small amount of the kinetic energy of the piston is dissipated to overcome friction between the piston and center body and this friction is included in the model as another damping term. The modeling of the friction is important because it determines the velocity of the piston and the stroke of the piston. The ground is considered to be a large energy dissipater i.e. large damping terms. The human hand is also modeled as a very heavily damped system. The stiffness and damping terms in the model are dependent on the individual stiffness and damping terms of the two connecting components as explained in Figure 2.31. It should be noted that the structural model predicts the vibration response only in the x-direction.

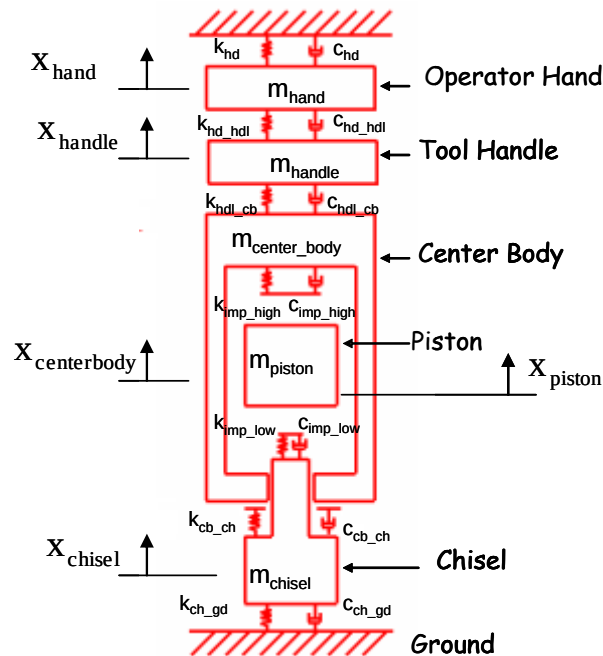


Figure 2.31: Structural dynamic model of the impact hammer.

The load driving the piston is obtained from the fluid flow model. It is known that the force produced by the pressurized air on the piston is equal to the product of the area of the bore of the center body and the pressure differential across the piston. To balance the force on the piston, an equal and opposite force was applied on the center body.

The time dependent stiffness terms k_{imp_high} , k_{imp_low} and k_{cb_ch} are used to model the impact as mentioned before. These are constant value springs which have very large stiffness when in contact and zero when not in contact. This is a simple but effective method to model the impacts. The impact is the most important event in the hammer operation and occurs when the piston impacts the chisel on its downward stroke and the kinetic energy from the piston is transferred to the chisel. There is also a small bumper made of plastic at the top end of the chamber but the handle acceleration measurement results show that there no impact at the top end of the stroke.

Fluid Model

The fluid flow model calculates the effective mass flow rates coming into the upper and lower chambers. From this, the pressures inside the chambers and the time varying forcing input given to the piston can be calculated. In this section the general theory behind the fluid flow model is briefly described. The assumptions made for modeling the fluid flow behavior are: the supply pressure was assumed to be constant at all times, the ideal equation of state applies to the air, the air flow through a bleed orifice is assumed to be a quasi steady-state isentropic flow, and the discharge coefficient of all orifices is assumed to have constant value i.e. $C=0.65$.

Coupling of Structural and Fluid Models

In addition to the displacement and velocity of the individual components of the structural model, the masses of air in the upper and lower chambers were be formulated as states. The mass of air in the upper chamber m_{uc} and the mass of air in the lower chamber m_{lc} are calculated by integrating the difference between the mass flow rate entering and leaving the respective chambers. The mass flow rates are a function of time and can not be modeled as part of the state matrix in the state space formulation. Runge-Kutta-4 was used for numerical integration. They were modeled as augmented state vectors.

Estimation of Parameters

The parameters of the chipping hammer were then estimated to implement the model. The masses of the components of the impact hammer were measured directly. The mass and stiffness of the hand-arm as well as the stiffness of ground were obtained from literature⁰. To get stiffness values for individual components, the finite element models of the individual components were used, e.g. handle, center body, and chisel. The finite element models were described in section 2.4.3. A distributed unit force was applied to the finite element model and the corresponding deformation for the model was used to estimate the stiffness. The stiffness of the spring to model the impacts were assumed to be very large compared to the component stiffness. Finally, the damping terms used in the model are function of the complex mechanism between the impacts of components. They were obtained by trial and error.

Validation of the Model

To validate the model, the results obtained from the numerical model were compared to the experimental results described previously. Figure 2.32 shows the comparison between experimental and numerical exhaust jet velocities from the upper and lower exhaust ports. The results show a very good agreement both in the magnitude of the peaks as well as in the trends

between them. Also the tool impact frequency measured from the lab tests and the tool impact frequency calculated from the numerical model is approximately 27 Hz.

Figure 2.33 shows the comparison between the experimental and numerical pressure profiles in the upper chamber. The upper pressure profiles obtained from the numerical model matches very well with the pressure profiles from the experimental tests. The model predicts the identical cycle timings as that of the experiments. Also the model predicts the pressure release point exactly to be the same as the experimental tests. Unfortunately the maximum pressure in the upper chamber couldn't be measured since the probe is blocked by the piston. Figure 2.34 illustrates the comparison between the experimental and numerical pressure profiles in the lower chamber. The lower chamber pressures profiles also match with the experimental pressure profile well with respect to the cycle timings. The release of the pressures from the lower chamber is exactly as predicted by the model. However the experimental results show the building of the pressures in the lower chamber is quite slow compared to the numerical model prediction. The pressure probe is blocked by the piston when the pressure in the chamber reaches the maximum value.

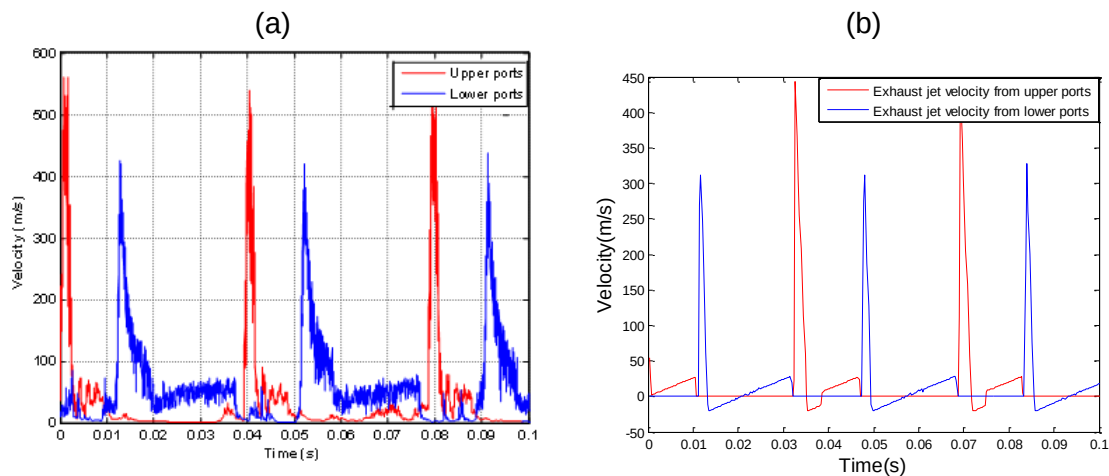


Figure 2.33: a) Experimental and b) predicted exhaust jet velocities from upper and lower ports.

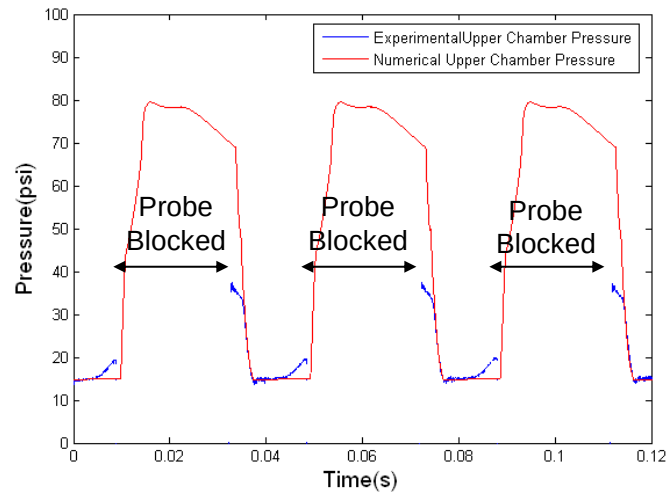


Figure 2.34: Comparison between the numerical and experimental upper chamber profiles.

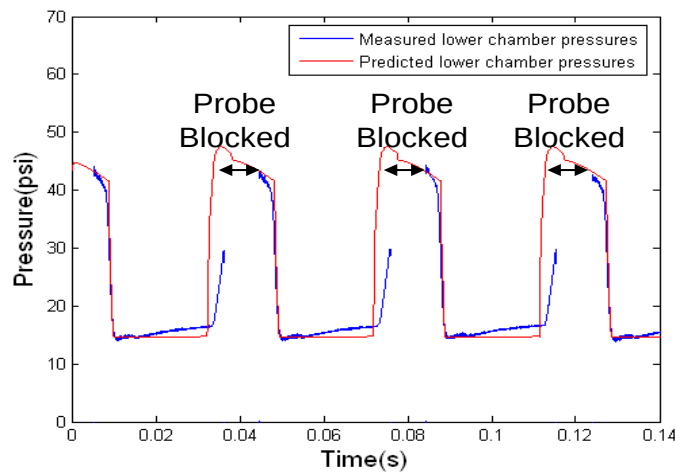


Figure 2.35: Comparison between the numerical and experimental lower chamber profiles.

The experimentally measured power spectral density of the tool handle accelerations compared with that of the numerically computed the power spectral density of the tool handle as can be seen in Figure 2.36. The numerically computed levels of accelerations match very well with that of the experimentally measured. The model also predicts the 500 Hz handle resonance successfully. However, the model over-predicts the higher frequency vibrations. Overall the numerical response shows the same trends. The difference in the two results could be due to the fact that the model assumes dynamics of the ground and support (hand) that are not same as those tested experimentally.

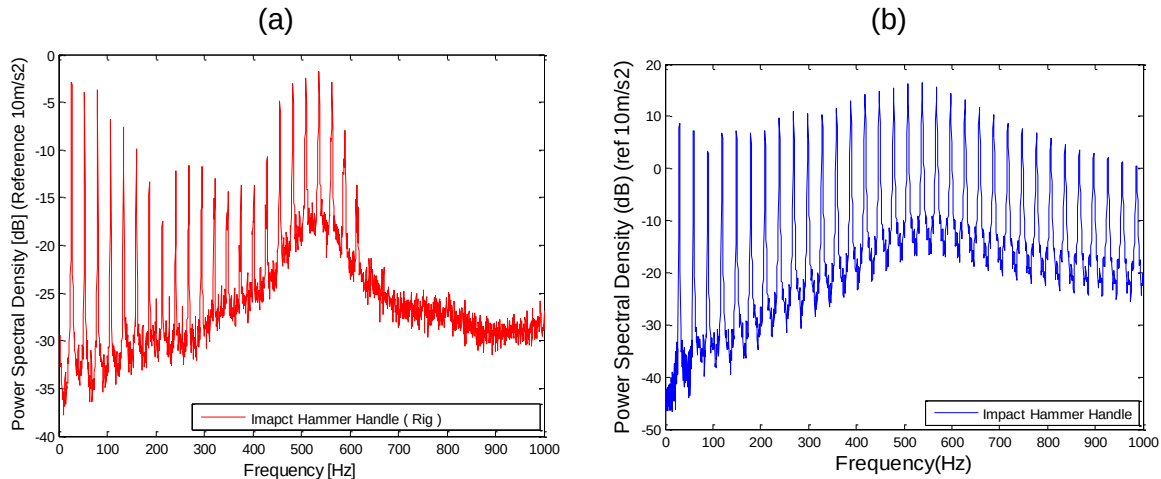


Figure 2.36: Comparison between the power spectral densities of the tool handle a) experimental result, b) numerical result.

Phase VI: Noise Control of the Discharge Pulse

The work described in the previous sections provided a clear description of the noise source characteristic, levels, and source mechanisms of the tool. The goal was to use this information to develop effective and practical noise control solutions. A preliminary noise control study was undertaken here for discharge pulses from the exhaust of the tool which is the dominant noise source. In this study, the approach to reduce the discharge pulse source was to apply commercially of the shelf (COTS) industry available pneumatic silencers to the exhaust ports of the chipping hammer. The main objective was to reduce the jet velocity and dissipate the pulse through losses in the silencers. Six COTS pneumatic silencers were used as shown in Figure 2.37. Most of the silencers are made of stainless steel. However, the silencer shown in Figure 2.37f is made of thermoplastic and is extremely light in comparison to the other silencers. The silencers shown in Figure 2.37c,d, and e are variable flow and can control the volume flow rate.

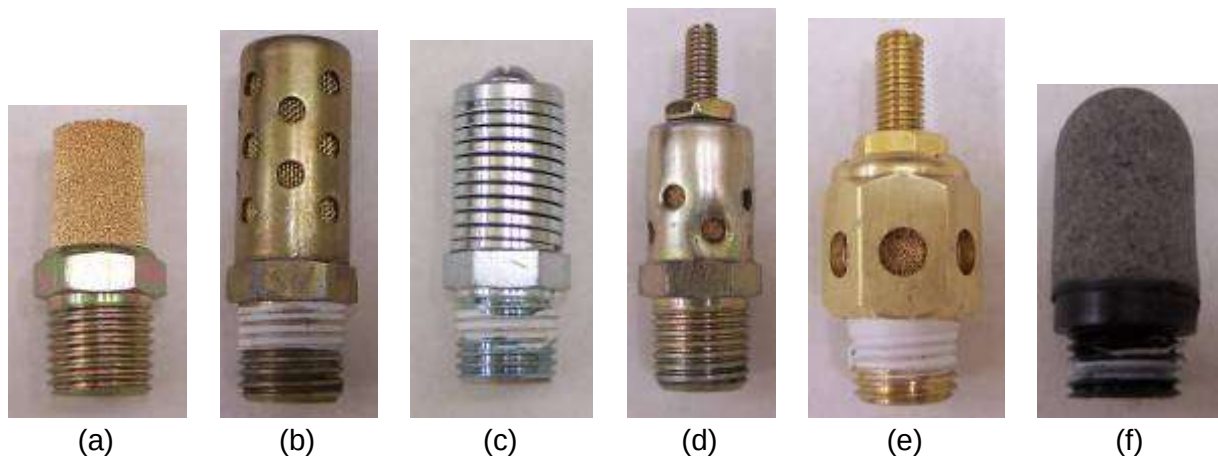


Figure 2.37: The mufflers used in the preliminary noise control measurements.

A simple aluminum encasement was designed and machined to fit over the center body of the tool as shown in Figure 2.38. The design of the encasement involved a tubular setup cut lengthwise down the middle. On each side of the encasement a $\frac{1}{4}$ " NPT pipe thread hole was tapped. The silencers were attached to these holes. The two halves were brought together around the center of the tool creating a cavity between the encasement and center body that the exhaust must pass through to reach the ambient surroundings. This region is referred to as the buffer or settling volume where the fluid can expand prior to exiting to ambient. This buffer volume encompassed both the upper and lower ports.



Figure 2.38: The aluminum encasement used to enclose the center body of the tool for the silencer experiments.

The exhaust area of the tool (six ports open) is $1.6965 \cdot 10^{-4} \text{ m}^2$ and the exhaust area of the encasement is $1.9 \cdot 10^{-4} \text{ m}^2$. Therefore, the flow area expands through the settling volume and through the encasement exhaust holes. If the assumption of incompressible flow is valid, then by conservation of mass the velocity of the flow out of the encasement will be lower which the intended result is. Decreasing the exhaust speed can have tremendous impact on the sound produced. However, from the fluid measurements of the tool, it is known that the exhaust speeds are supersonic ($\sim$ Mach 1.0) and thusly the flow should be compressible. If this is the case, then the exhaust has the capability of taking advantage of the buffer volume between the encasement and the tool. The exhaust would have the opportunity to expand in the buffer volume and exhaust to atmosphere over a longer period of time through a larger area.

It should be noted that if the flow is compressible and the buffer chamber is utilized as an expansion chamber as described in the previous paragraph, then there will be a certain amount of backpressure exposed to the exhaust ports of the tool. Since the tool is intended to operate between a 90 psi supply pressure and atmospheric pressure, lowering the supply pressure to 80 psi while in the same atmospheric environment could mimic the same results as if the atmospheric pressure was raised (as is the case for backpressure). As the supply pressure is lowered to 80 psi, the operating frequency of the tool is decreased from 27.5 Hz to 25 Hz. Therefore, a decrease in operating frequency can indicate a decrease in operating

efficiency. The decrease in operating frequency was used to assess the back pressure introduced by the silencer. The error in the operating frequency estimation is ± 0.1 Hz.

Table 2.4 described the test configurations. The configurations tested included the blank tool, the tool with the encasement only, and the tool equipped with the different silencers. In addition, the configurations described above were tested at different supply pressures.

Table 2.4: The definition of the cases and sub-cases for the preliminary noise control measurements.

Case #	Encasement	Muffler	Supply Pressure, psi	Chisel
1a	Without	n/a	90	short
1b	Without	n/a	80	short
1c	Without	n/a	60	short
1d	Without	n/a	90	long
2a	With	n/a	90	short
2b	With	n/a	80	short
2e	With	n/a	90	long
3a	With	a	90	short
3b	With	A	80	short
3e	With	A	90	long
3f	With	A	60	short
4a	With	B	90	short
4b	With	B	80	short
5a	With	C	90	short
5b	With	C	80	short
6a	With	D	90	short
6b	With	D	80	short
7a	With	E	90	short
7b	With	E	80	short
8a	With	F	90	short
8b	With	F	80	short

This section discusses the results of the preliminary noise control measurements. The comparison between the baseline blank tool and the normalized baseline is shown in Figure 2.39. The sound power levels for the relevant frequency bands are also compared. From the plots, it is shown that the addition of the encapsulating structure reduces the low frequency discharge pulses by 5 to 15 dB for each harmonic. This reduction in sound power is attributed to the settling volume that was added to the structure. The high frequency broadband levels are also slightly affected by the addition of the encasement. The noise reduction is mostly in the broadband levels. Reduction in high frequency broadband levels can be attributed to lower exhaust speeds⁰. The larger exit area and the buffer volume are the likely cause of the lower

speeds. However, measurements were not performed to confirm the lower velocities and future work should be directed towards determining this exit velocity.

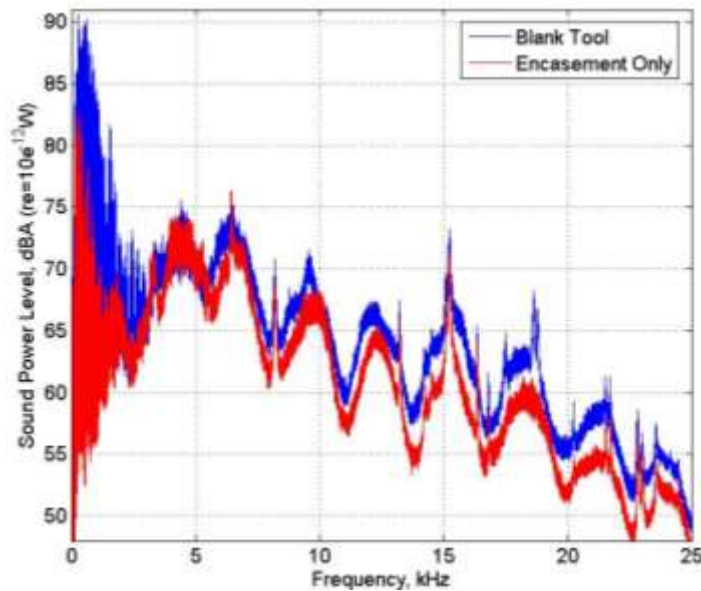


Figure 2.39: Sound power spectrum comparison between the blank tool and the tool with encasement. Overall sound power level: Blank tool =112.2 dBA and Tool with encasement = 108.5 dBA.

The sound power levels for the six silencers in various frequency ranges are shown in Table 2.5. It is shown that the addition of the silencers reduces the total sound power (0-25 kHz). More importantly, the addition of the silencers greatly reduces the sound power in the low frequency region by 6-10 dB. This is explained by the addition of the settling volume included between the encasement and the tool, but also because the exhaust profile is smoothed even more by the addition of the silencers. The high frequency region is not greatly affected by the addition of the silencers. Figure 2.40 compares two of the six silencers and the blank tool with the encasement. From the table, silencer “C” produced the best results. The reason for this result is explained by the reduction of flow and additional backpressure caused.

Table 2.5: Sound power level comparison between the six mufflers and the tool with encasement configuration.

Configuration	0-25kHz (dBA)	0-1500Hz (dBA)	1500-25kHz (dBA)
Tool with Encasement	108.5	98.9	108.0
Muffler A	107.7	92.6	107.6
Muffler B	107.5	92.8	107.4
Muffler C	103.9	88.8	103.8
Muffler D	106.5	90.2	106.4
Muffler E	107.1	91.5	107.0
Muffler F	108.0	93.8	107.8

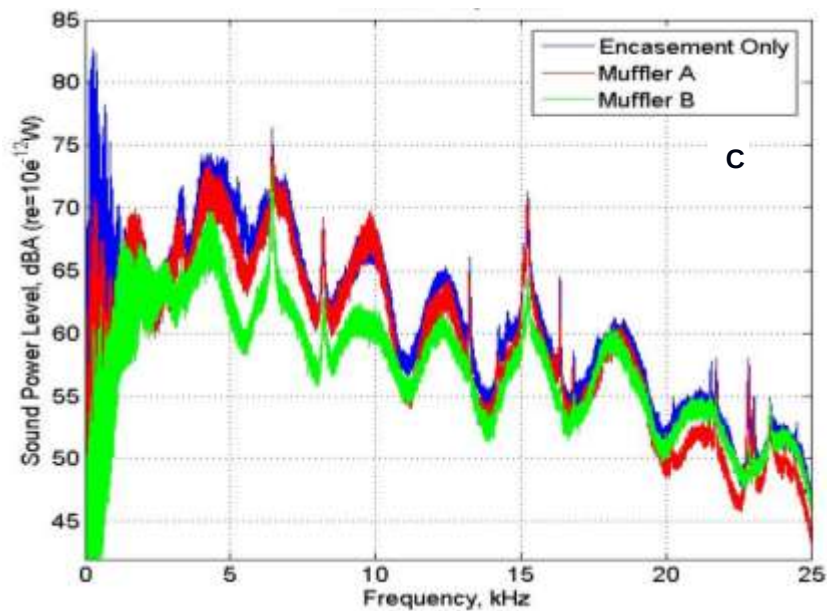


Figure 2.40: The sound power spectrum of two selected mufflers and the tool with encasement.

The results found from the muffler comparison suggest that a backpressure has been introduced to the system, which can cause a reduction in operating efficiency. Although a test for operating efficiency has not yet been developed, the operating frequency of the tool is a good indicator of how much backpressure is present. A plot showing the operating frequencies versus total sound power for the different configurations is shown in Figure 2.41. Generally, the operating frequency decreases with reduction in sound power. However, the maximum decrease in operating frequency is only of 2% relative to the blank tool case. Thus, it can be concluded that the operating efficiency of the tool is not affected by the backpressure caused by the addition of the silencer even for the most restrictive case, silencer C.

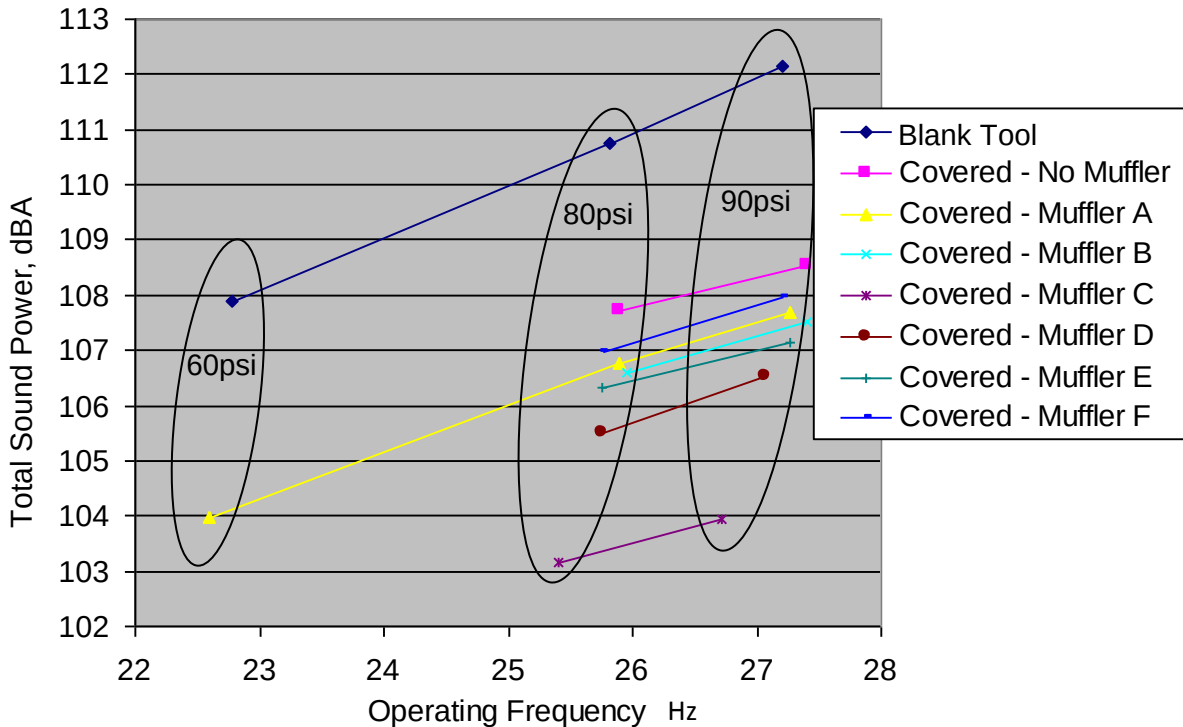


Figure 2.41: The operating efficiency curve defined by the operating frequency of the tool and the supply pressure.

Phase VII: Vibration Control

There are many solutions for vibrations and noise in machine tools. The traditional method of reducing vibrations is to use a dynamic vibration absorber (DVA). The DVA does well at reducing a single targeted frequency, but requires a significant mass and does not reduce other frequencies. The multi mass DVA consists of multiple masses connected in series or in parallel and is effective in a broader frequency band. The drawbacks of the multi mass DVA are similar to that of the DVA, the amount of damping is highly dependent on the mass ratio of the DVA compared to the subject and has less influence on the operating frequency. The impact damper, or impact vibration absorber (IVA) was developed for rotating machinery such as lathes, cutting tools, and boring bars. The impact damper uses a mass to counteract vibration by impacting the body. This impact dissipates the vibration energy of the system and has been proven effective in rotating machinery. Cutting tools were able to increase rotation speed and depth of cuts while NASA has been able to increase turbine fan speeds with less vibrations.

The numerical tool model described in section 2.4.5 was used to explore the different vibration control techniques. The approach followed was to change the various structural and fluid parameters in the model and compute the tool response to assess the vibration reduction.

Preliminary Vibration Control Concepts

The first a most simple approach to reduce the vibration to the operator is to stiffen the handle. It has been mentioned before that the bending mode shape of the tool handle is responsible for the 540 Hz resonance. This resonance could be a principal cause for finger injuries. The

resonance at 540 Hz can be pushed beyond the frequency range of interest (0-1000 Hz) by increasing the stiffness of the handle. This can be simply achieved by changing the C-shape handle into a D-shape handle which would increase the stiffness significantly at the expense of small addition of weight. Figure 4.42 shows this concept. A finite element model was used to determine that the D-handle increases the stiffness by a factor of approximately 10 (i.e. 1.5×10^8 N/m). Implementation of D-handle resulted in vibration attenuation of 10 dB at 540 Hz resonance as shown in Figure 2.43. The D-handles are used in commercial impact hammers nowadays.

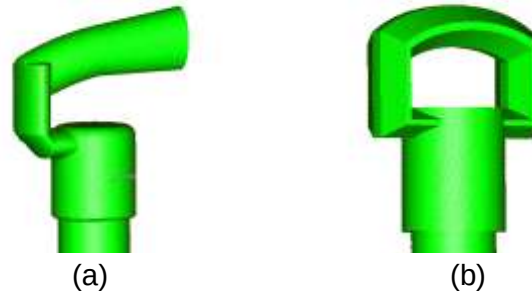


Figure 2.42: Finite element model of (a) C-handle, (b) D-handle.

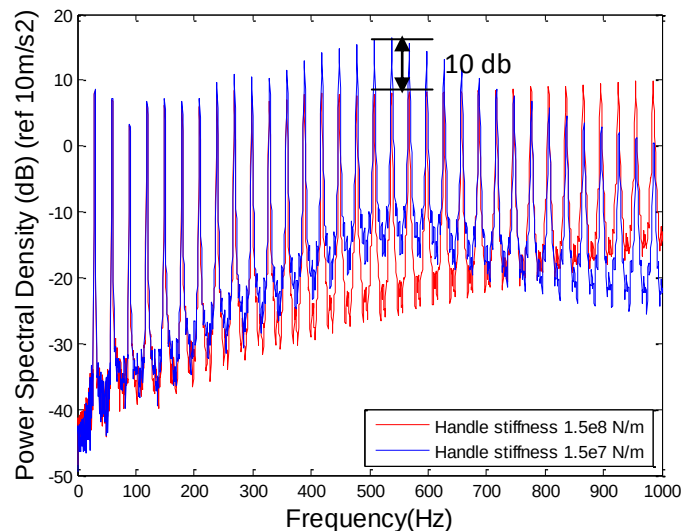


Figure 2.43: Effect of the D-handle on the tool handle's power spectral density.

Another approach investigated to reduce the vibration was to increase damping to the handle. Figure 2.44 shows the effect of the increasing handle damping by a factor of 2. The increase in the handle damping reduced the amplitude of the handle resonance by 5-6 dB at 540 Hz. But there is no change in the primary impact and the low frequency vibration amplitudes. The handle damping could be increased by adding some visco-elastic damping to the handle.

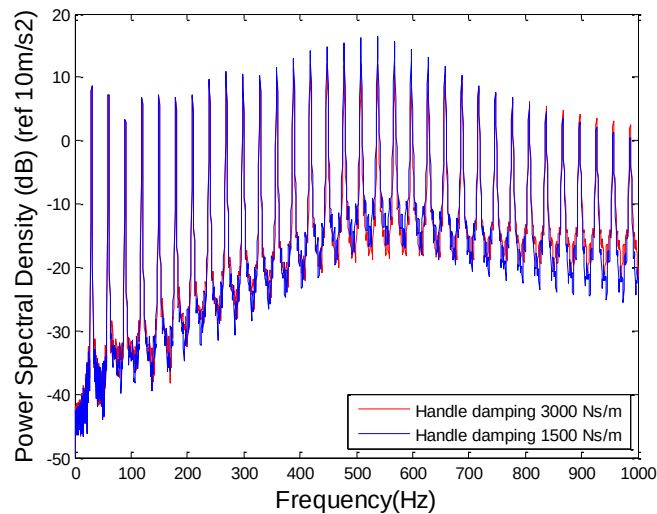


Figure 2.44: Effect of the increasing damping on the tool handle's power spectral density.

Figure 2.45 demonstrates the effect of the increased piston weight on tool handle's power spectral density. The increase in the piston weight would necessitate more force to accelerate it and in turn it would reduce the maximum velocity of the piston. Therefore the increase in the piston weight reduces the primary impact frequency by 3 Hz. The reduced piston velocity attenuates the amplitude and the frequency of the primary impact between the piston and the chisel. However the overall the power spectral density spectrum has very similar trends.

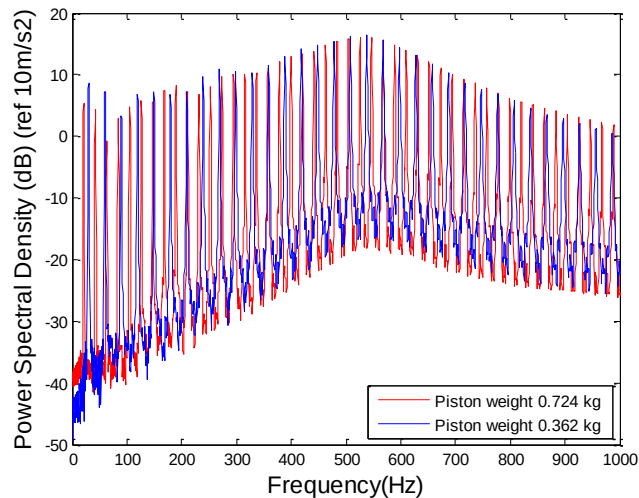


Figure 2.45: Effect of the increased piston weight on tool handle's power spectral density.

The vibration transmitted to the operator is due to the impact of the piston to the chisel. The chisel in turn impacts the tool and this is then transmitted to the operator. Thus, a potential approach to reduce the vibration to the operator is to minimize the impact between the chisel and center body. Figure 2.46 shows the effect of the increase in the chisel-center body stiffness on the tool handle's power spectral density. The impacts occur between the chisel and the

piston which thrusts the chisel into the ground. The resulting reaction forces between the ground and chisel slams the chisel back into the center body. The shock wave propagates through the center body to the handle. The vibration isolation treatment between the chisel and center body is another technique to reduce the vibration levels at the handles. This could become very significant vibration control technique for any impact hammer. A softer spring between the chisel and center body reduced the high frequency levels in the range 3-5 dB.

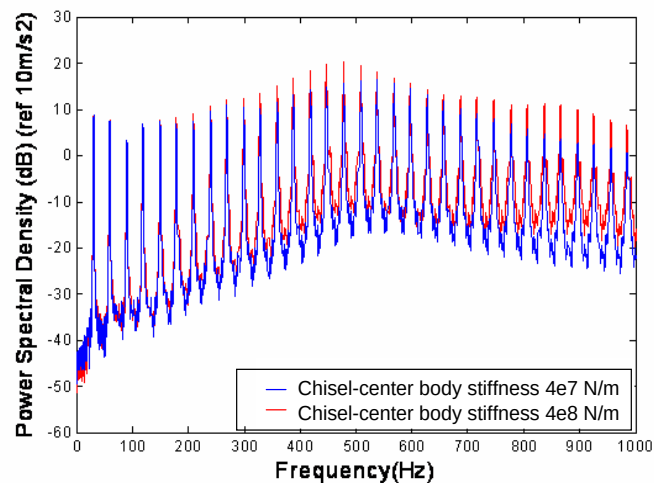


Figure 2.46: Effect of the increase in the chisel-center body stiffness on the tool handle's power spectral density

Figure 2.47 shows the application of a visco-elastic vibration isolator between the chisel and center body. The advanced vibration isolator placed between the chisel and center body will reduce the energy transferred from the chisel to the center body. Figure 2.48 illustrates the effect of the vibration absorber on the handle response. It can be seen that the absorber is very effective in the higher frequency range i.e. above 150 Hz. The vibration levels reduce in the range of 5-10 db above 150 Hz. However the peaks of the lower frequency response increase due to the isolator. The results also indicate that the passive methods of vibration control aren't effective in the lower frequency range. Some random values of mass, stiffness and damping values chosen for the an vibration isolator example were as follows,

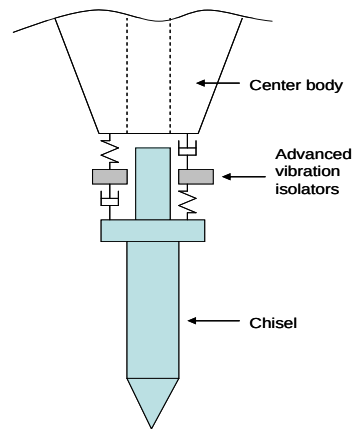


Figure 2.47: Advanced vibration isolator between the chisel and center body ($M=0.2$ kg, $K=4e2$ N/m, $C=5000$ Ns/m).

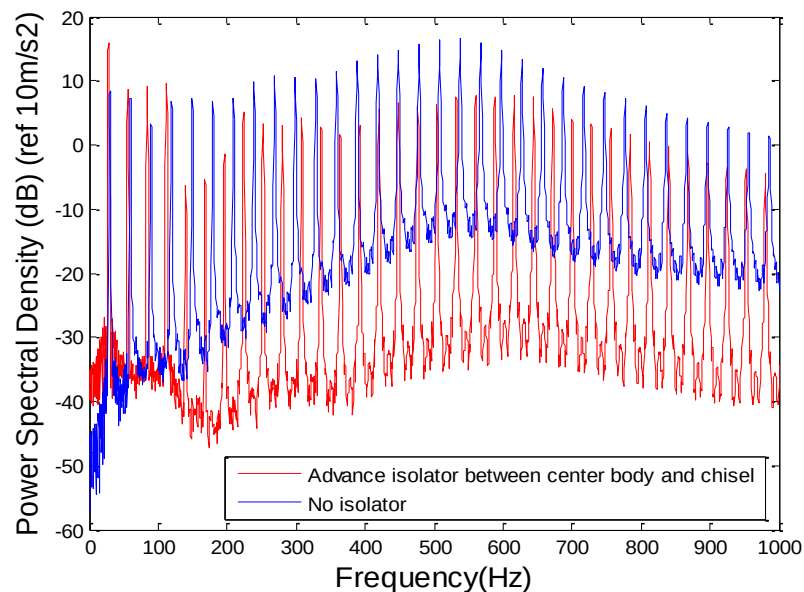


Figure 2.48: Effect of vibration absorber on the handle response.

Impact Vibration Absorber

Recent developments in vibration control using IVAs were researched and it was determined to be promising for the chipping hammer. An IVA is a simple and efficient auxiliary mass damper that employs momentum transfer between the theoretically frictionless impacting mass and the vibrating system. In addition, there is mechanical energy dissipation during the impacts that also attenuates the response of the primary vibrating system. Figure 2.49 shows the concept of the IVA. The mass (sphere) is free to move in the cavity with gap length g . By comparison to dynamic vibration absorbers, IVAs are attractive for the following reasons: (i) they can provide effective damping over a wide range of frequencies and accelerations, (ii) they have a very simple and inexpensive design, and (iii) they can operate in harsh environments.

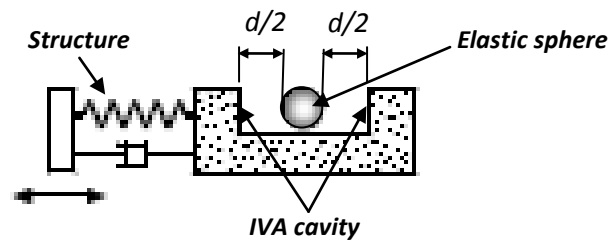


Figure 2.49: Impact vibration absorber concept.

The IVA has been successfully used in such applications as cutting tools, turbine blades, and various types of structures and structural elements. The use of vibration absorbers on machine tools has been researched by many individuals. The use of impact dampers has been found to be the most promising solution for cutting tools and most rotating machinery because their damping affects do not change with time, are resistant to chatter, and not sensitive to change in system components. Another advantage of the impact damper is that it is effective over all the natural frequencies of the various modes of a system.

To investigate the potential of the IVA device, a prototype was fabricated that allowed to test different combination of the materials for the mass (sphere), the cavity where the mass slides, and the cavity length. From this initial study, it was determined that the best combination of materials was tungsten for the mass and bronze for the cavity. Using this information a prototype IVA devices to be mounted on the chipping hammer was developed. Figure 2.50 shows the prototype device disassembled (tungsten spheres 8 mm diameter) and mounted to the chipping hammer. The device actually consisted of an array of 6 individual IVAs. The body housing the six cavities was made of bronze and fits to the tool center body. The devices also form a cavity for the exhaust jets of the tools. The gap in the device was set using bolts of predetermined lengths as shown in Figure 2.50a.

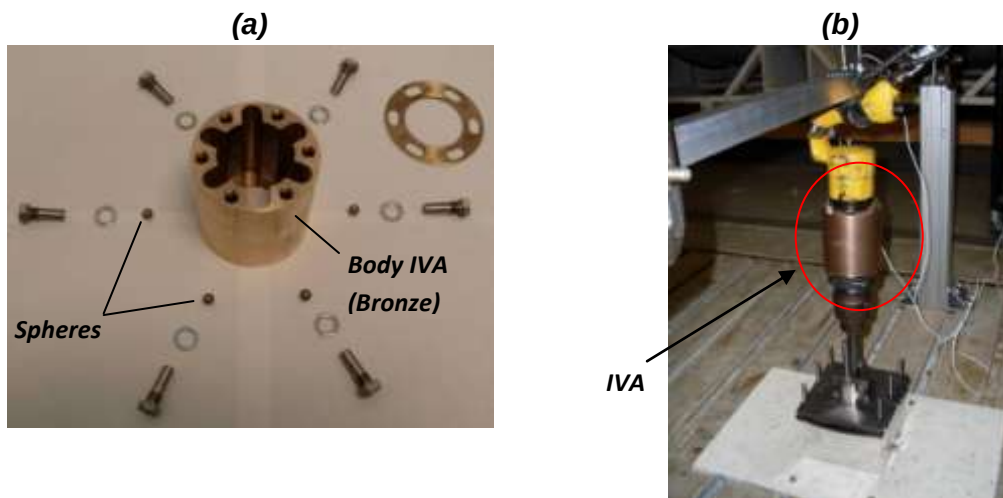


Figure 2.50: Prototype impact vibration absorber a) disassembled and b) attached to chipping hammer.

Figure 2.51 shows a typical result for the acceleration time history for the tool with and without the optimized IVA device. Note that the cavity gap length g is the main design variable and it was found to be 2 mm for this application. It is important to mention that the baseline case (tool without IVA) included the weight of the bronze IVA housing and the spheres, e.g. the baseline data was obtained by locking the spheres by setting gap $d=0$. The results show a very good peak-to-peak reduction of the impulse created by the tool as shown in the figure. It is important to note that the reduction of the impulse implies a reduction of the entire frequency component in the acceleration spectrum.

To assess the peak-to-peak reduction, a cepstrum analysis of the acceleration time data in Figure 2.51. The cepstrum is useful to quantify impulsive signals. By definition, the cepstrum of a signal is the Fourier transform of the logarithm (with unwrapped phase) of the magnitude of the Fourier transform of the signal. The independent variable of a cepstral graph is called the quefrency. The quefrency is a measure of time, though not in the sense of a signal in the time domain, and allows identifying the frequency of the impulses. For example, if the sampling rate of an audio signal is 44100 Hz and there is a sequence of impulses with 100 Hz periodicity, the cepstrum will show a large peak at $44100/100 = 441$ Hz. The amplitude of the peak will indicate the average impulse amplitude in the original signal. Figure 2.52 shows the corresponding cepstral analysis of the data in Figure 2.51. The red curve corresponds to the baseline without vibration control while the blue line corresponds to the tool with the IVA included. The cepstrum shows a dominant peak at the quefrency of 42.6 Hz that corresponds to the impulse sequence seen in the time data in Figure 2.51, e.g. signal sampled at 1024 Hz and impulse frequency of 24 Hz leads to quefrency= $1024/24=42.6$. The reduction of this peak shows a reduction of the peak-to-peak amplitude of 63 %. This clearly demonstrates the potential of the IVA as an effective control device.

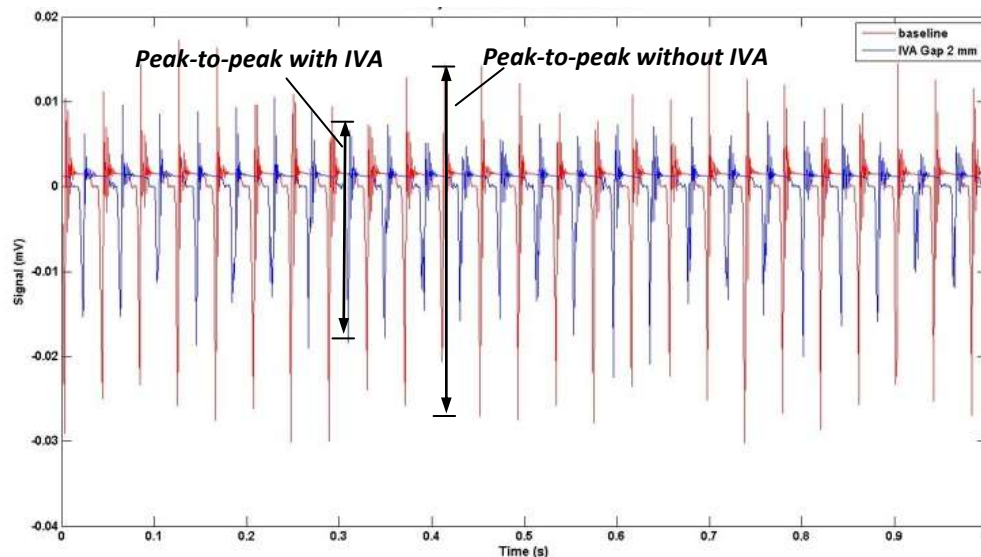


Figure 2.51: Acceleration time history of tool without (—) and with (—) optimum IVA.

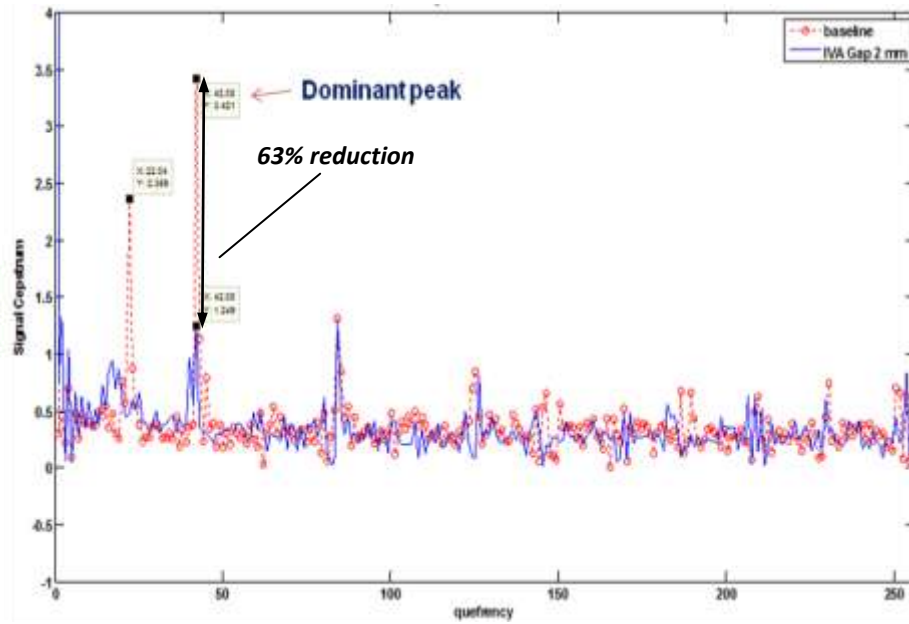


Figure 2.52: Cepstrum of acceleration time history of tool without (—) and with (—) optimum IVA..

Phase VIII: Modeling of Impact Vibration Absorber

The work performed in the previous phase demonstrated the potential of the IVA as an effective vibration control device. The literature on IVAs provides a number of design guidelines for harmonic type of input. Unfortunately, the review also revealed a lack of modeling tools that can be used to design the IVAs for impulsive loads. Thus, it was determined that there was a need to develop a model of the IVA that could potentially be incorporated into the tool model for response predictions and eventually as a design method. The modeling of the IVA presented here is new and will be briefly described.

Here the IVA is modeled as a two-degrees-of-freedom as shown in Figure 2.53. The host system has mass m_1 , damping coefficient c_1 , and stiffness k_1 . The impact mass has a mass m_2 and it is assumed to slide without friction in the cavity. The mass m_2 can traverse a maximum distance of $2d$ (gap) without contacting the walls of the cavity. The impact is modeled with a stiffness k_2 and damping coefficient c_2 . The viscous damper has been used to model the loss associated with the inelastic collision between the particle and the cavity wall. This type of loss will be discussed later where the coefficient of restitution ϵ will be introduced.

In this model, the equations of motion governing the motion of the impact mass are non-linear since the contact forces are piecewise functions, e.g. these forces vanish when the impact mass m_2 does not make contact with the cavity end walls and they are non-zero otherwise.

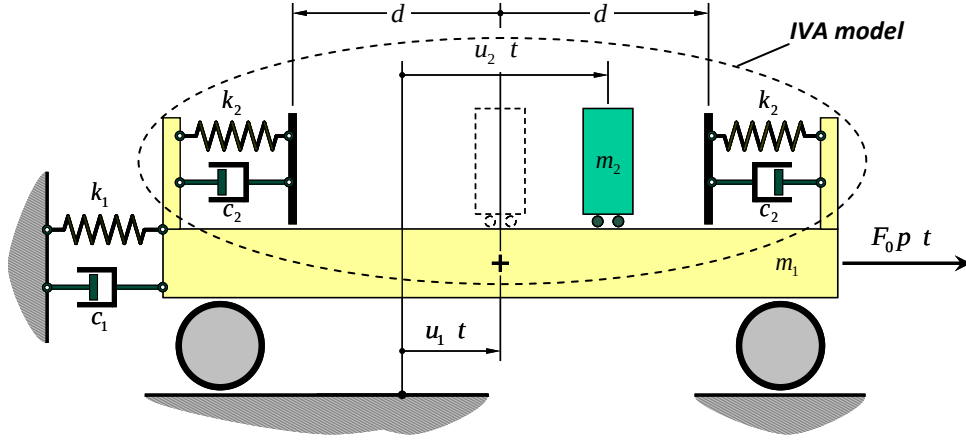


Figure 2.53: Schematic diagram of the single particle IVA damper.

The key innovative aspect of the IVA model here is the mathematical relationship between the restitution coefficient ϵ (based on the material properties of the components) and the damping coefficient c_2 . This relationship is described in more details.

Consider the frictionless impacting mass, m , that is traveling at a constant velocity v_0 , as shown in Figure 2.54a. The barrier is modeled as a spring k and viscous damper c in parallel (same as the impact of the IVA). If the impacting mass hits a stationary barrier, then after the impact, the displacement and velocity of the mass are those given by

$$x(t) = \frac{v_0 e^{-\zeta \omega_n t}}{\omega_d} \sin \omega_d t \quad (1)$$

and

$$\dot{x}(t) = v(t) = -\frac{v_0 e^{-\zeta \omega_n t}}{\sqrt{1-\zeta^2}} \sin \omega_d t - \varphi \quad (2)$$

where

$$\omega_d = \omega_n \sqrt{1-\zeta^2}, \quad \varphi = \tan^{-1} \frac{\sqrt{1-\zeta^2}}{\zeta}, \quad \zeta = \frac{c}{2\omega_n m} \quad (3)$$

These results are used to determine the coefficient of restitution of the system and the amount of energy that has been dissipated until the time the impacting mass is no longer in contact with the barrier.

The impacting mass is in contact with the barrier only while the sum of the forces

$$kx(t) + c\dot{x}(t) > 0 \quad (4)$$

that is, while the spring-damper combination is being compressed. At the instant when they are no longer in compression the acceleration is zero, e.g. $kx(t) + c\dot{x}(t) = 0$. The first time instance at which the acceleration is zero is given by

$$\omega_d t_{vm} = 2\varphi + p\pi, \quad p = 0, 1, 2, \dots \quad (5)$$

for $p = 0$, and the corresponding velocity is given by

$$\dot{x} t_{vm} = -1^{p+1} v_0 e^{-2\varphi + p\pi / \tan \varphi}, \quad p = 0, 1, 2, \dots \quad (6)$$

Based on Newton's law of impact, the coefficient of restitution ε is defined as

$$\varepsilon = \frac{-v_{\text{impacting mass}} - v_{\text{barrier}}}{v_{\text{impacting mass}} - v_{\text{barrier}}} \bigg|_{\text{after impact}} = \frac{v_{\text{impacting mass}}}{v_{\text{impacting mass}}} \bigg|_{\text{after impact}} \quad (7)$$

where $v_{\text{impacting mass}}$ is the impacting mass velocity, v_{barrier} is the velocity of the barrier, and the assumption that v_{barrier} is zero has been used, e.g. the barrier is fixed. The restitution coefficient is computed from the material parameters.

Then, making use of eq.(6) and (7) with $p = 0$, we find that

$$\varepsilon = \frac{-\dot{x} t_{vm}}{\dot{x} 0} = \frac{v_0 e^{-2\varphi / \tan \varphi}}{v_0} = e^{-2\varphi / \tan \varphi} \quad (8)$$

that relates the coefficient of restitution ε to the damping c using eq.(3). It is interesting to make use of eq.(8) to examine the behavior of the coefficient of restitution ε in terms of the damping factor ζ . Considering first the undamped case, we note from eq.(8) that $\varphi / \tan \varphi \rightarrow 0$ as $\zeta \rightarrow 0$ and, therefore, $\varepsilon \rightarrow 1$. In other words, there are no losses and the system leaves with the same velocity with which it arrived. This is consistent with the fact that this is an elastic collision. On the other hand, when $\zeta \rightarrow 1$ (critically damped) leads to $\varphi / \tan \varphi \rightarrow 1$ and, therefore, from eq.(8) we find that $\varepsilon \rightarrow e^{-2}$. That is, the impacting mass leaves the barrier with a velocity of $0.135v_0$.

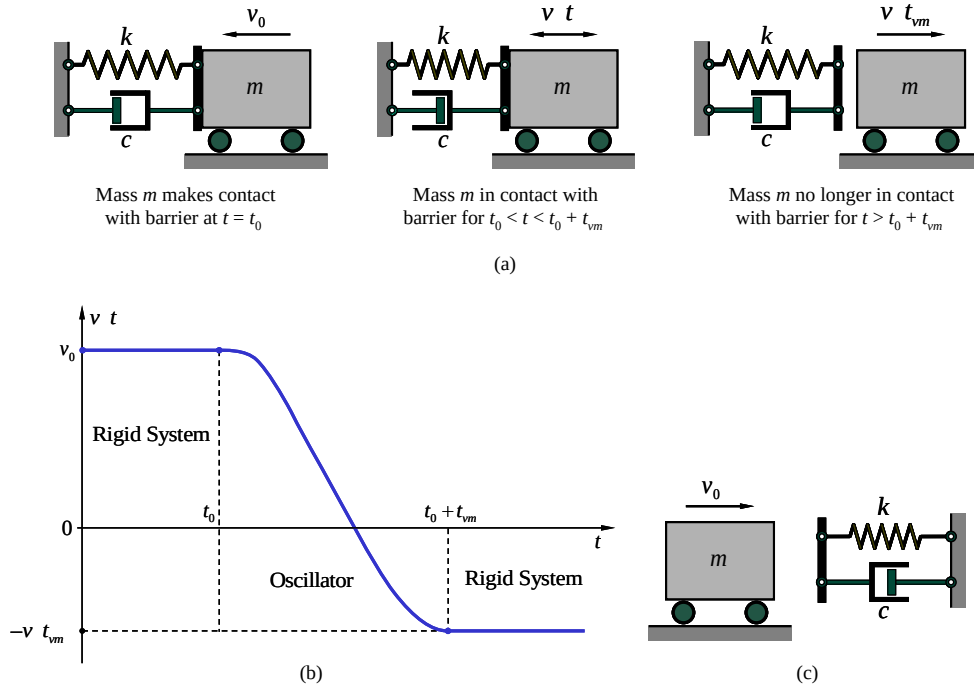


Figure 2.54: (a) Model of a frictionless impacting mass colliding with a stationary barrier; (b) time history of velocity of mass; and (c) equivalent impact configuration. In this equivalent

configuration, a mass moving with a velocity v_0 , impacts a barrier, which is represented by a spring and damper combination.

The amount of energy that the system dissipates during the interval $0 \leq t \leq t_{vm}$, is the difference between the initial kinetic energy and the kinetic energy at separation. Note that here we consider that the impacting mass does not have any potential energy when it is not in contact with the barrier. Thus,

$$E_{\text{diss}} = \frac{1}{2}mv_0^2 - \frac{1}{2}m\left[\dot{x} \big|_{t_{vm}}\right]^2 = \frac{1}{2}mv_0^2 - \frac{1}{2}mv_0^2 e^{-4\varphi/\tan\varphi} \quad (9)$$

or

$$\frac{E_{\text{diss}}}{E_{\text{init}}} = \left[1 - e^{-4\varphi/\tan\varphi}\right] \quad (10)$$

where $E_{\text{init}} = mv_0^2/2$. It must be noted that these results have been obtained for a collision with a single impact.

Numerical simulations were performed using the model for the IVA developed to illustrate the potential of the tool. To this end, a simple axial model was developed using finite elements as shown in Figure 2.55. This model could be a simple representation of the chipping hammer and the input is the imposed acceleration at the base in the form of impulses as shown in Figure 2.56. The displacement response of the end of the tool (n^{th} dof) with and without the IVA is shown in Figure 2.57. It shows the same trends as found in the experiments, e.g. the IVA reduces the impulses for a given gap. In the example shown in Figure 2.57, the reduction is approximately of 25%. This result demonstrates that the model can be used in the future as a design tool to implement IVAs. It will require incorporating an optimization routine to find the optimum impact mass and gap.

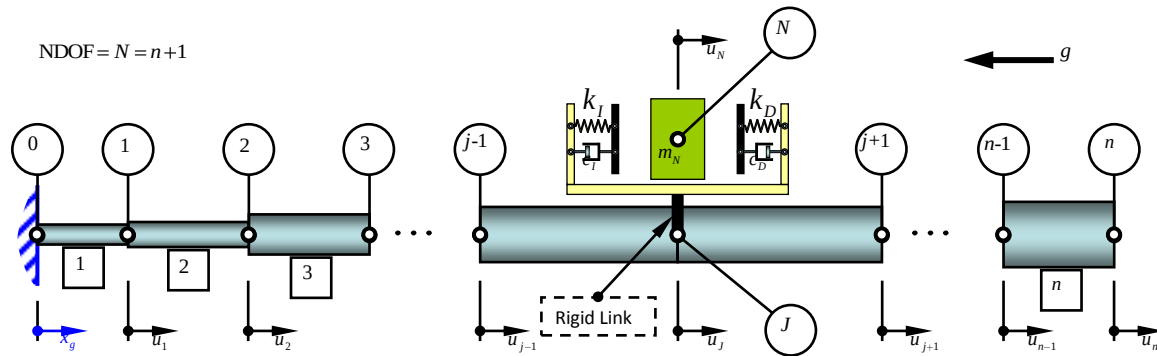


Figure 2.55: Simple axial model to demonstrate IVA modeling.

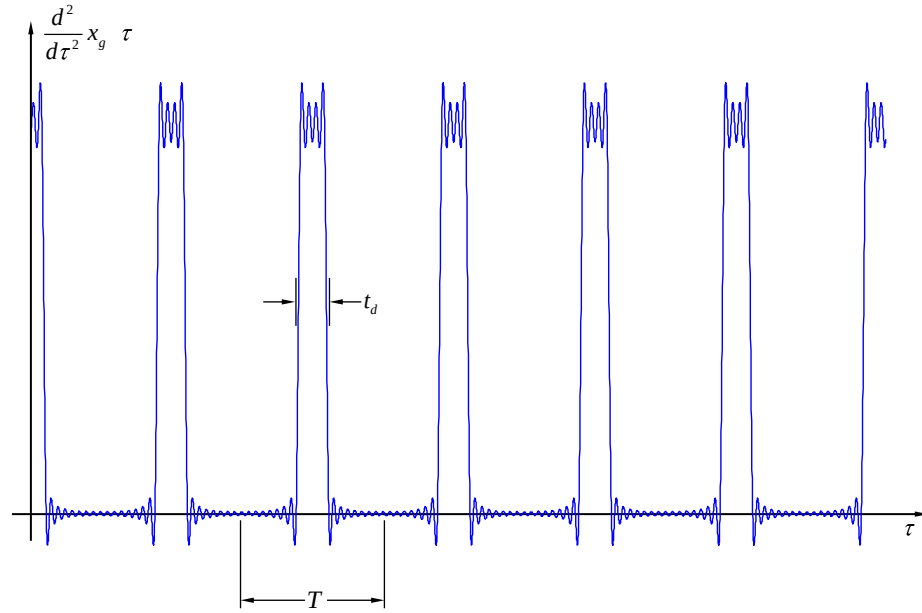


Figure 2.56: Input to the system as an imposed acceleration to the fixed end of the tool.

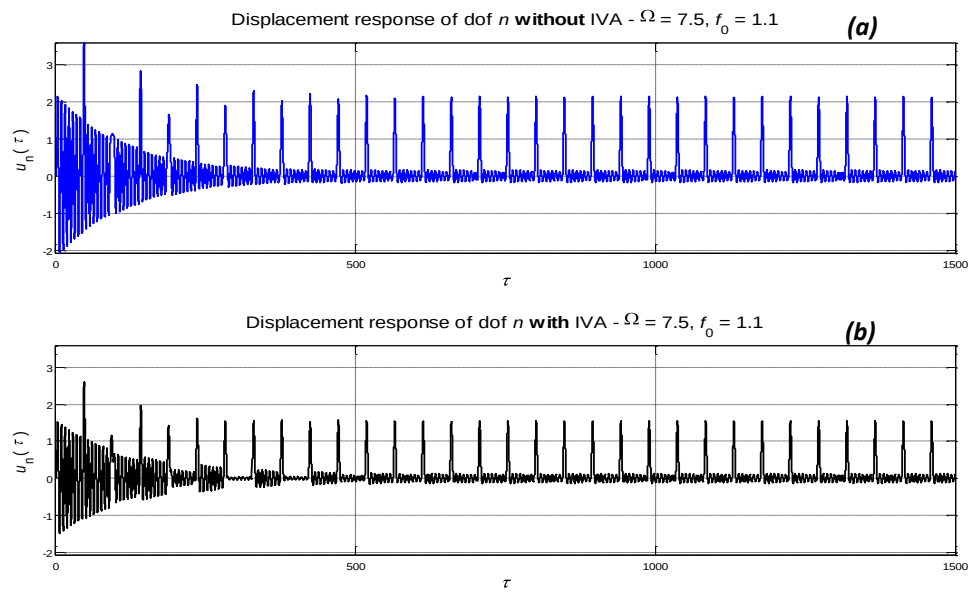


Figure 2.57: Displacement response of the n^{th} dof (a) without and (b) with IVA.

Materials Available for Other Investigators

The software for the modeling of the pneumatic tool is available. Noise and vibration data is also available. Please contact the PI to access the data and software (limited to research purposes only).

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4.DECISION SUPPORT TOOL FOR ERGONOMIC CONSTRUCTION DESIGN

(Nussbaum and Shewchuk) September 15, 2004 – September 30, 2009

Abstract

Prior funding, part of the current Virginia Tech Center for Innovation in Construction Safety and Health, was used to develop a prototype Decision Support System (DSS). Our DSS provides designers with a first-cut evaluative tool for mitigating ergonomic hazards at the design stage (i.e., “Prevention through Design” or PtD). Specific application is to residential construction using panelized (prefabricated) walls to take advantage of the centralized (panel) design involved. Major activities involved health effects and intervention research.

Work-related musculoskeletal disorders (WMSDs) are prevalent among residential construction workers; our long-term goal is to reduce these disorders, particularly those related to the handling of panelized walls. Such walls are used increasingly in residential construction, but are large and difficult to handle and result in high exposures to WMSD risk factors. Our work addresses the need for improved PtD, specifically by providing a software system that can be used by the panel designer or others (e.g., contractor). As such, changes at the design stage in the construction life cycle can positively affect a large number of construction sites and workers. Our multidisciplinary approach included both ergonomics and production issues as fundamental components, and both are improved through use of the system. It thereby addressed the need to support the economic/business case for PtD and increases the likelihood that the system will actually be used. The system also supports the development and assessment of interventions to reduce ergonomic exposures and risks.

We conducted several phases of work involving a combination of field measures and surveys, task analyses, software development, and lab-based ergonomic assessments. We surveyed and interviewed several designers, primarily regarding their practices, knowledge of ergonomics, and potential barriers to incorporating ergonomics in their designs. In parallel, a taxonomic description of construction using panels was developed, along with detailed task identification and work sampling efforts, based on extensive field observations. To complete this preliminary work, we surveyed construction workers who use panels and identified from them the most physically demanding tasks and body parts stressed. Using the results obtained from the designers, the field observations, and workers, we designed and completed a lab-based study. In this study, participants completed recreated tasks involving panelized walls, and we undertook a detailed assessment of ergonomic exposures and risk. We developed heuristic algorithms for panelization (dividing walls into panels) and stacking (how panels are formed into stacks, when each stack is delivered to the job site, and where they are dropped off), as well as various decision rules to be used by the workers for construction planning (what tasks to use, who does what and when, etc.). We also explored mathematical modeling for the stacking problem and developed several math models. An object-oriented, discrete-event simulator for panelized residential construction has been developed, as has a utility for generating 3D animations of the resulting construction process.

We concluded that there are clear inherent barriers to PtD in panelized construction and that tools are needed to help designers appreciate and address the consequences of their design. The lab study provided the first formal ergonomic investigation and evaluation of

manual tasks used during construction with panelized walls. Our prototype software tool is the first to consider ergonomic aspects in addressing the panelization, stacking, and construction planning problems, and does so in an integrative manner. Initial reviews by potential users (designers and builders) have been quite favorable. Subsequent work is planned to: 1) improve and evaluate the DSS, 2) facilitate its implementation, and 3) conduct a field assessment of effectiveness.

Section 1: Decision Support Tool for Ergonomic Construction Design

Highlights/Significant Findings

Our first step was to understand better our end user, who initially is the residential construction designer (in particular, the panel designer). We completed an investigation into the practices, knowledge regarding ergonomics, and potential barriers to incorporating ergonomics in design among a sample of panel designers. Designers reported having little knowledge about ergonomics or about the potential impact of their designs on construction workers. As a whole, they were neutral or slightly resistant to incorporating ergonomics into their designs, primarily because of a perceived lack of responsibility for worker health, limited potential influence, and an anticipation of increased workload and costs and decreased flexibility. They were also neutral to slightly negative regarding the feasibility of including ergonomics into their designs, yet most agreed on the necessity to reduce health and safety risks. Our results also indicated that PtD tools (software) must accommodate or address current design practices. Standards of practice and key inputs in decision-making were incorporated into our subsequent software development.

A task analysis was completed through field observations of home building sites. The panel erection process could be comprehensively represented by four fundamental tasks and 10 supplemental tasks. Work sampling was performed on 1,443 manual handling tasks to facilitate identification of ergonomics exposures and to guide lab-based analysis and software simulations. Eighteen workers responded to questionnaire regarding their work with wall panels; results indicated the tasks perceived as most difficult and demanding, body parts at greatest injury risk, and panel aspects most influencing physical demands. Experimental participants completed task recreations in a laboratory. From these, detailed measures of exposures were obtained, as well as ergonomic risk assessments (the latter using a suite of tools). These results, along with fundamental information on the effects of important task variables (i.e., panel size, panel mass, use of an additional workers, and task type), were used to create an “exposure and risk” database within the DSS. While effects of task parameters were generally unsurprising (e.g., heavier panels results in higher exposures and risks), the measured effects of an additional worker were less intuitive and supported the need for a more comprehensive system to analyze design impacts.

The overall design and planning process for panelized residential construction was divided into three closely related problems: panelization, stacking, and construction planning. Panelization consists of breaking up walls into discrete panels, and incorporates several user-set parameters. Stacking refers to groups of panels that are bundled and delivered to the work site. Construction planning involves determining which panels are worked on, how, and by which workers. Our approach to the last problem is to develop one or more construction rules that can be employed in the field to achieve specified goals (e.g., minimize ergonomic risks). Software, including several novel algorithms, has been developed to address these three problems; our approach stems from several fundamental principles, many of which are based on concepts derived from lean manufacturing.

A variety of software applications and programs were developed and implemented. Ergonomic risks for a given design are obtained from a combination of task simulations and use of the aforementioned database. A 3D simulation animation of the construction process is

provided to the user. Several construction designers and builders have reviewed our prototype system. All indicated a high level of interest and the approach was seen as feasible and as a method to gain both greater efficiency and safety.

Translation of Findings

Our results support several specific recommendations and general guidance to prevent workplace injury in residential construction (and beyond).

- Similar to the case for “design for safety”, there are inherent barriers to the use of prevention-through-design (PtD) to reduce ergonomic exposure in residential construction. PtD tools (software) must accommodate or address current design practices.
- The effects of major panel design parameters on physical exposures and risks are quite complex, often with opposing influences on ergonomic and productivity aspects. This emphasizes the need, in such complex work situations, for a system that can collectively consider physical demands and productivity and that allows users to assess the tradeoffs involved.
- Use of task-based analyses, as conducted here, are an efficient and likely effective approach to achieving PtD in complex work situations such as residential construction.
- Integration of traditional engineering concepts (simulation, lean, dispatching rules, etc.) can be effective in achieving PtD in residential construction.
- PtD approaches that jointly consider ergonomic and productivity aspects of a design, and can reasonably quantify each, are likely to be well received in the construction industry.

Outcomes/Relevance/Impact

Findings from the present work offer several areas of guidance for future investigations and research, both to continue a process to improve panelized wall construction and more generally to achieve PtD in this sector and others.

- The core of our approach – a simulation of complex tasks comprising a job together with task-based ergonomics assessments and heuristics to facilitate decision making – should be considered as an approach for other jobs and/or sectors. Such an approach should be applicable wherever there is (or could be) a central design effort, and has the potential for substantial “downstream” positive effects.
- Our work has identified several gaps in the area of ergonomic risk assessment. Specifically, future work is needed to facilitate both interpolation and extrapolation of risks associated with discrete, measured tasks, in order to allow for estimations to be generated for a wider range of tasks (i.e., to obviate the need for extensive data collection). Future work is also needed to provide both conceptual and concrete approaches to: 1) compiling ergonomic assessments either across different types of exposures and body regions, or across multiple workers, and 2) including time-dependent effects of exposures (e.g., related to task sequencing or fatigue).

- Subsequent investigation should assess the use of such decision support tools: 1) for training and education; 2) to identify safety (in addition to ergonomic) concerns; 3) as a method to specify worker accommodations.
- Use of simple construction rules, provided to workers and similar to dispatching rules in manufacturing, may be a useful adjunct to traditional intervention approaches.

Section 2: Decision Support Tool for Ergonomic Construction Design

SCIENTIFIC REPORT

1. Background

Overview. Our primary motivation in conducting this project was to reduce the prevalence of occupational injuries and illness among residential construction workers. Occupational injury rates are high in construction compared to the general workforce. In 2002, over 417,700 non-fatal workplace injuries and illnesses were reported in the construction industry (BLS, 2004). Approximately 10% of these injuries and illnesses were attributed to overexertion and repeated trauma. A total of 3,300 lost workday cases were reported, with a median of 10 days away from work, highlighting the substantial costs associated with these injuries. The majority of injuries relating to overexertion have to do with lifting, pushing, pulling, and other manual materials handling activities. As with other statistics of this nature, it is suspected that these numbers are an underestimation of actual incidence rates.

As highlighted by Dement and Lipscomb (1999), although BLS data (as cited above) is the most common source of construction-related injury statistics, it does not capture differences that exist between residential construction (the focus of our project) and other construction sectors. In their analysis of workers' compensation claims specifically for residential construction in North Carolina, these same authors clearly indicate the extent of the problem we will address. An overall relatively high rate of cases was found (16.4 per 200,000 hours) for a seven-year period ending in 1994, with no obvious increasing or decreasing trend. When examined by the nature of injury, muscle strain was identified most frequently among all other mechanisms, and except for minor injuries, the back and shoulders were by far the most frequent sites of injury. When examined by construction trade or skill, carpenters had the highest number of cases, and were among groups with the highest rates. Although limited to a single state, it is reasonable to assume that these data apply across the country as well. On the basis of this evidence, we argue that new methods are needed to address non-fatal occupational injuries among carpenters in residential construction.

Current Approaches to Safety and Ergonomics in Construction

Prevention of fatal and non-fatal injuries in construction is more difficult than in many other industries. Nevertheless progress has been made in recent years, particularly in large construction organizations. Many books have been published that address safety planning and provide practical strategies for preventing accidents and injuries (e.g. MacCollum, 1995; Levitt and Samuelson, 1993, Hinze, 1997, and Goetsch, 2003). Other authors suggest that safety planning is important as part of the construction planning process. Sweeney et al. (2000) advocated a hierarchy of injury control strategies for injury prevention in construction safety. The first step in the hierarchy involves eliminating the hazard through changes in work practice, substitution, or redesign. The problem is that few tools exist for undertaking this first step. Traditional approaches involve introducing a safety program in the construction company. These programs involve establishing responsibility in the construction organization, developing a project safety program, observing OSHA regulations, analyzing hazards, having safety

meetings, establishing substance abuse programs, emergency plans and accident reporting systems (Hinze, 1997). These traditional programs generally consider construction safety as a site-based problem, and give little consideration to changes in the design of the constructed facility or hazard limitation through changes in the design of the construction process. The problems faced become more substantial as the size of the construction organization diminishes. Hinze (1997) notes the penchant the construction industry has for shedding risk and avoiding liability. The owner tries to move the liability (usually through written clauses in the contract) to the contractor, the contractor tries to move liability to the subcontractor, and so on.

At present, residential construction is a craft-based enterprise driven by a design, but disconnected from the actual method of assembly and its impact on the human worker. Modern designers are typically removed from most onsite production activity and rely heavily on a distribution of subcontractor construction and installation knowledge associated with the various systems that make up a house. These subcontractors are provided with little or no guidance on acceptable construction methods associated with the design, other than material specifications and schedule expectations. This process of construction, from design to occupancy, has been extensively documented in research undertaken by one of the co-PIs (Wakefield), for the US Department of Housing and Urban Development study: *Industrializing the Residential Construction Site* Phase I (O'Brien et al., 2000), Phase II (Wakefield et al., 2001) and Phase III (O'Brien et al., 2002). Results of this study confirm the link between onsite assembly errors and the lack of adequate design information related to the new construction processes. Generally, in the design stage, no consideration is given to the effects of panel (prefabricated walls) design on the construction process or the on-site labor (O'Brien et al., 2002). This example is representative of the residential construction process in general, where fragmentation and sub-optimization is the rule, and process design and integration are rarely considered. The result of this experience is that work crews are left to their own devices in terms of designing a construction process for panel erection. This situation ultimately results in an increased exposure to hazard and injury.

What is missing from the residential construction industry are evaluative tools for mitigating ergonomic hazards at the design stage. By empowering designers with construction process information, including ergonomic evaluations, their initial design choices should promote more optimized production and a safer work environment.

Panelization

Construction work, and the design activities that lead to it, are obviously quite diverse and dependent on the specifics of the end product and tools and materials being employed. Given the novelty of our approach, and our explicit goal of demonstrating the worth of the approach, we have chosen to focus implementation on an assessment of construction using panelized walls.

The term 'panelized', or panelization, refers to one example of the current trend in construction towards increasing use of premanufactured components. Panelized walls, in particular, are in contrast to more traditional 'stick built' walls. The latter involves the familiar process of assembling and erecting walls starting from relatively raw lumber (e.g. two-by-fours). Panelized walls, in contrast, arrive at the work site more completely assembled. The designer

can specify a number of different levels of pre-assembly, with common alternatives including wood-only (e.g. studs, footers, and headers, Figure 1.1), sheathed (Figure 1.2), or complete (with sheathing, conduit, insulation, etc.). A carpentry crew carries and erects the panels at required locations on the site (Figure 1.2). The panels can be heavy, large, and difficult to maneuver (Figure 1.2). While the work of framing crews has substantially changed due to the change in the construction process, the potential improvements in ergonomic design resulting from this change have not and cannot at present be easily considered or realized.



Figure 1.1: Workers remove wall panels from delivery pallet (left) and position panel at installation point (right).



Figure 1.2: Workers lift a sheathed panel from a pallet (left) and into a vertical orientation (right).

Previous work (Wakefield et al., 2001) documented the present and fairly rapid shift among residential production builders from traditional lumber stick built construction to a panelized form of construction. Panelization is also representative of other premanufactured construction materials, in that it tends to be a post-design activity undertaken by a specialty subcontractor who ultimately provides fabrication and delivery services to a site erection subcontractor. This current trend toward panelization within the housing industry provides an excellent opportunity

to develop an ergonomic analysis tool that can inform designers, improve efficiency, and promote safety, since the centralized designer can impact a large number of construction sites.

Use of Existing Manufacturing Methods

The panelization design and construction planning problems are analogous to the product design and process planning problems in manufacturing. These manufacturing problems have been investigated at length and successful solution methods are well established.

Consequently, we aim to transfer these manufacturing methods to the construction industry to the extent possible. Design-for-manufacture/assembly (DFM/A, e.g., Boothroyd et al., 2001) has been used for many years to design products such that they will be easy to fabricate and/or assemble. In most instances, the anticipated fabrication and assembly processes are manual. Typically, a set of DFM/A “rules” are invoked during product design, and used to guide the design process. In a similar manner, we envision developing a set of “design-for-construction” (DFC) rules for prefabricated wall construction, making the construction process safer. Computer-automated process planning (CAPP, e.g., Chang and Wysk, 1984) has been available to automatically generate process plans in specific manufacturing applications since the mid-1980s. One CAPP approach which is well suited to construction planning is generative process planning (GPP). In GPP, a set of sequential decision rules is developed for generating process plans automatically, based upon the product drawing. Similarly, we envision developing a rule-based and sequential decision logic for generating construction plans from panelization designs.

While the goal is to employ these proven manufacturing techniques in the construction industry directly, it is likely that additional modeling and solution methods may be necessary. Both the panelization design and construction planning problems can be modeled as discrete optimization problems, allowing the use of standard operations research (OR) techniques. Such techniques include both optimal methods (e.g., dynamic programming) and heuristics (e.g., search methods, genetic algorithms). The use of OR techniques to solve problems involving assignment, allocation, scheduling and sequencing, etc., is well-documented in both manufacturing and service industries (e.g., Askin and Standridge, 1993). While the use of such techniques to-date in the construction industry is limited, there is no inherent reason why such techniques cannot be successfully applied.

In order to successfully employ OR techniques in the construction industry, it is necessary to quantify the human element. One available approach is to simulate the human operator (or worker), in particular their behaviors, associated task demands, and resulting ergonomic exposures. Simulation, as opposed to direct measurement in the field or laboratory, has clear benefits in terms of efficiency and economy. A critical limitation towards this end has been the prediction of human postures and motions (the former addressing a static instance of the latter, or temporal sequence). As posture and motions have a major influence on both physical demands and worker capacity, accurate estimation is essential towards ergonomic exposure assessment. Numerous approaches towards posture/motion prediction have been and are being examined, including control theory, optimization, neural networks, etc. Despite this, few approaches have been quantitatively evaluated, while those that have, have failed to generate reasonable levels of accuracy except under limited circumstances.

A number of commercial packages are also available, some of which incorporate ergonomic evaluation tools along with human simulation and animation (e.g. Delmia, 2004; EDS, 2004; Human Solutions, 2004). These systems also contain virtual environments in which designers can develop and test prototypes. All contain posture prediction algorithms, but again quantitative evaluation is essentially non-existent (and the algorithms are proprietary, discouraging independent evaluation). We suggest that this questionable empirical validity is one reason to avoid the use of existing commercial packages (and published algorithms), and argue below that more direct measurement is required. A second reason is simply that commercial packages (or implementation of published algorithms) are cost-prohibitive. With site licenses on the order of tens of thousands of dollars, and multiple days of required training to become proficient, it is unlikely that these existing methods will receive widespread adoption in the near future, particularly for construction designers who have insufficient resources for such tools. Based upon these facts, laboratory and field studies were used in this research, rather than simulation, to model, analyze, and quantify the human element. This was expected to help us provide a decision support tool that is both highly usable and low in cost.

Simulation has an alternative use, however, which is of keen interest for this research. This is the use of simulation and high-quality graphics to provide a “simulation animation” of a process, for the purpose of aiding in process visualization. Many high-end simulation packages are available (e.g., QUEST, Delmia Corporation) which offer this capability, and the use of simulation for this purpose is well established in manufacturing (Shewchuk et al., 2002). To this extent, we incorporated the use of simulation animation to aid the construction designer, manager, and others in visualizing how a given construction plan would be realized in the field. This not only improves understanding of the process, but aids in subsequent evaluation and decision-making.

A final comment concerns the existing availability of software analysis tools. Such tools exist for ergonomic assessment (e.g. ErgoIntelligence™, NexGen Ergonomics Inc.), but require actual tasks or mockups in order to perform analysis, and are not extendable to include new developments in assessment tools. Software also exists to assist with safety analyses in construction design (e.g. Design for Construction Safety Toolbox, Construction Industry Institute®), though ergonomic issues are not addressed, and again the tools are not extendable. While both types of existing tools are reasonable in terms of cost, and require only modest training for use, for the reasons noted we believed that they were still unlikely solutions towards our long-term goals described below.

Long-term Goals

As previously discussed, there has been considerable use of decision science and OR techniques in the manufacturing sector. In particular, DFM/A and CAPP methods have been successfully used for product design and process planning, activities that mirror panelization design and construction planning in prefabricated wall construction. Additionally, simulation animation has been used in both manufacturing and service industries to aid in process understanding and decision-making. With the ergonomic analysis and assessment tools and techniques now available, great potential exists to take these proven approaches and successfully transfer them to the labor-intensive manual construction industry. Our long-term goal is to foster the development of computer-based tools for implementing such approaches in

the residential construction industry, to improve worker health, safety, and effectiveness. To this end, the development, implementation, and evaluation of a decision support tool for residential prefabricated wall construction process can serve as the exemplar of the wider construction field and its processes. After completion of this project, the tool can be expanded in the future to encompass a wider variety of construction tasks, number of design options, and incorporate emerging ergonomic assessment technologies.

Summary

Epidemiological evidence highlights the large and ongoing problem of occupational injury and illness in residential construction. We have argued that current approaches to safety, in general, are often haphazard or poorly organized for the small-sized contractors who perform the majority of residential home building. There is an increasing trend toward premanufacturing, specifically panelization. This 'centralization' of design provides an opportunity to promote ergonomics in the design process, a pro-active approach that is likely to be more effective than traditional re-active efforts at the job site. A body of evidence exists for similar approaches in manufacturing, and took advantage of this, as well as the diverse expertise represented in the project investigators, to develop a decision support tool for construction designers.

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2. Specific Aims

The design phase of constructed facilities has traditionally centered on developing a model of the final product (the facility), with little emphasis on the construction process. The construction industry is moving towards using more industrialized methods, including more prefabrication. In many ways this shift parallels the move to concurrent engineering in other areas of product manufacturing. At present, design of prefabricated assemblies for use in residential construction takes little or no account of the ergonomics of how the assemblies will be erected in the field. Design and development of the construction processes are the responsibility of field construction crews, who are often ill-equipped to perform such tasks. This approach results in field construction procedures that are ad-hoc and place workers at risk from a health and safety perspective. The approach also fails to take full advantage of the benefits offered by prefabrication from a cost and quality approach. Existing evidence suggests that among large construction firms, the majority (~75%) believe that safety is not considered in design or only occasionally considered. The percentage is likely higher for smaller construction firms who, generally, have fewer resources for safety, and for issues related to ergonomics (though no formal studies have been conducted).

This project developed a prototype computerized support tool for rapid and effective ergonomic evaluations, integrated in the design phase of a residential construction project. No comparable, inexpensive, alternative is currently available that is feasible for residential construction design. By addressing ergonomic exposures at the design stage, rather than the traditional reactive approach, long-term success towards reducing the high prevalence of musculoskeletal injuries in residential construction should be maximized. Following initial development of the tool, a limited scale application was conducted for prefabricated (panelized) wall assembly in residential home construction as a demonstration of proof-of-concept. Our overall approach was to use computer-based methods to: 1) generate panelization designs (prefabricated panel types and sizes to employ, panel arrangement, etc.), 2) construction plans (construction sequence, lift and handling methods, etc.), and 3) provide the designer concurrent ergonomic analyses of the impacts of their designs on workers and productivity. The computerized decision support tool we developed to achieve this will employ decisional science and operations research techniques, database methods, ergonomic tools, and simulation. Using a database approach provides important efficiencies in that the data can be reused any number of times to provide accurate assessments of ergonomic exposures. These assessments can be generated automatically for the user. The tool also provides a framework for ensuring that construction worker health and safety is considered at the design stage of the construction project, thus promoting safe field construction.

Through this project, software has been created for construction designers to generate alternative panelization designs and construction plans rapidly and inexpensively. The approach used will allow designers to quantitatively establish and evaluate the ergonomic consequences associated with these alternatives. This project was focused on technology development and application to facilitate safe design. In the process of developing the technology, we also determined current attitudes and opinions of construction designers towards ergonomics, and conducted a formal ergonomic assessment of common tasks in residential construction (fabrication and erection of walls).

3. Input from End Users

Our first step was to understand better our end user, who initially is the residential construction designer (in particular, the panel designer). This was not to ignore the on-site construction workers, as their health and safety is our end goal. We completed an investigation into the practices, knowledge regarding ergonomics, and potential barriers to incorporating ergonomics in design among a sample of panel designers in the eastern U.S. (11 companies, 12 designers). They reported having little knowledge about ergonomics or about the potential impact of panel designs on construction workers. As a whole, they were neutral or slightly resistant to incorporating ergonomics into their designs, primarily because of a perceived lack of responsibility for worker health, limited potential influence, and an anticipation of increased workload and costs and decreased flexibility. They were also neutral to slightly negative regarding the feasibility of including ergonomics into their designs, yet most agreed on the necessity to reduce health and safety risks.

From this study, we concluded that the situation with respect to designing for ergonomics is similar to earlier evidence regarding designing for safety. Simply, there are inherent barriers to the use of prevention-through-design (PtD) to reduce ergonomic exposures in panelized construction design. Our results also suggested that PtD tools (software) must accommodate or address current design practices. Panel designers indicated that transportation and stacking issues had important influences on decision-making, whereas panel weight and crew size were of low importance. The latter two have consequences for ergonomic exposures. Panel manufacturers also have standard panel dimensions that are based on such factors as shipping costs, trucking capacity, and available lumber dimensions. These standards were incorporated into our subsequent software development.

Kim S, Seol H, Ikuma LH, Nussbaum MA: [2008] Knowledge and opinions of designers of industrialized wall panels regarding incorporating ergonomics in design. International Journal of Industrial Ergonomics 38: 150-157

Abstract

As residential construction moves towards industrialized construction methods, ergonomic exposures of construction workers may increase due to heavier components and changes in construction activities. Ergonomic considerations early in the design stages are expected to have the most impact, provided that designers are aware of ergonomic risks and are willing to incorporate ergonomic principles into designs. To determine current knowledge and opinions regarding ergonomics in the context of one commonly used industrialized construction method (prefabricated wall panels), 12 panel designers completed a questionnaire, and seven of those designers participated in a semi-structured interview. Results showed that panel designers generally have little knowledge about the influence of panel designs on workers' ergonomic risks. Panel designers were neutral or slightly resistant to incorporating ergonomics into designs, due to perceptions of lack of responsibility and influence over workers' long-term health. Though the participants acknowledged the necessity of ergonomics in panel design, they were concerned with the possibilities of increased workload, costs, and decreased design flexibility. To advance the incorporation of ergonomics in panel design, panel designers need to recognize the potential ergonomic impact of their panel wall system designs. Current research

represents an initial step in creating support tools for use in designing wall panel plans that decrease the risk of work-related injuries and illnesses in construction workers.

Relevance to Industry: Understanding the background knowledge and opinions of panel designers regarding ergonomics in construction is necessary to develop successful design support tools that incorporate ergonomic principles into panel design.

Introduction

Residential building construction is the seventh largest U.S. industry representing approximately 4% of the nation's annual economic activity (NAHB Research Center, 2002), but it is also characterized by a high number of occupational injuries. Residential construction workers sustain disproportionately higher fatalities and non-fatal injuries compared to other employees. While residential construction workers make up 0.83% of the US workforce, they account for 2% of the total work-related fatalities and 0.97% of the total non-fatal work-related injuries (BLS, 2004a; BLS, 2004b). In 2004, there were 38,900 non-fatal injuries reported, with an incidence rate of 5.0 (per 100 full-time workers) compared to 4.5 for all US employees (BLS, 2004b). The actual incidence rate and severity of occupational injuries in residential building construction may be higher due to under-reporting of minor injuries or company-paid cases (Glazner et al., 1998; Morse et al., 2005; Morse et al., 2001), as well as the lack of injury data specific to residential building construction (Dement and Lipscomb, 1999; Methner et al., 2000). Occupational injuries may result from single events or prolonged exposure to ergonomic risks, which can lead to problems such as lower back injuries, tendonitis and other injuries. (Punnett and Wegman, 2004).

A new trend in residential construction is the increasing use of industrialized-housing methods (O'Brien et al., 2000). In contrast to traditional stick-built framing, industrialized-housing methods involve more pre-assembled, factory-built components. These methods may increase exposure of residential construction workers to ergonomic risks through handling larger and heavier building components. A representative example of industrialized construction methods is the use of panelized walls, also known as panels or prefabricated walls (NAHB Research Center, 2002). These panels are constructed in a manufacturing facility and shipped to construction sites on pallets. Panels are transferred from the pallets and erected in a sequence of designated positions. Workers are required to handle these large and heavy panels, which increases the risk of incurring work-related injuries.

Mitigating ergonomic risks in residential construction can be addressed by using the concept of safety in design. Traditional safety and work design guidelines promote improvements to work systems at the design level through engineering controls before making changes at the administrative or personal level; i.e., employee training or personal protective equipment (Goetsch, 2002). Changes in the early stages of any process would be effective because they take a proactive approach to systems improvement. Safety in design specifically promotes safety considerations in early design phases (Gambatese et al., 1997). In residential construction, ergonomic hazards can be addressed by applying safety in design concepts to ergonomics (Gambatese, 1998; Hecker and Gambatese, 2003; Hinze and Wiegand, 1992). Although ergonomic interventions could be introduced at several levels of the system, ranging from the architect to the construction worker, implementing changes at the design level may be

the most effective according to this concept. Provided that designers have the proper tools and training to increase worker safety, these early-stage considerations will have the largest influence in decreasing ergonomic risks of construction workers.

The construction community has gradually become interested in the safety in design concept. Gambatese and colleagues (2005) noted that designing for safety can be a viable tool to improve workers' safety and health because the concept is easy to implement. A study by Behm (2005) reported that a large number of fatalities and injuries in construction sites were linked to design, and those fatalities and injuries could have been eliminated by applying the concept of safety in design.

For this study, panel design was targeted for potential ergonomic interventions in the earlier stages of the construction process. Panel designers play a central role in designing panel wall systems by generating a "panel plan" based on floor plans. They also make decisions regarding panel size, materials, stacking order, and panel assembly layout. On site workers then passively use the designed panels. Designers' panel plans are directly linked to on site workers through design choices that influence workers' tasks and physical demands. The centralized control over panel design decisions suggests that panel designers have the potential to reduce the likelihood of work-related injuries by incorporating ergonomics early in the construction process at the panel design stage, thus following the guidelines of safety in design.

Despite the need to reduce the risk of injury and illness in this new trend of panelized wall systems, no ergonomic analysis has been formally completed for the panel erection process to the authors' knowledge. Further, the incorporation of ergonomics in panel design has not been advanced in the residential construction industry. To develop methods to facilitate ergonomic principles in panel design, the current study used survey and interview data to provide a summary of the current ergonomic awareness of panel designers, patterns of panel installation, and opinions toward the incorporation of ergonomic principles into designers' work.

Methods

A two-phase study was conducted to determine the current knowledge and opinions of panel designers regarding aspects of the panel design process and ergonomics. Panel designers completed a 56-item questionnaire, and a subset of the respondents completed an additional interview on these topics.

Participants

In order to assure breadth and depth of ideas acquired, 12 panel designers from 11 different companies completed a questionnaire (10 males and 2 females). Seven of these designers then participated in a semi-structured interview after completing an informed consent procedure approved by the local IRB. Designers were first contacted by phone to solicit their participation and to confirm that they had the desired qualifications to complete the questionnaire. All participants worked for companies in the mid-Atlantic region of the United States (Virginia, North Carolina, and Maryland) or Illinois that are panel suppliers to production home builders. They had 3 to 30 total years of experience in the construction industry (Mean = 15, SD = 10 yrs) and 1.5 to 30 years of experience in panel design (Mean = 13, SD = 12 yrs). Seven respondents

had hands-on experience in installing panels at the job site as a part of job training or personal interest.

Survey and semi-structured interview development

A combination of a questionnaire and semi-structured interview was employed to assess panel designers' general knowledge, opinions, and experience regarding panel design, principles, and practices; ergonomics; perceptions of barriers to incorporating ergonomics into construction design; and promotion of the inclusion of ergonomics in design. The questionnaire was completed first, followed by the semi-structured interview at a later date.

A 56-item questionnaire was generated on the topics noted above through a collaborative process with seven graduate students from four areas of expertise: ergonomics, construction management, architecture, and data management. Questions were revised based on relevance to research goals and ease of comprehension for panel designers who may not have been familiar with ergonomic concepts. The group went through several iterations of questionnaire development with feedback from two of the principal investigators in the project. The final version included simple "yes/no" questions, Likert-type ratings, and open-ended questions. It was distributed to designers using an online survey tool (<http://survey.vt.edu>). Items in the questionnaire consisted of demographics (e.g., age, education and experience in panel design) and questions pertinent to the four categories listed above. Participants could complete the questionnaire in less than one hour.

A semi-structured interview script was developed to incorporate: questions that were too time-consuming for the questionnaire, participant-specific clarifications based on individual responses to the questionnaire, and hypothetical scenarios allowing participants to describe their thought processes during panel design. A similar iterative process involving researchers from different areas of expertise was performed to develop the interview questions. The underlying interview script contained 33 questions with additional questions (probes) based on the participants' responses to the questionnaire. Interviews were conducted at the participants' places of employment and lasted 40 - 70 minutes. All interviews were voice recorded with permission. The interview recordings were reviewed by the authors along with the results of the questionnaire for clarification purposes.

Results

Questionnaire results, combined with the interview results, were organized into four categories: panel design, ergonomics in panel design, perception of incorporating ergonomics, and promotion of the inclusion of ergonomics in design.

Panel design, principles and practices

Panel designers indicated that decisions regarding panel design are most constrained by the required floor plans for a house and panel installation, followed closely by location of openings (for windows and doors), panel size, and transportation (Figure 3.1). Panel designers ranked panel weight and crew size as having the lowest importance in panel design. Eight designers (67%) noted that they have to take into account specific requirements for a different floor (e.g., extra load carrying, the floor system of a house, etc).

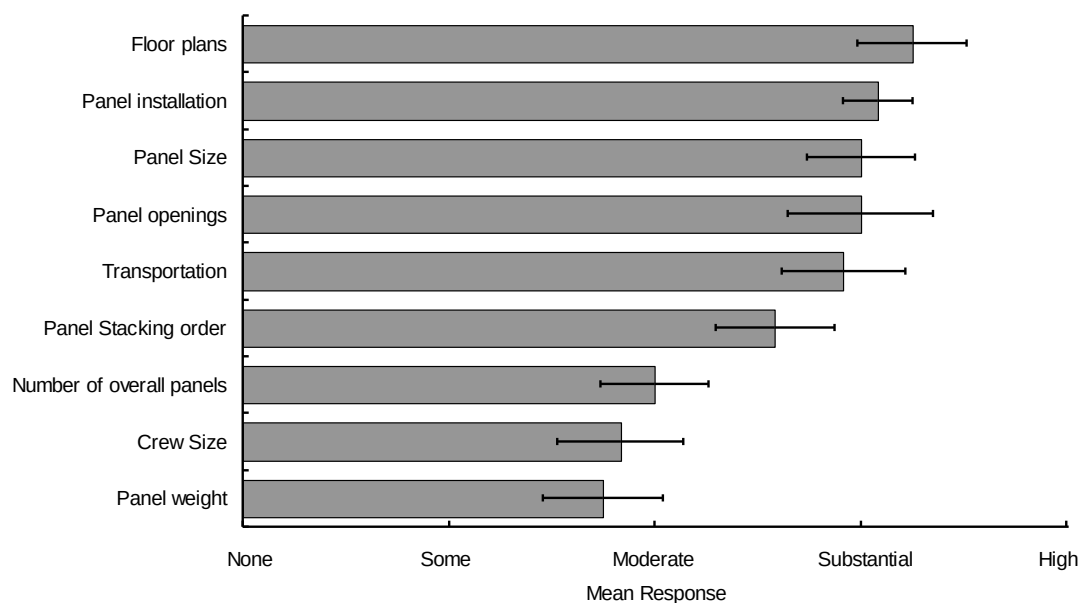


Figure 3.1: Designers' perceptions of importance of specific factors in panel design. Error bars here and in other figures indicate standard errors.

Three major concerns noted by designers in creating panel designs were: dividing a wall into multiple panels, shipping panels (cargo greater than 3.05 m [10 ft] wide requires special permits in most areas), and stacking panels on pallets. Floor plan information on opening locations, lengths, heights, materials, and stud spacing is input in computer software. The software output includes panelized wall patterns, materials lists, panel assembly plans, stacking orders, as well as other information required for panel erection depending on the software. Seven panel designers (58%) replied that they verify all output and make corrections as needed.

The most common standard panel length is 3.66 m (12 ft), regardless of panel type (sheathed or unsheathed). Sheathing, which is a covering nailed directly to a panel frame to distribute loads and strengthen the wall, is commonly available as 1.22 by 2.44 m (4 by 8 ft), and the lengths can increase in increments of 0.61 m (2 ft). According to interview responses, the standard panel size is selected based on shipping costs, trailer load capacity, standard lumber lengths, and the designers' experience. The ideal panel sizes (from a materials waste perspective) start at 2.44 m (8 ft) and increase/decrease by 1.22 m (4 ft) increments; at these sizes no material waste is produced.

Designers responded that efficiency of panel installation on site is most influenced by panel size (both height and length), followed by stacking order (Figure 3.2). Distribution of panel weight was the least influencing factor. Panel designers indicated during the interviews that panel stacking order could impact productivity on site.

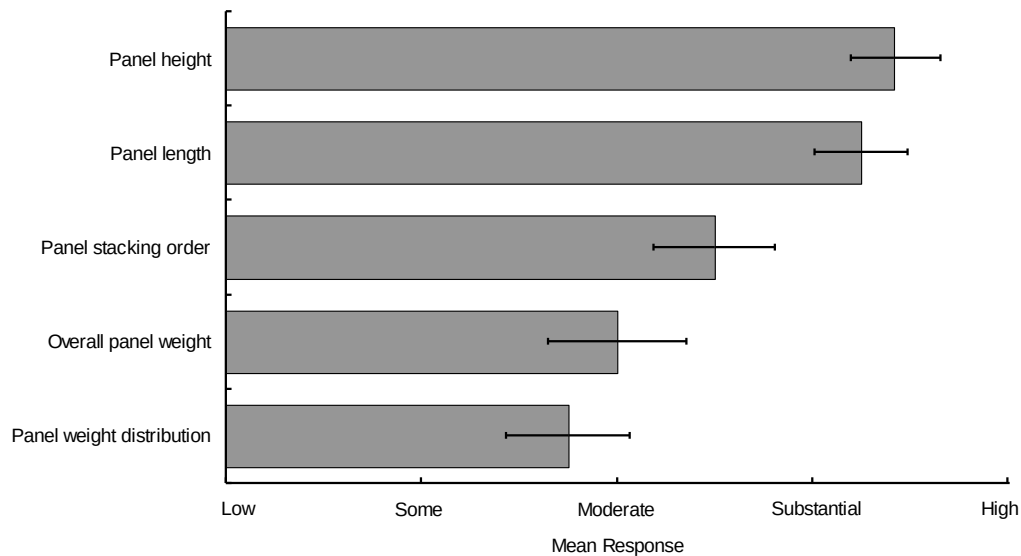


Figure 3.2: Designers' perceptions of factors that influence efficiency of panel installation.

Ergonomics in panel design

Most respondents (80%) were unaware of ergonomics in the context of construction. None of the respondents ranked their knowledge of ergonomics as “high,” and the mode response was “moderate.” Panel designers had difficulty providing specific examples of ergonomic principles. Some respondents mentioned that “workers should lift with the legs and not the back.” One of the respondents mentioned proper working heights during the interview, and when further questioned, he said his company had just raised tables in the panel plant to improve work heights. Of the 12 respondents, only one had formal ergonomic training, but this regarded office environments. During the interview a few panel designers mentioned safety training for operations in the panel manufacturing plant, but no safety instruction was related to the on-site panel installation process.

In the questionnaire participants were asked, “For a person who spends years as a construction worker, what body parts will most likely give them problems?” The panel designers responded that the lower back is most likely, followed by the knee and upper extremity. Designers said they selected these body regions because people complain about these areas as they age, and because these body regions are addressed during safety training for the plant. Designers ranked fatigue as the most possible cause of injuries, followed by over-exertion due to the weight of a panel (Figure 3.3). They stated that workers would make more mistakes that could lead to injuries when fatigued.

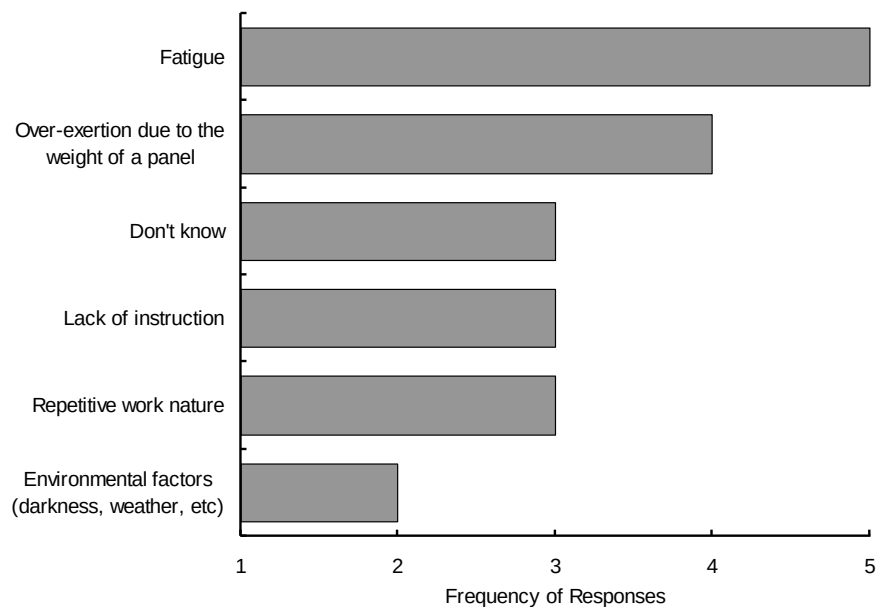


Figure 3.3: Designers' perceptions of potential sources of injuries to on site workers.

Perceptions of incorporating ergonomics into construction design

Half of the respondents replied that designers should consider ergonomics in the design phase, and the other respondents replied that ergonomics was not their responsibility. Five respondents (42%) believed that ergonomic principles were already reflected in their panel designs because they divide a panel in two small panels if the panel is extremely long. One respondent noted that he considered the weight of a panel during design because the panel design software provides the weight associated with the design choices.

When asked to rank the level of responsibility for work-related injuries, panel designers gave themselves the least amount of responsibility and gave construction workers the highest amount of responsibility. Rankings were predicated by the fact that designers have little influence or control over workers because designers are not in direct supervision of workers. In addition, designers believed that on site workers would have a better idea of safety in their work environment.

When asked to rate the level of resistance or acceptance of assorted stakeholders to the concept of ergonomics in design, panel designers reported slight resistance on average. "Some" or "high" resistance was reported by 25% of the respondents while 50% were neutral (Figure 3.4). From their comments, the participants were willing to incorporate ergonomics on the condition that workload, cost, and time did not increase. They believed that incorporating ergonomics would make designs less flexible. However, 75% of the designers expected that on site workers would be the most accepting because they have the most to gain.

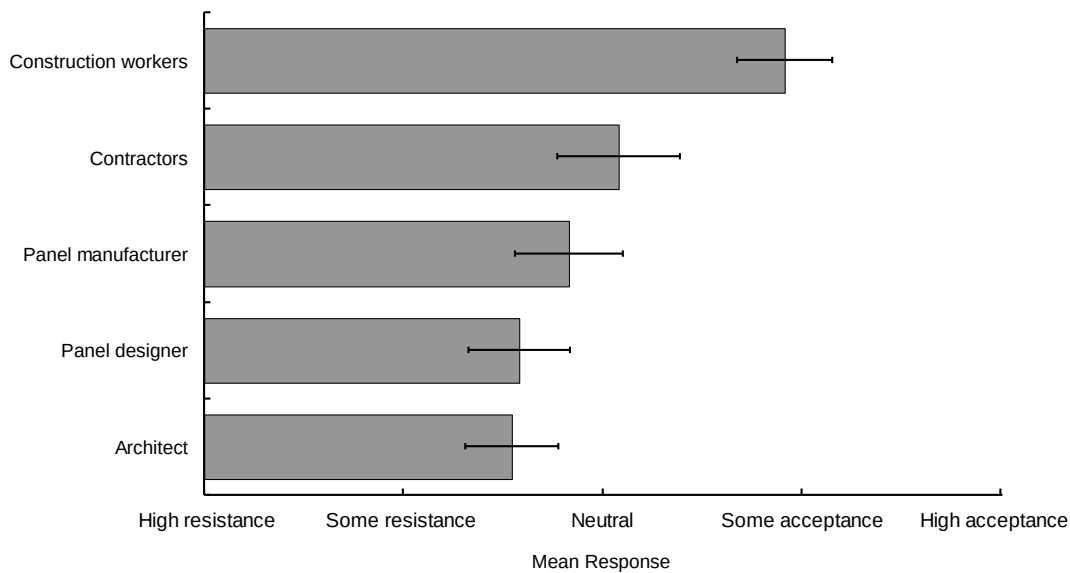


Figure 3.4: Designers’ perceptions of acceptance/resistance of each stakeholder to ergonomics in panel design.

Promotion of the inclusion of ergonomics in design

Panel designers, in general, took a neutral stance (37%) or a slightly negative stance (27%) toward the feasibility of incorporating ergonomics in panel design. Although all respondents agreed on the necessity of ergonomics to reduce workers’ risk of injury, they cited two main reasons for the slightly negative stance: ergonomics should be considered at job sites and ergonomics in panel design would increase their workload. The panel designers regarded “decreasing injuries” as the best reason to incorporate ergonomics when asked to rank reasons to incorporate ergonomics into design.

Panel designers responded that “less injuries to workers” would be the most expected outcome of incorporating ergonomics in their design while “more regulations to follow” and “more time consuming construction process at the site” were tied as the next likely outcomes (Figure 3.5). “Lower workers’ compensation costs” was also rated as a major expected outcome. In addition, the panel designers expected that the inclusion of ergonomics in design would lead to an increase in the overall cost of panel wall systems due to additional training, equipment and software upgrades, extra materials to build panels, and a decrease in on site productivity.

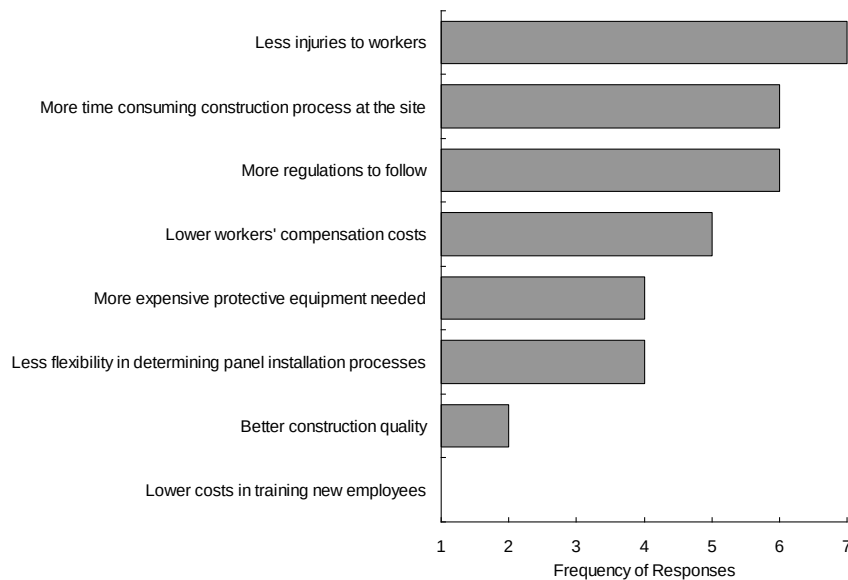


Figure 3.5: Expected outcomes of incorporating ergonomics in panel design.

Panel designers mentioned one reason for the success of their product is the speed of installation compared to “stick-built” construction, as well as the easy compliance with construction codes. During the interviews, the designers emphasized that on site productivity and compliance with construction codes should not be compromised by the incorporation of ergonomics in design. Several designers indicated that they would be open to the incorporation of ergonomics in design if it required minimal change in their design process and did not compromise the merits of the existing panel wall system.

Discussion

The objective of this study was to understand panel designers’ general knowledge, opinions, and experience regarding ergonomics with respect to designing panels. The results of the survey and interview indicated that panel design is largely influenced by floor plans and by the manufacturing and transportation aspects of panels. Panel designers make design decisions under these constraints, which in turn affect on site workers who handle panels. Nonetheless, the results of this study show that panel designers do have flexibility in design to incorporate ergonomics into panel wall systems.

Respondents expressed some resistance to the inclusion of ergonomics in their design process while accepting the need for ergonomics in design. Some designers thought ergonomic concerns were already reflected in their panel designs through dividing larger and heavier panels into multiple smaller panels. However, they transferred responsibility for ergonomic issues to the field and expected workers and supervisors to handle all situations. Panel designers considered the incorporation of ergonomics more feasible at the job site level rather than at the design level. As shown in Figure 5, panel designers expected that the inclusion of ergonomics in panel design would lead to more regulations and more time-consuming construction processes. Moreover, they believed ergonomics in design would

increase the current workload of panel designers due to added regulations and less design flexibility. This could account for resistance to ergonomics in the design process and a neutral or slightly negative stance toward the feasibility of ergonomics in design.

A similar gap was found between designers' self-stated knowledge of ergonomics and awareness of ergonomics in construction. They generally regarded their knowledge of ergonomics as moderate while reporting essentially no awareness of ergonomics in construction. This is consistent with previous studies which showed that lack of training, education, and guidelines are barriers to promoting designing for safety (Gambatese, 2005; Hinze and Wiegand, 1992; Toole 2005). Interviews revealed that panel designers regard their panel wall system designs as being disconnected from the on-site construction processes, and they were uncertain how their design choices could impact ergonomic exposures of workers. This implies that the designers may not have a thorough or sufficient understanding of on-site construction activities.

Despite the general resistance to ergonomics in panel design and the lack of knowledge of ergonomics, panel designers have great influence over the design of panel wall system in all aspects such as material choices, panel size, stacking order, and panel assembly layout. For instance, designers stated that panel stacking order, which is an output of panel design software, can affect on site productivity by reducing double-handling of panels. Panel designers, however, failed to see how a reduction in double-handling of panels could be linked to ergonomic exposure of workers, which is comparable to how designers (or architects) in construction responded regarding the inclusion of safety in their design (Gambatese et al., 1997; Hinze and Wiegand, 1992). Designers' lack of understanding of the safety-in-design concept and construction processes have been identified as major barriers to its implementation and diffusion (Gambatese et al., 2005; Toole, 2005). To place issues such as double-handling in some context, the mass of the most common panel size (3.66 x 2.44 m) was conservatively estimated to be 118.7 kg when sheathed and 49.5 kg when unsheathed (from mass per dimension data reported by Wakefield & O'Brien, 2004). These relatively high masses indirectly support a potential increase in ergonomic exposures of workers. Previous evidence (Perttula et al., 2003) suggests that overexertion accounts for most minor injuries (3 – 30 days away from work) and can be minimized by reducing material handling.

During the interviews, several panel designers mentioned that home builders are paying a premium to use wall panels instead of stick framing. They provided four reasons: the installation of wall panels is substantially faster than traditional stick framing, there are rarely any framing/structural code violations when wall panels are used, the assembled wall panels are straighter and more level than traditional framing, and using wall panels reduces on site theft. Incorporating ergonomics in panel design could lead to an increase in productivity and better construction quality because improved panel design potentially reduces exposures (e.g. double-handling) without compromising the structural integrity or strength of a wall panel system.

In the safety-in-design concept, computerized safety tools (including graphics capabilities, guidelines, safety knowledge-based databases, etc.) are viewed as a viable solution to provide design suggestions for on-site workers' safety, and such tools could compensate for designers' lack of understanding of the safety-in-design concept (Gambatese et al., 1997; Toole, 2005). Given the analogy between safety in design and ergonomics in design,

ergonomic assessment tools can be developed in a similar manner to provide design alternatives that reduce ergonomic exposures of on-site workers with little or no increase in panel designers' work. The development of ergonomic assessment tools is challenging because it requires comprehensive understanding of on-site panel erection processes as well as how changes in panel design could affect ergonomic exposures of workers. Further, design changes intended to improve material handling may be particularly difficult to address in early design stages compared to design changes for safety (Weinstein et al., 2005). Still, workers' ergonomic exposures can be minimized by well informed designers who use effective tools and supportive regulations.

In conclusion, panel designers had limited knowledge regarding ergonomics, and negative or neutral attitudes regarding ergonomics in panel design. Yet, panel designers have a crucial role to play in terms of proactive control of worker injuries and illnesses, as their design choices have broad impacts on ergonomic exposures of construction workers. Such control, or 'ergonomics in design,' will require panel designers to recognize the ergonomic impacts of their design. This might best be achieved through a combination of appropriate education and effective tools. We envision that one such tool might be software that integrates with existing panel design software and facilitates a rapid and iterative evaluation of ergonomic exposures. The present results, which identify the knowledge and opinions of eventual users, are considered an initial step toward this goal.

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4. Taxonomy, Task Identification, and Input from Workers

An initial goal was to develop a taxonomy of the panel erection process. A broad or taxonomic approach permits more complete hazard identification by characterizing the process and identifying frequently performed tasks with high risk exposures. Hierarchical task analysis (HTA) was used as it can effectively organize diverse subtasks of the task of interest (i.e., operations) and can establish conditions that determine when subtasks are carried out to achieve operating goals. In the current taxonomy, two conceptual levels (i.e., tasks and subtasks) were used, and two functional categories were introduced (fundamental and supplemental) as described below.

Tasks were identified by reviewing video recordings obtained during the framing phase of 10 different home building sites in the Washington, D.C., area. Construction of both single family and town homes was observed, with crews of 3-8 workers. Tasks were named to conform to an operational goal. Tasks were divided into subtasks, and multiple levels of subtasks were defined. Subtasks were characterized by a series of physical actions (e.g., lifting, lowering, carrying) that a worker performs to attain a simple work goal and that are transferable from one worker to another. Tasks, including their subtasks, were categorized into “fundamental” tasks and “supplemental” tasks in order to discriminate tasks that are sequential and commonly observed on every site from those that are nonsequential and not commonly observed. The panel erection process could be comprehensively represented by four fundamental tasks – unbind panel stack, formulate work sequence, prepare to move panel, and install panel – and 10 supplemental tasks.

Work sampling was performed on manual handling tasks to facilitate a better identification of ergonomic exposures and to guide subsequent lab-based analyses and simulations. We recorded primary panel-handling techniques, the number of workers, type of panel, time duration, and frequency of each of the identified tasks and subtasks. Primary panel-handling techniques and associated activity duration were identified for lifting, carrying, moving, erecting, and lowering activities. In all, 1,443 panel handlings were recorded, and frequencies were identified for alternative techniques, panel types, and other relevant dimensions (e.g., initial hand position, transfer distances, etc.). Summary statistics (e.g., time durations) were generated from 1,321 fundamental and 614 supplemental tasks.

We also gathered input from construction workers to help identify the most physically demanding tasks occurring during panel erection. Field managers in residential home-building companies in the Washington, D.C., area distributed a questionnaire to individual carpenters (a Spanish language translation was made available), and 18 responded. Across the different panel-handling tasks, carrying and modifying a panel on site were rated the most difficult and most physically demanding. Carrying and erecting panels were most frequently indicated as potentially leading to injury. Body parts most frequently identified as being at risk were the lower back (50%), upper back (22%), and arms (22%). Panel size and weight were indicated as having the largest effects on physical demands.

Kim S, Seol H, Nussbaum MA: [2006] Heirarchical task analysis (HTA) and work sampling of residential panelized wall erection. Unpublished Technical Report, Industrial Ergonomics and Biomechanics Laboratory, Virginia Tech, Blacksburg, VA.

Introduction

The department of Housing and Urban Development (HUD) indicated that residential construction is moving toward industrialized-housing techniques from conventional housing techniques (Michael et al., 2000). Conventional housing techniques (i.e., lumber “stick-built” framing) can be characterized by labor-intensive processes on sites and relatively low productivity within the construction industry. On the other hand, industrialized-housing techniques differ from conventional housing techniques in that they utilize more factory-built components so as to increase productivity and efficiency on site.

A representative example of industrialized-housing methods is wall panels (prefabricated walls), which are manufactured in the factory and arrive at the construction site more completely assembled than traditional “stick-built” framing materials. Hence, the use of panels requires some on-site processes that differ from conventional processes of site-built walls. With the use of these new on-site processes, working behaviors are expected to change and workers are likely to be exposed to different ergonomic risk factors. However, no study to date has formally conducted ergonomic assessments of residential wall panel erection.

The construction industry as a whole has high rates of occupational injuries with non-fatal injuries reported as the 4th highest (BLS, 2005b). Construction also has the highest percentage of injuries and illness in the private industry sector and the 2nd highest number of median days away from work (BLS, 2005a). More specifically, over 399,000 nonfatal occupational injuries were reported in the construction industry and 10% of these injuries occurred in residential building construction. Further, the construction industry accounted for 9.4% of all musculoskeletal disorder (MSD) cases and ranked the 5th highest in the private industry sector. MSDs in construction were found to be associated with a higher likelihood of long-term work loss (NIOSH, 2004).

The prevalence and severity of occupational injuries in residential building construction may be even more severe than Bureau of Labor Statistics (BLS) reports. Reasons for this include: 1) BLS data may substantially undercount occupational injuries due to underreporting of minor injuries, company-paid cases, and so forth (Glazner et al., 1998; Morse et al., 2005; Morse et al., 2001); 2) BLS data provide little information specific to residential building construction (Dement & Lipscomb, 1999; Methner et al., 2000). In addition, no ergonomic assessment has been specifically performed for industrialized-housing techniques. Therefore, it is necessary to evaluate industrialized-housing techniques to understand ergonomic risk factors and to provide basic information for the further studies.

In order to ergonomically assess the new techniques in industrialized-housing, a descriptive approach is first required to investigate ergonomic aspects of the new trends (i.e., panel walls) in residential building construction. The descriptive approach can provide an understanding of how the on-site panel erection process is associated with ergonomics risks as well as what tasks in the process contribute to ergonomic hazards. Findings from the descriptive approach can then guide more detailed ergonomic investigations, as Schneider and Susi (1994) noted that ergonomic hazard identification should precede exposure measurements. Therefore, the objective of this study is two-fold. The first objective is to develop a taxonomy of the panel erection process to provide a framework for further studies on prefabricated walls. A broad or taxonomic approach permits more complete ergonomic hazard identification that can help characterize the process and identify frequently performed tasks with

high ergonomic exposures (Moir et al., 2003). The second objective of the study is to provide the basis for detailed biomechanical analyses of identified tasks by using a work-sampling method. The work-sampling method, designed specifically for the present study, aims to capture characteristics of panel erection tasks in relation to manual material handling (MMH) methods.

Background on the panel erection process

Panel stacks are delivered to a work site as pallets. A pallet of panels contains a varying number of panels, ranging from ~15-40 panels, and the height of a pallet is typically 1-3 meters. Panel walls consist of two primary types, sheathed or unsheathed, and can be functionally divided as load-bearing and non-load-bearing. For example, an exterior panel is a load-bearing wall and an interior panel used as a partition is a non-load-bearing wall. Sheathed panels may have no opening or have one or more openings for windows and doors.

Illustration of the structural components of a panel and definition of each component are provided in Appendix A. The basic components of a panel are studs, plates and sheathing. Studs represent a vertical structural element in wall framing. Plates are a lumber perpendicular to studs and to which studs are nailed for framing. Sheathing is a composition board encasing a panel. Sheathing materials are Oriented Strand Board (OSB), plywood, Thermoply™, etc., with OSB most commonly in use.

The panel erection process is described in the following. Prior to panel erection, workers draw panel layout lines and mark panel numbers on the floor, according to panel layout drawings that come with panel stacks. The layout lines indicate the actual location of each panel, and the panel number matches with the number labeled on the panel. Afterwards, panel stacks are placed either on the floor or near the floor using a forklift and workers erect panels in designated locations. In summary, panel erection involves placing a panel wall to the layout lines and numbers on the floor and then affixing the panel in position.

Methods

Video recordings were made of panel erection during the framing phase of ten different home building sites around the Washington, D.C. area. Both single family homes and town homes were visited with the size of the house and the crew size varying by site. The crew size ranged from 3 to 8. Panel erection was recorded for the first or the second floor depending on the site. Prior to any video recording, members of the research team explained to on-site supervisors that the company name would not be disclosed and the data collected would be used only for study of the panel erection process within the context of an ergonomic investigation. Throughout the video recordings, care was taken not to interrupt or disturb workers.

Development of a taxonomy

HTA: Hierarchical task analysis (HTA) was used to develop a taxonomy of the panel erection process. HTA is a broad approach that can effectively organize various subtasks of the task of interest (i.e., operations) and can establish conditions that determine when subtasks are carried out to achieve operating goals (Kirwan & Ainsworth, 1993). Overall, HTA is a hierarchical tool used to develop a description of the task in terms of operations and conditions. Operations are simply referred to as subtasks that constitute a task of interest (hereafter the term, task, was

employed instead of operation for simplicity). A series of conditions is, in general, referred to as a plan. In the current taxonomy, two conceptual levels (i.e., tasks and subtasks) were used and two functional categories were introduced, *fundamental* and *supplemental*. The classification of each level and category is given in the following.

Task: Tasks are central to developing an HTA. Tasks can be defined as a sequence of subtasks and/or activities performed by an individual or a group of workers to accomplish a specific purpose (Moir et al., 2003). Tasks in the panel erection process were identified by review of the video recordings described previously. The name of each task was selected to conform to an operational goal of the task. A task was further divided into subtasks and multiple levels of subtasks were defined, depending on the level of detail required (or of interest). Separate tasks could share the same subtask.

Subtask: In this study, subtasks were considered equivalent to activities defined by Moir and his colleagues (2003). Subtasks were characterized by a series of physical actions (e.g., lifting, lowering, twisting, etc) that an individual worker performs to attain a simple work goal and that are transferable from one worker to another. Subtasks were identified when an important change in a series of physical actions was observed.

Activity: In the panel erection process, a group of workers usually performs a subtask that includes multiple activities. For example, when nailing down a panel, one worker performs a hammering activity while other workers perform a holding activity to keep the panel in position.

Fundamental vs. Supplemental Task: Tasks including their subtasks were categorized into *fundamental* tasks and *supplemental* tasks, in order to discriminate tasks that are sequential and commonly observed on every site from tasks that are non-sequential and not commonly observed. That is, *fundamental* tasks are defined as required tasks that are sequentially completed for panel erection. In contrast, *supplemental* tasks are conditionally done during the course of panel erection, depending on house type, builder practice, etc.

Work sampling

HTA can effectively describe how and what activities workers actually perform to accomplish the given task; however, HTA itself does not provide detailed quantitative data on how often or how long a certain task, subtask, or activity is conducted. According to a critical review of MSD epidemiology (NIOSH, 1997), physical work factors that are associated with or causally linked to MSDs are repetition, posture, vibration, heavy physical work, forceful movement, and so forth. In order to facilitate a better identification of exposures to these risk factors and guide subsequent lab-based analyses, a work sampling method was designed with a focus on MMH techniques. This work sampling was conducted to record primary panel handling techniques, the number of workers, type of panel, time duration, and frequency of each of the identified tasks and subtasks. This work sampling was implemented after the development of the HTA for panel erection was completed. In essence, the HTA served as a framework for the work sampling. Primary panel handling techniques and associated activity duration were identified for *lifting*, *carrying*, *moving*, *erecting*, and *lowering* activities. Work sampling was performed by

two Industrial and Systems Engineering graduate students and cross-checked to ensure consistency and minimize errors.

Time duration

Time duration was recorded (from review of the videotapes) only for actual physical efforts — the time required to formulate a work sequence or to interpret a panel layout drawing was not taken into account. In addition, time duration of two work activities were not measured: simple tape measurements without handling of panels or hand tools, and cutting a lumber plate or a 2x4 piece of lumber to a certain length. Simple tape measurements were often observed during the course of the panel erection process, yet these measurements were only used to ensure exact matches between actual panel length and floor plan, and thus did not involve any physically demanding activities. Cutting a plate or a 2x4 piece of lumber was excluded due to difficulties in tracking all the workers on site. A worker frequently walked out of the field of view of a camcorder to modify materials using an electric circular saw and/or to fetch 2x4 lumbers. In addition, the time involved in descending a ladder was disregarded because workers were frequently observed to stay on the ladder even after they finish their job (in order to converse with co-workers or without any particular reason).

Coding primary panel handling techniques

Primary panel handling techniques for lifting, carrying, erecting, moving, lowering activities were identified by observing the video recordings. Table 4.1 shows the coding used for panel handling activities and descriptions of techniques. Detailed classifications are provided below.

Table 4.1: Primary panel handling technique coding and descriptions.

Activity	Technique	Description	Notes
Lifting	L1	▪ Lift a panel while maintaining it oriented horizontally.	▪ Eight initial hand positions
	L2	▪ Lift a panel as orientating it vertically so that the panel is held vertically at the completion of lifting.	
Carrying	C1	▪ Carry a panel while it is lifted in a horizontal orientation.	.
	C2	▪ Carry a panel while it is lifted in a vertical orientation.	
	C3	▪ Carry a panel oriented vertically while it is held slanted over the shoulder.	
	C4 _{A/B/C}	▪ C4 is only for a single worker, while the rest of carrying techniques may be done by a single worker or multiple workers.	
Moving	M1	▪ Push/pull a panel while it rests on the deck in a vertical orientation.	.
	M2	▪ Push/pull a panel by holding up one side of the panel while the other side rests on the deck.	
	M3	▪ Push/pull a panel without lifting the panel.	
Erecting	E1	▪ Lower one side of a panel to touch the deck and pushes upward on the panel until it stands vertically	▪ Five initial hand positions
	E2	▪ Rotate a panel to be oriented vertically without touching the deck.	
Lowering	LW	▪ Lower a panel on the floor.	.

First, *lifting* techniques are classified into two types, L1 and L2 (Figure 4.1). Type L1 is distinct in that a panel is initially placed in a horizontal orientation and is lifted as oriented horizontally. Observations on the video recordings show that panels are stacked horizontally at the start of the panel erection process. Regardless of the initial panel orientation, a lift is classified as type L2 if a panel is oriented vertically at the completion of lifting. Consequently, type L2 is not as straightforward as type L1, in that type L2 involves a combination of the erecting and the lifting activities. The erecting activity will be explained in detail in a subsequent paragraph. The initial height of the worker's hands is set to have eight different heights (1—8), based on observations. These heights (1—7) include below ground, ground, knee, knuckle, elbow, shoulder, and above shoulder. The last level (8) indicates when one hand is near elbow height and the other hand is around waist or knee height. This hand position was generally observed when a panel was stacked or placed vertically against any support.



Figure 4.1: Lifting (Above: L1, Below: L2) — Carrying techniques (C1 and C2) are extensions of type L1 and L2, respectively.

Carrying techniques are classified into four types. Type C1 and C2 can be respectively seen as extensions of type L1 and L2 lifting. Workers transfer a panel while holding it oriented horizontally (type C1) or vertically (type C2). Type C3 is when a worker(s) transfer a panel while keeping the panel vertical and slanted toward (or over) the shoulder, as shown in Figure 4.2. A panel is held either in front of workers' bodies or at the side of workers' bodies. Type C3 can be viewed as a variation of type C2. Type C2 and C3 are distinguished in that workers do not hold both sides of a panel in the case of type C3. As is illustrated in Figure 3, type C4 involves a single worker and includes three alternatives as follows:

- Type C4_A occurs when a worker carries an unsheathed panel or a panel with opening on one shoulder with the arm around the opening of a panel.
- Type C4_B occurs when a worker carries a panel by holding the panel over the shoulder.
- Type C4_C occurs when a worker carries a panel by grasping one side of the panel.



Figure 4.2: Carrying (C3).

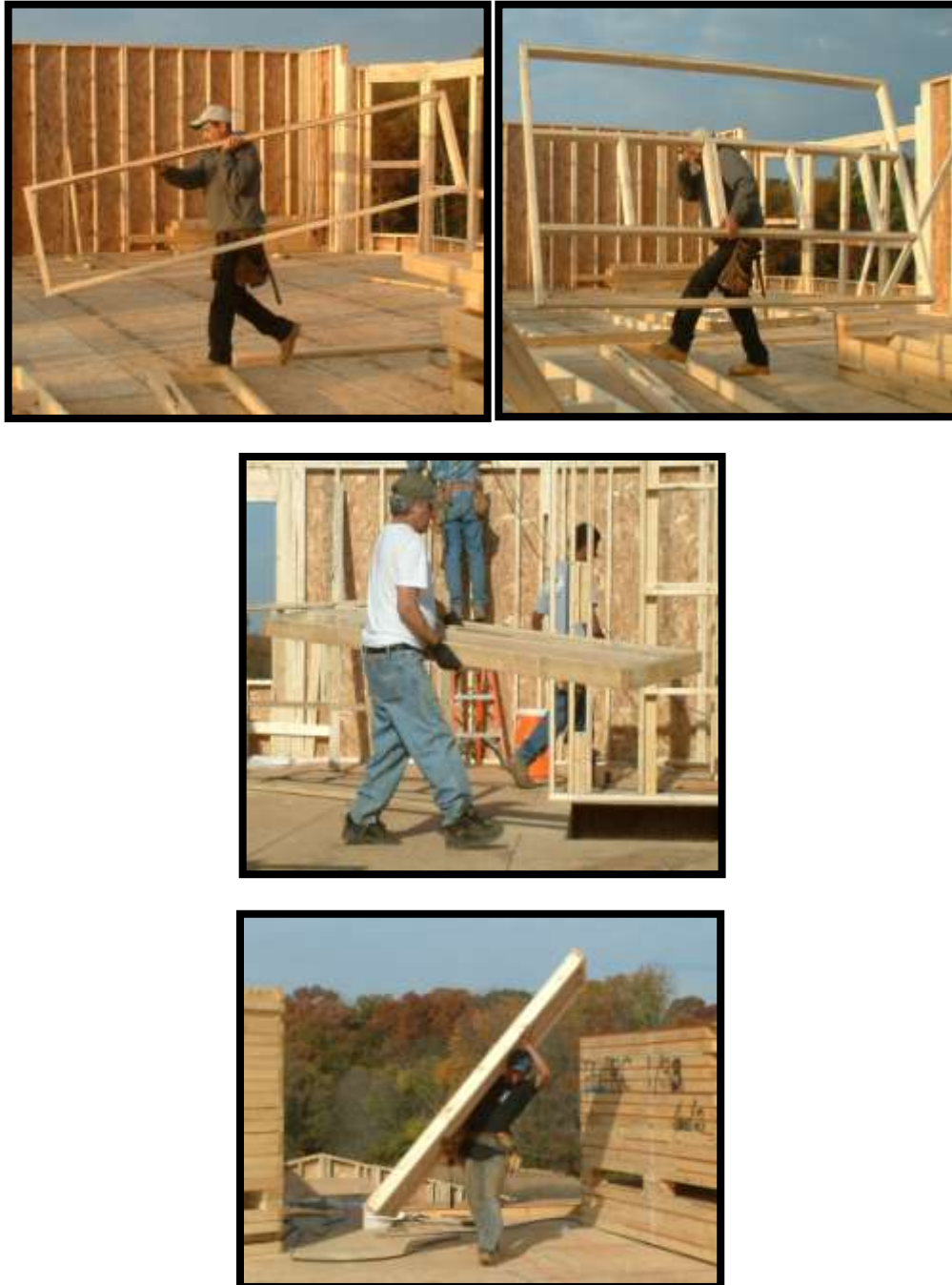


Figure 4.3: Carrying (Top: C5a, Middle: C5b, Bottom: C5c).

Moving techniques include three variations, illustrated in Figure 4.4. *Moving* is distinguished from *carrying*, in that *moving* is defined as transferring a panel from one place to the other place while at least one side of the panel makes contact with the deck (floor).



Figure 4.4: Moving (Top: M1, Middle: M2, Bottom: M3).

Erecting begins with lowering or lifting one side of a panel to change the panel orientation from horizontal to vertical. Two erecting techniques are defined as follows. Type E1 erecting technique occurs when a worker(s) lowers one side of a panel to touch the deck and pushes upward on the panel until it stands upright. The second erecting technique (E2) occurs when a worker(s) rotates a panel such that it is oriented perpendicular to the deck without touching the deck, and then puts the panel down while keeping the panel oriented vertically. Figure 4.5 illustrates these two types of erecting techniques. Initial hand positions when workers push up on a panel to stand it vertically are defined to have five different heights (1—5): ground, knee, knuckle, elbow, and shoulder.



Figure 4.5: Erecting (Above: E1, Below: E2).

Erecting techniques may be confused with type L2 lifting because type L2 includes, to some extent, erecting activities changing an orientation of a panel from horizontal to vertical. However, type L2 is ultimately to lift a panel off the floor for the carrying activity. Whereas, *erecting* techniques are to transform an orientation of panel to the vertical for moving or adjusting the panel in position.

Lastly, the *lowering* activity is sampled simply to distinguish lowering a panel to the deck from dropping a panel. When lowering a panel, a worker(s) generally lowers one side of the panel to the deck and then lowers the other side slowly without sudden movements (Figure 4.6).



Figure 4.6: Lowering.

Results

Taxonomy of panel erection

The HTA for panel erection was completed based on video recordings from 10 different sites and the task classifications defined above. A hierarchical diagram for panel erection is presented in Figure 4.7 where the panel erection is comprehensively represented by four fundamental tasks and ten supplemental tasks. To erect a panel wall, fundamental tasks are sequentially carried out and supplemental tasks are performed as they are required. The fundamental task plan is presented as the flowchart in Figure 4.8, which indicates in what order the fundamental tasks are performed and how the supplemental tasks are interrelated with the fundamental tasks.

The name of each task was assigned to reflect an operational goal of task. Four fundamental tasks were identified: *Unbind panel stack* (F1), *Formulate work sequence* (F2), *Prepare to move panel* (F3), and *Install panel* (F4). Ten supplemental tasks were identified: *Put aside panel* (S1), *Attach shear straps* (S2), *Attach fire blocks* (S3), *Attach house wrap* (S4), *Apply caulking* (S5), *Level installed panels* (S6), *Align top plates* (S7), *Brace installed panels* (S8), *Drill anchor bolt holes* (S9), and *Modify panel* (S10).

Unbind panel stack (F1) involves cutting off metal bindings that keep panels in a pallet, and/or to pull out toe-nails and 2x4 lumbers that also hold panels in the pallet. *Formulate work sequence* (F2) includes matching panels in the unbound stack with panel layout drawings or layout lines on the floor and determining the panel erection order.

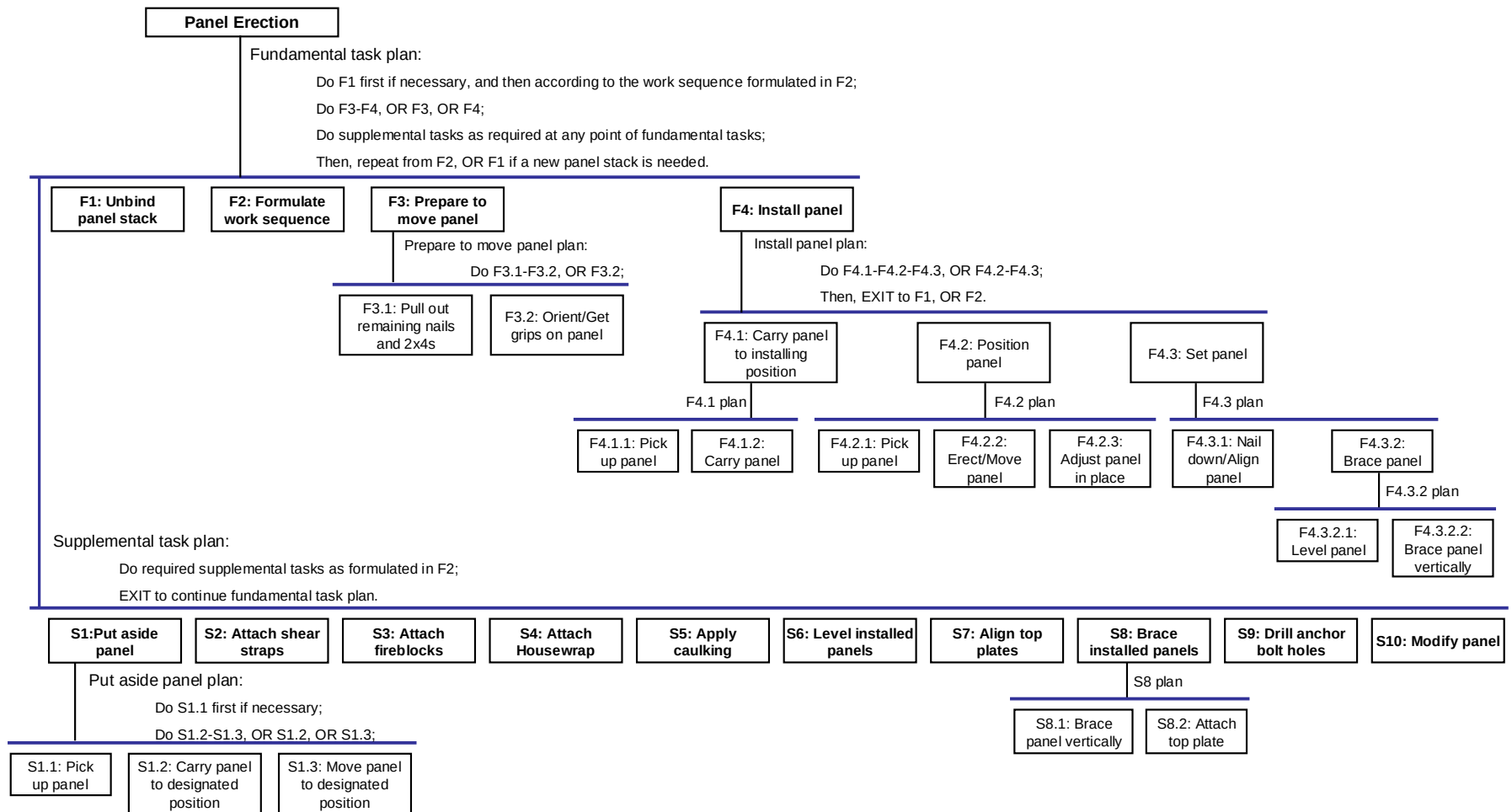


Figure 4.7: Hierarchical diagram for panel erection.

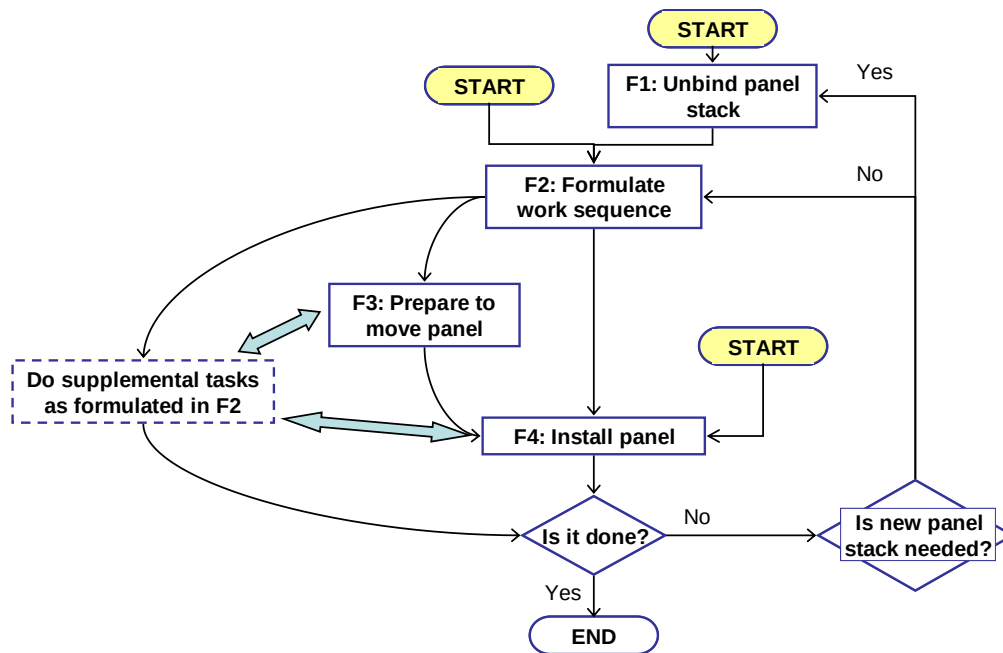


Figure 4.8: Flowchart of fundamental task plan. Panel erection can be completed by beginning the process from three different starting points.

Prepare to move panel (F3) includes two subtasks, which are *Pull out remaining nails and 2x4s* (F3.1) and *Orient/Get grips on panel* (F3.2). Figure 4.9 illustrates the plan for F3 where *Pull out remaining nails and 2x4s* (F3.1) is conditionally done. In the figure a black-solid arrow indicates a path within the plan, and a thick red-solid arrow indicates a path from one task to the other task or from one plan to the other plan. *Orient/Get grips on panel* (F3.2) involves re-positioning a panel on the stack so that a panel is properly oriented for erection or for a better hand grip.

Install panel (F4) consists of three subtasks; *Carry panel to installing position* (F4.1), *Position* (F4.2), and *Set panel* (F4.3). Further, each of subtasks includes hierarchically lower-level tasks. For simplicity, they are referred to as sub-subtasks. *Carry panel to installing position* (F4.1) has two sub-subtasks; *Pick up panel* (F4.1.1) and *Carry panel* (F4.1.2). *Position panel* (F4.2) has three subtasks; *Pick up panel* (F4.2.1), *Erect/Move panel* (F4.2.2), and *Adjust panel in place* (F4.2.3). *Erect/Move panel* (F4.2.2) may be broken into two separate sub-subtasks, *Erect panel* and *Move panel*. However, observations indicated that there is no specific order in moving and erecting a panel. *Erect panel* can precede *Move panel* and vice versa. F4.1.1 and F4.2.1 are the same task although placed under different higher-level tasks.

Set panel (F4.3) includes two sub-subtasks; *Nail down/Align panel* (F4.3.1) and *Brace panel* (F4.3.2). Further, *Brace panel* (F4.3.2) is defined to have another lower level of tasks; *Level panel* (F4.3.2.1) and *Brace panel vertically* (F4.3.2.2). Time duration for F4.3.2.1 cannot be measured separately from F4.3.2.2 because F4.3.2.1 is accomplished by adjusting bracings. Figure 4.10 shows the overall *Install panel* (F4) task and the plan for each subtask.

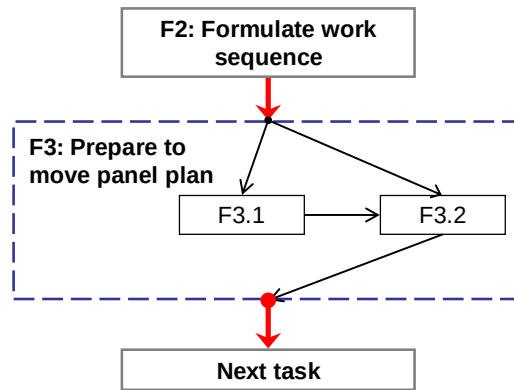


Figure 4.9: Plan for *Prepare to move panel* (F3) – Black arrows indicate a path within the plan. Red arrows indicate a path from one task to another task, or one plan to the another plan.

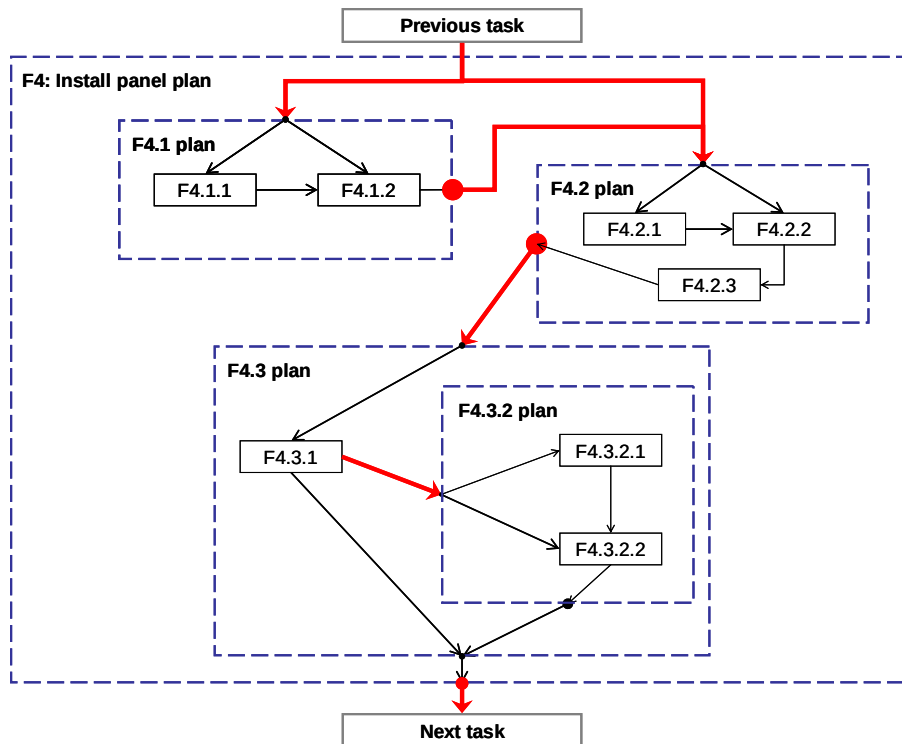


Figure 4.10: Overall plan for *Install panel* (F4) and the plan for each subtask – The plan for each task is demarcated by the dotted-lined box, and arrows indicate possible paths to accomplish the plan for F4.

For the supplemental tasks, *Put aside panel* (S1) is defined to have three subtasks; *Pick up panel* (S1.1), *Carry panel to designated position* (S1.2), and *Move panel to designated position* (S1.3). *Put aside panel* (S1) and its subtasks are essentially the same as F4.2 and its subtasks, except that the goal of S1 is to put aside a panel for later use. The plan for S1 is given in Figure 4.11. *Attach shear straps* (S2), *Attach fireblocks* (S3), and *Attach housewrap* (S4) are straightforward. S2, S3, and S4 respectively represent nailing shear straps; nailing fire-blocking materials; and attaching housewraps (e.g., Tyvek™) on the panel. *Apply caulking* (S5) involves spreading silicone on the deck using a caulking gun.

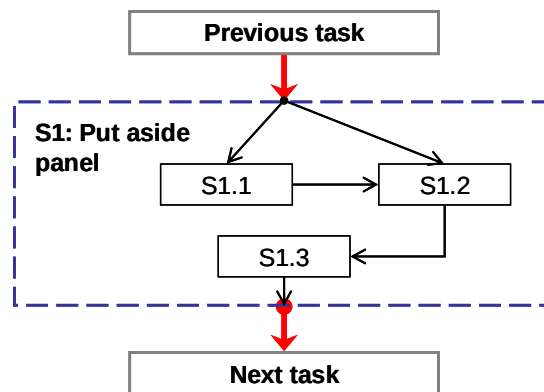


Figure 4.11: Plan for *Put aside panel* (S1).

Level installed panels (S6), *Align top plates* (S7), and *Brace installed panels* (S8) are associated with installed panels. *Level installed panels* (S6) ensures that panels stand perpendicular to the floor and the goal is essentially the same as F4.3.2, in that workers adjust installed panels to be perpendicular to the floor by adjusting bracings. S6 can be done at any time during the panel erection process. S6 is performed, to a varying degree, to finalize the panel erection process after all the panels are installed.

Align top plates (S7) involves nailing top plates of panels such that they are horizontally aligned to each other. Workers were observed to stand on the ladder or to sit on the top plate to complete S7. *Brace installed panels* (S8) consists of two subtasks; *Brace panel vertically* (S8.1) and *Attach top plate* (S8.2). S8.1 is the same as F4.3.2.2 and the purpose is to support a panel to stand in place. S8.2 involves attaching an additional top plate on the top plate of a panel (i.e. double top plate), and the goal of S8.2 is to structurally strengthen a panel. The plan for S8 is presented in Figure 4.12.

Drill anchor bolt holes (S9) is required when an exterior panel is erected on a concrete slab where anchor bolts are fixed. *Modify panel* (S10) includes any field modification to a panel such as cutting off an unnecessary part of the sheathing material, fixing a broken panel during delivery, changing a stud position, etc.

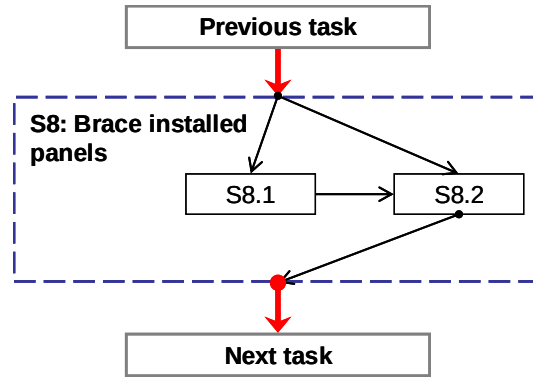


Figure 4.12: Plan for *Brace installed panels* (S8).

Work sampling results

Time duration

A total of 1321 fundamental tasks and 614 supplemental tasks were observed from 10 residential construction sites, based on the developed HTA for panel erection. Table 4.2 and Table 4.3, respectively, provide the summary of collected data for each of fundamental tasks and supplemental tasks. An average duration and one standard deviation across sites are provided for time duration.

Table 4.2: Summary of time durations for fundamental tasks.

Fundamental task	Time duration Mean $\pm$ s.d. (seconds)	Minimum duration (seconds)	Maximum duration (seconds)
<i>Unbind panel stack</i> (F1)	144 $\pm$ 76	57	253
<i>Prepare to move panel</i> (F3)			
F3.1	39 $\pm$ 24	7	88
F3.2	29 $\pm$ 37	9	135
<i>Carry panel to installing position</i> (F4.1)			
F4.1.1+F4.1.2	16 $\pm$ 5	6	23
F4.1.2	14 $\pm$ 6	7	26
<i>Position panel</i> (F4.2)			
F4.2.1+F4.2.2	36 $\pm$ 21	17	88
F4.2.2	18 $\pm$ 6	10	26
F4.2.3	38 $\pm$ 12	23	64
<i>Set panel</i> (F4.3)			
F4.3.1	47 $\pm$ 20	20	80
F4.3.2.1+F4.3.2.2	67 $\pm$ 56	23	130
F4.3.2.2	31 $\pm$ 23	13	85

Table 4.3: Summary of time durations for supplemental tasks.

Supplemental task	Time duration Mean $\pm$ s.d. (seconds)	Minimum duration (seconds)	Maximum duration (seconds)
<i>Put aside panel (S1)</i>			
S1.1+S1.2	27 $\pm$ 12	16	47
S1.2	13 $\pm$ 5	6	25
S1.1+S1.3	20 $\pm$ 23	3	65
S1.3	14 $\pm$ 8	7	31
<i>Attach sheer strap (S2)</i>	217 $\pm$ 41	188	246
<i>Attach fireblocks (S3)</i>	79 $\pm$ 28	62	112
<i>Attach housewrap (S4)</i>	206 $\pm$ 31	170	251
<i>Apply caulking (S5)</i>	12 $\pm$ 2	10	16
<i>Level installed panels (S6)</i>	62 $\pm$ 20	35	87
<i>Align top plates (S7)</i>	63 $\pm$ 27	37	113
<i>Brace installed panels (S8)</i>			
S8.1	49 $\pm$ 34	26	73
S8.2	116 $\pm$ 60	70	192
<i>Drill anchor bolt holes (S9)</i>	26 $\pm$ 17	10	59
<i>Modify panel (S10)</i>	149 $\pm$ 106	23	339

In Table 4.2 and Table 4.3, a '+' sign between two tasks denotes that two tasks are inseparable; they are done simultaneously or time duration of one task is too short compared to the other task. For example, F4.1.1 (Pick up panel) +F4.1.2 (Carry panel) indicates that workers carry a panel as lifting the panel off the floor. A transition from the lifting to the carrying can often not be clearly identified when time duration of lifting is very short. In this case, a '+' sign is used and time duration is considered an aggregated duration for the completion of both tasks. To visualize a time profile of fundamental tasks and supplemental tasks, Table 4.2 and Table 4.3 are graphically represented in Figure 4.13 and Figure 4.14, respectively. For fundamental tasks, a time profile is also given for each panel type (Figure 4.15). Panel walls were categorized into three types; 1) exterior panel with opening (Type A), 2) exterior panel without opening (Type B), and 3) interior panel (Type C). In the case of interior panels, a load-bearing interior panel and a non-load-bearing interior panel (i.e., interior partition) were considered as the same. The reason is that a non-load-bearing interior panel was much more frequently observed than a load-bearing interior panel and differences in types of interior panels were difficult to distinguish when viewing the video recordings.

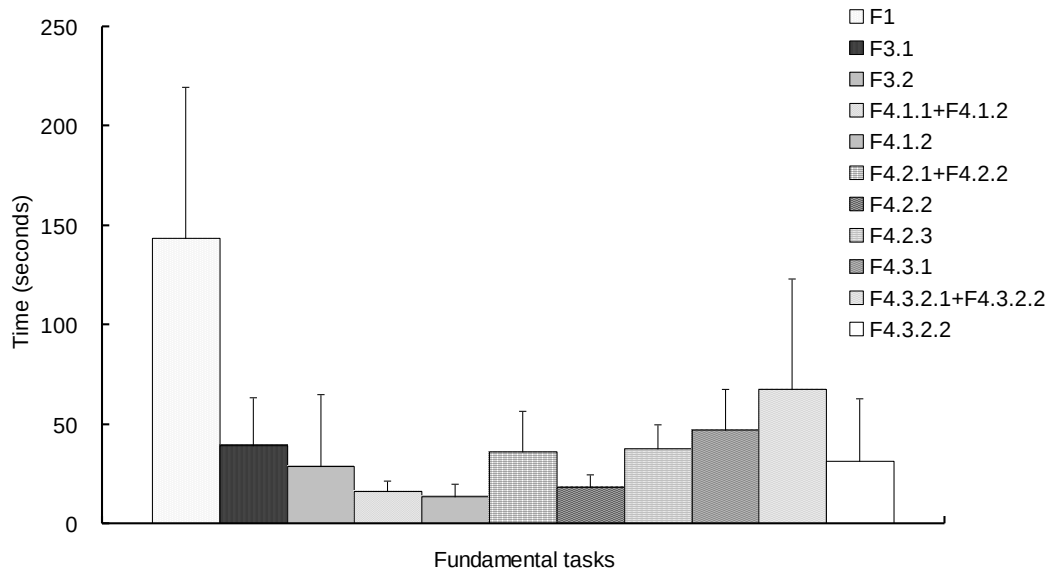


Figure 4.13: Time profile of fundamental tasks (error bars indicate +sd).

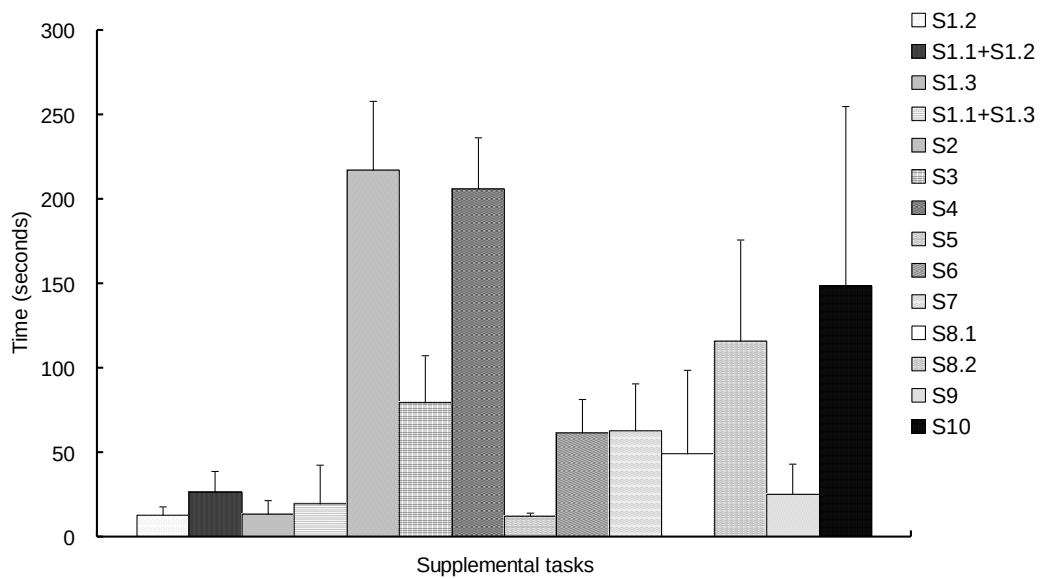


Figure 4.14: Time profile of supplemental tasks (error bars indicate +s.d.).

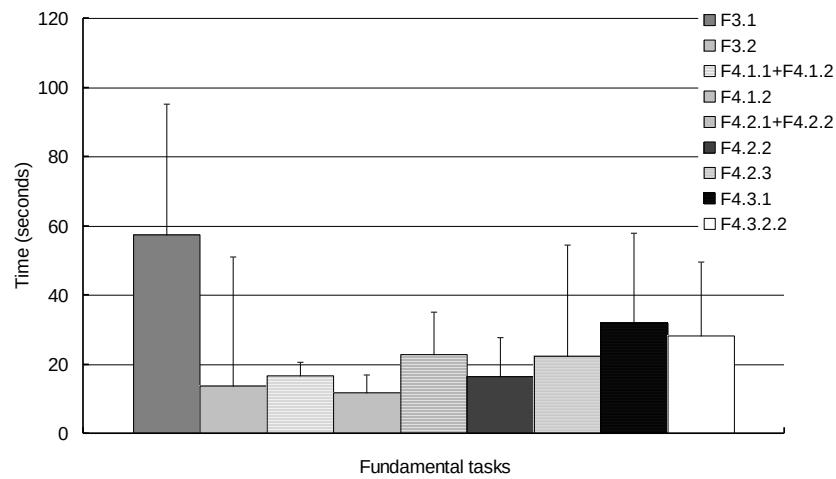
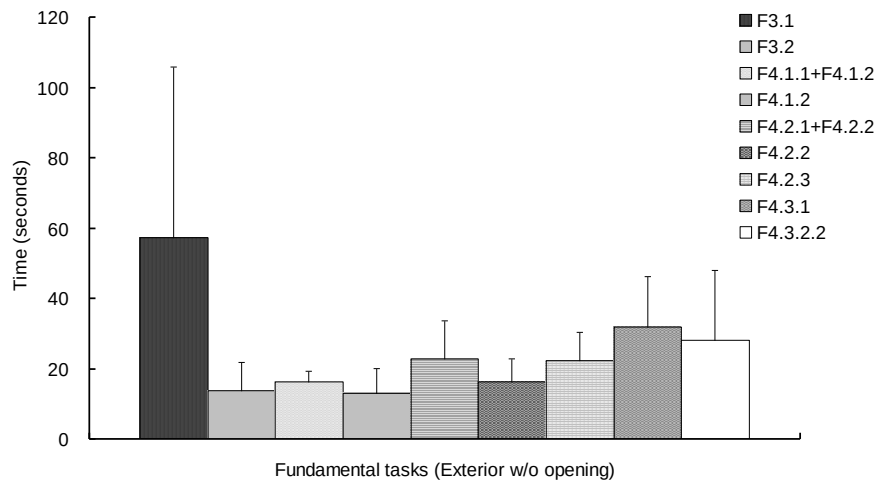
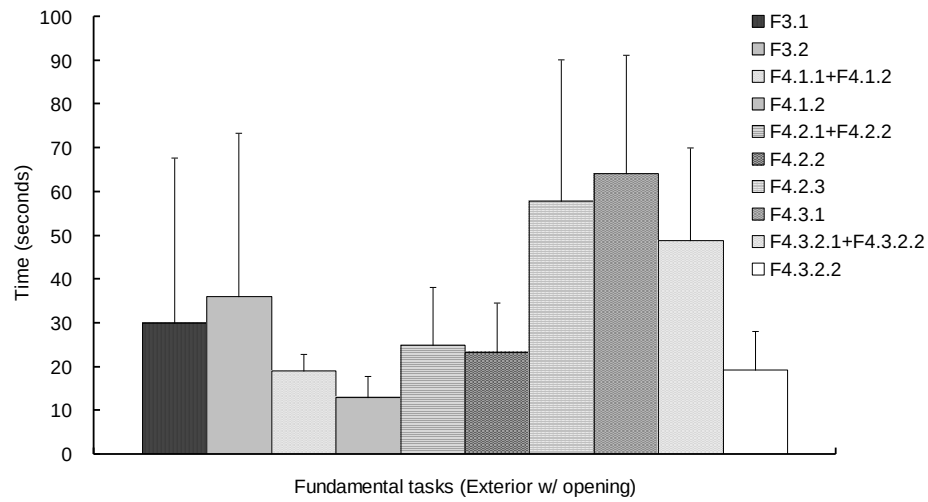


Figure 4.15: Time profile of fundamental tasks for each panel type (TOP: exterior with opening; MIDDLE: exterior w/o opening; BOTTOM: interior panel).

Panel dimensions (length x height) were obtained from panel layout drawings if available; otherwise, panel dimensions were estimated from video recordings. The weight of a panel was estimated based on the HUD report (Michael et al., 2000) because panel layout drawings provided no information on weights or material properties of panel components. The HUD report provided no estimate for weight of exterior walls with opening. Thus, it must be noted that panel weights given below are conservatively approximated and the same estimate was employed for both the exterior wall with opening and without opening. The weight of an exterior wall with an opening may be over-estimated in a large extent due to the fact that sizes of openings and header materials for opening were not taken into account.

The width of a panel varies from 0.15 to 4.5 meters and the height of panels ranged from 0.9 to 3.3 meters. The most commonly observed panel dimensions and estimated weights are:

- 3 m x 2.4 m (98.9 kg for the exterior and 41.3 kg for the interior)
- 2.4 m x 2.4 m (79.1 kg for the exterior and 33 kg for the interior)
- 1.8 m x 2.7 m (66.7 kg for the exterior and 27.9 kg for the interior)
- 1.8 m x 2.4 m (59.3 kg for the exterior and 24.8 kg for the interior)
- 1.2 m x 2.7 m (44.5 kg for the exterior and 18.6 kg for the interior)
- 1.2 m x 2.4 m (39.6 kg for the exterior and 16.5 kg for the interior)

The largest panel observed was 4.5 m x 2.4 m (61.9 kg) for an interior panel and 4.2 m x 2.7 m (155.7 kg) for an exterior panel.

An average time for the panel erection is shown in Figure 4.16 with respect to the panel types. The average time was computed for each construction site. Supplemental tasks were not considered as the supplemental tasks vary across construction sites and supplemental tasks may be considered as unproductive (albeit necessary) activities (e.g., repeating Put aside panel (S2), Level installed panels (S6), etc). It is evident that exterior panels require a longer erection time than interior panels. The average erection time without considering supplemental tasks is 159 seconds (2 min. 39 sec.) for an exterior panel with opening, 127 seconds (2 min. 7 sec.) for an exterior panel without opening, and 83 seconds (1 min. 33 sec.) for an interior panel.

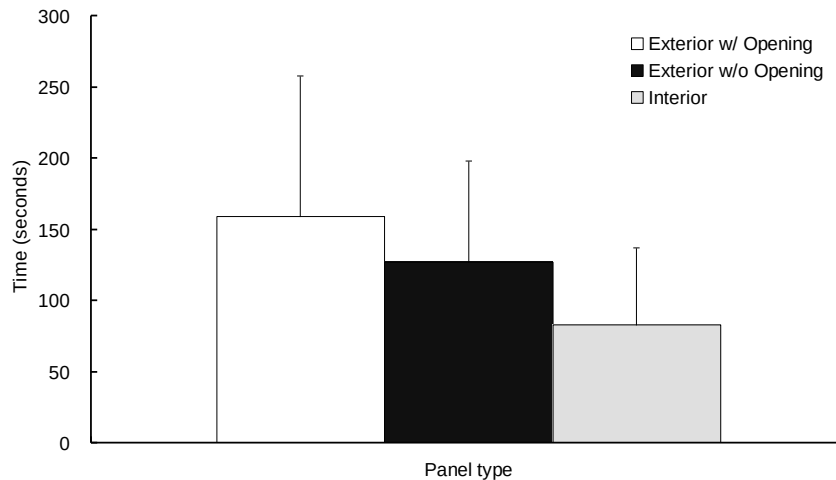


Figure 4.16: Average time for the panel erection, not including supplemental tasks.

Primary panel handling techniques

A total of 1443 panel handlings were recorded and are summarized in Table 4.4 and Table 4.5 which provide the frequency of each handling and its percentage. Table 4.4 shows that both lifting techniques (L1 and L2) are almost equally employed and L2 is dominantly employed for the interior panels. In Table 4.5, the horizontal carrying technique (C1) appears to be the most commonly-employed carrying technique. However, carrying techniques (C2 and C3) are equivalent in a large sense in that both techniques keep a panel vertical during carrying. In this regard, the horizontal carrying technique (C1) accounts for 41% of total observations and the vertical carrying technique (C2 and C3) accounts for 32.5% of total observations. Overall, the dominant technique for each handling activity is different according to the panel type, although the number of observations for each type of panel was not equivalent. The review of video recordings showed that lifting and carrying techniques, in general, tend to change as the panel erection process advances. Techniques with which a panel can be vertically oriented are more often employed during the later phase of the panel erection process since working space becomes limited due to installed panels.

Table 4.4: Summary of primary panel handling techniques (Lifting, Erecting and Lowering).

Activity	Technique	Panel type	Initial hand position	Number of workers Mean (min, max)	Total frequency
Lifting	L1: 191 (50.7%)	A: 63 (33%) B: 47 (24.6%) C: 81 (42.4%)	Ground: 58 (30.4%)	2 (1, 4)	377
			Knee: 48 (25.1%)	2 (1, 3)	
			Knuckle: 37 (19.4%)	2 (2, 4)	
			Elbow: 34 (17.8%)	2 (1, 5)	
			Shoulder: 10 (5.2%)	2 (1, 3)	
			Above shoulder: 4 (2.1%)	2 (1, 3)	
			Below ground: 1 (0.5%)	1 (1, 1)	
	L2: 186 (49.3%)	A: 29 (15.6%) B: 23 (12.4%) C: 134 (72%)	Ground: 60 (32.3%)	1 (1, 3)	
			Knee: 19 (10.2%)	1 (1, 2)	
			Knuckle: 15 (8.1%)	1 (1, 2)	
			Elbow: 44 (23.7%)	1 (1, 3)	
			Shoulder: 27 (14.5%)	2 (1, 3)	
			Elbow-Waist (Knee): 20 (10.8%)	2 (1, 3)	
Erecting	E1: 165 (81.7%)	A: 54 (32.7%) B: 37 (22.4%) C: 74 (44.8%)	Ground: 35 (21.2%)	2 (1, 4)	402
			Knee: 12 (7.3%)	2 (1, 4)	
			Knuckle: 43 (26.1%)	2 (1, 4)	
			Elbow: 49 (29.7%)	2 (1, 4)	
	E2: 37 (18.3%)	A: 5 (13.5%) B: 4 (10.8%) C: 28 (75.7%)	Shoulder: 26 (15.8%)	2 (1, 3)	
			Knuckle: 5 (13.5%)	2 (1, 3)	
			Elbow: 22 (59.5%)	2 (1, 3)	
			Shoulder: 10 (27%)	1 (1, 2)	
Lowering		A: 33 (26.8%) B: 25 (20.3%) C: 65 (52.8%)		2 (1, 5)	123

* Type A: the exterior wall with opening

* Type B: the exterior wall without opening

* Type C: the interior wall

Table 4.5: Summary of primary panel handling techniques (Carrying and Moving).

Activity	Technique	Panel type	Transfer dist. Mean ± s.d. (meters)	Time duration Mean ± s.d. (seconds)	Number of workers Mean (min, max)	Total frequency
Carrying	C1: 165 (41%)	A: 59 (35.8%)	3.8 ± 2.7	11 ± 7	2 (2, 5)	402
		B: 44 (26.7%)				
		C: 62 (37.6%)				
	C2: 46 (11.4%)	A: 2 (4.3%)	3.3 ± 2.3	9 ± 5	2 (2, 3)	
		B: 3 (6.5%)				
		C: 41 (89.1%)				
	C3: 85 (21.1%)	A: 3 (3.5%)	4.2 ± 3.0	9 ± 7	2 (2, 3)	
		B: 3 (3.5%)				
		C: 79 (92.9%)				
C4 _A : 51 (12.7%)	A: 3 (5.9%)	3.9 ± 2.0	9 ± 4	1 (1, 1)		
	B: 3 (5.9%)					
	C: 45 (88.2%)					
C4 _B : 39 (9.7%)	B: 3 (7.7%)	3.6 ± 2.4	9 ± 7	1 (1, 1)		
	C: 36 (92.3%)					
	A: 1 (6.3%)					
C4 _C : 16 (4%)	B: 3 (18.8%)	4.6 ± 3.7	7 ± 4	1 (1, 1)		
	C: 12 (75%)					
	A: 1 (6.3%)					
Moving	M1: 252 (74.3%)	A: 55 (21.8%)	1.9 ± 1.85	8 ± 8	2 (1, 4)	339
		B: 34 (13.5%)				
		C: 163 (64.7%)				
	M2: 80 (23.6%)	A: 29 (36.3%)	1.7 ± 1.2	6 ± 4	2 (1, 3)	
		B: 16 (20%)				
		C: 35 (43.8%)				
	M3: 7 (2.1%)	A: 5 (71.4%)	1.5 ± 1.2	7 ± 6	1 (1, 2)	
		B: 1 (14.3%)				
		C: 1 (14.3%)				

* Type A: the exterior wall with opening

* Type B: the exterior wall without opening

* Type C: the interior wall

Remarks

Time durations and panel handling techniques for the tasks involved in the panel erection were quantified by the work sampling method. Time durations and panel handling techniques were varied by panel type (i.e. panel size and weight) and environmental conditions (e.g. work space).

The developed HTA for panel erection enabled us to capture a general panel erection process by introducing two functional categories for a task and its subtasks (*fundamental* and *supplemental*). Various work paths of plans in HTA highlighted a dynamic nature of the panel erection process, illustrated in Figure 8—12. In particular, the plan for supplemental tasks has no structured work path since they can be performed as required at any point of fundamental tasks. This makes the panel erection process more dynamic.

The amount of panel handling work in panel erection appears to increase with undesirable or unexpected conditions such as:

- An initial position of a panel stack — A panel stack can be placed on the deck or off the deck. When a panel stack is off the deck, workers first have to move all the panels to the deck. When a panel stack is on the deck, a position where the stack is placed may lead to additional panel handlings;
- Misinterpretation (or incorrectness) of panel layout drawings — Misinterpretation can be caused by unclear layout drawings, unclear panel numbering and workers' mistakes. This can result in erection of a panel on the wrong location, and will create additional panel handlings to re-install misplaced panels ;
- Worker's decision on panel erection order — Panel documents that come with panel stacks provide no information on panel erection order. Thus, workers have to decide each time which panel needs to go first based on their knowledge and experience. Depending on their decision, additional panel handlings may be required;
- Precision related to the panel size — A panel that does not fit in place can cause additional handlings such as modification of a panel and subsequent double-handling of the panel;
- Damaged panel during delivery — A damaged panel can cause additional handlings such as modification of a panel and subsequent double-handlings.

Overall, any type of error related to panel erection is likely to lead to an increase in the number of panel handlings. Further, it is important to note that all the errors enumerated above are not simply induced by workers' mistakes on sites. Some of these errors originate from the design phase but there is little communication between the factory designers and the workers on-site, which makes this problem worse. Errors leading to the number of panel handlings are expected to negatively influence not only productivity and efficiency on site, but also ergonomic exposures of on-site workers. Consequently, ergonomics in panel design should be incorporated during the panel design phase (and the manufacturing phase) to eliminate or minimize errors leading to the number of panel handlings. To incorporate ergonomics in panel design, panel designers are expected to be empowered with computerized ergonomic assessment tools that evaluate the ergonomic impact of varying panel designs during the panel design phase.

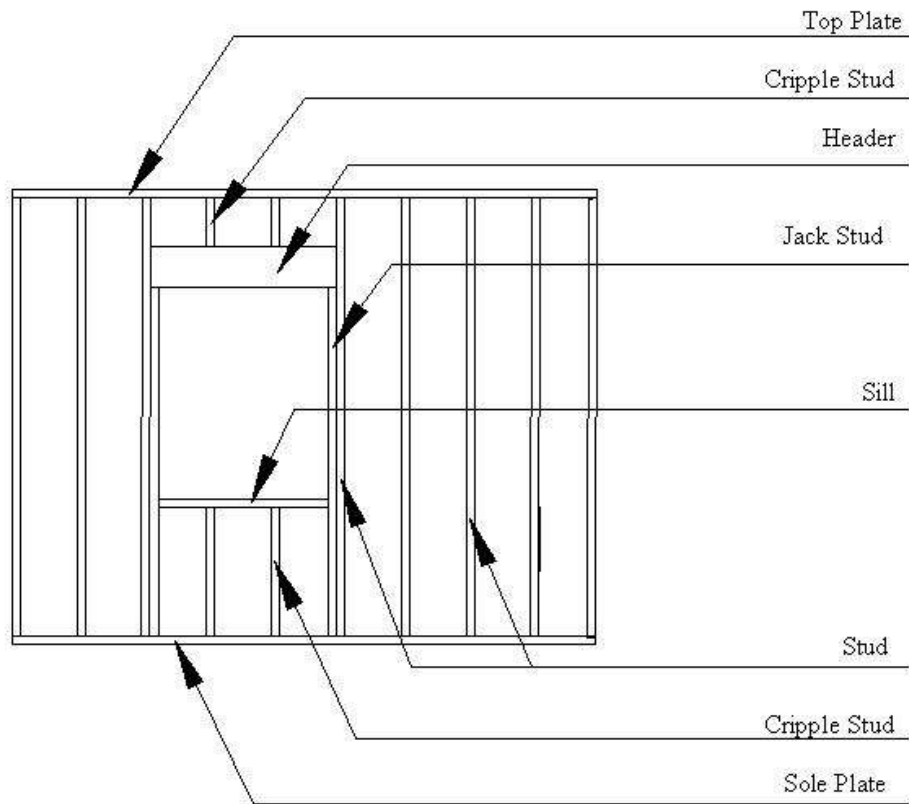
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Appendix

Panel terminology



Glossary

- Top plate: A plate that is placed at the top of a panel wall
- Sole plate: A plate that is placed at the bottom of a panel wall
- Header: A horizontal frame member over an opening frame (i.e., window or door) in the wall
- Jack stud: A stud that does not span the full height of a panel. It is used to support a header
- Cripple stud: A short stud between a top plate and a header, or between a sole plate and a sill.
- Sill: A horizontal member at the bottom of an opening frame to close the ends of cripple studs and to support the frame
- Sheathing: A covering nailed directly over a panel wall to distribute loads, strengthen the assembly of a wall.

5. Development of Decision Support Tool

This section summarizes our conceptual approach to developing the tool, and presents some preliminary results.

Given the building plan (blueprint) for a home, we divide the required decision-making into three steps. The first is concerned with establishing the panelization design, i.e., what panels to employ (dimensions, quantity of and location of openings) for a given plan. Next, we establish the stacking plan, which involves how panels are to be arranged into stacks, the stack delivery locations, and the stack delivery sequence. Finally, we generate the construction plan: how panels are sequenced for construction followed by which construction tasks are to be used and which workers perform which tasks.

To establish how good a particular solution (panelization design, stacking plan, and construction plan) is, three measures are employed: 1) some aggregate measure of overall ergonomic risk, 2) the quantity of workers used, and 3) total construction time. The overall objective in design and planning is to minimize one of the three measures, subject to specified constraints on the other two. Thus, ergonomic aspects are considered directly in formulating the panelization design, stacking plan, and construction plan, an approach that should improve worker health, safety, and performance. Previous efforts to develop computer-aided software tools for construction planning have separated ergonomic aspects from construction planning and scheduling. However, our goal is to address ergonomics in both design and planning, consistent with the PtD concept and approach.

Nussbaum MA, Shewchuk JP, Kim S, Seol H, Guo C: [2009] Development of a decision support system for residential construction using panellised walls: approach and preliminary results. Ergonomics 52: 87-103

Abstract

There is a high prevalence of work-related musculoskeletal disorders (WMSDs) among residential construction workers, yet control in this industry can be difficult for a number of reasons. A decision support system (DSS) is described here to allow early assessment of both ergonomic and productivity concerns, specifically by designers. Construction using prefabricated walls (panels) is the focus of current DSS development, and is based conceptually on an existing 'Safety in Construction Design' model. A stepwise description of the development process is provided, including input from end users, taxonomy development and task analysis, construction worker input, detailed laboratory-based simulations, and modeling/solution approaches and implementation. Preliminary results are presented for several steps. These results suggest that construction activities using panels can be efficiently represented, that some of these activities involve exposure to high levels of WMSD risk, and that several assumptions are required to allow for ease of mathematical and computational implementation of the DSS. Successful development of such tools, which allow for proactive control of exposures, is argued as having substantial potential benefit.

Introduction

An ongoing need exists to reduce the prevalence of work-related musculoskeletal disorders (WMSDs) among residential construction workers. Our focus here is on residential carpenters, and specifically the process of wall erection using pre-fabricated (panelized) wall systems. In the U.S., residential building construction is the seventh largest industry, involving about 4% of annual national economic activity (NAHB Research Center 2002). Compared to the general workforce, occupational injury rates are high in construction, with over 150,000 non-fatal workplace injuries and illnesses reported in the U.S. in 2005 (BLS 2005). Roughly 20% of these cases were attributed to overexertion and repeated motion. In Washington state, residential building construction was among the three highest industry groups for the most common and costly occupational injury types (Bonauto *et al.* 2006).

Control of WMSDs in construction can be more difficult than in many other industries, and a number of authors have highlighted the problems involved. Field studies are hampered by non-continuous employment and a changing and unpredictable workplace (Ringen and Stafford 1996), as well as substantial task variability and irregular work periods (Forde and Buchholz 2004). These, and an often complex project and organizational configuration, make construction a “demanding section in which to conduct research”, and may explain the relative dearth of papers on construction, even with it being a major economic activity around the world (van der Molen *et al.* 2005). As a result, the construction industry has been slow to address construction safety, despite the concerns noted above (Gambatese *et al.* 1997), and the same appears to be the case for ergonomics issues.

Safety in (construction) design has recently been promoted and studied in the construction industry (e.g. Gambatese *et al.* 1997, Gambatese and Hinze 1999, Hecker and Gambatese 2003, Weinstein *et al.* 2005). In this approach, primary attention is given to eliminating hazards through engineering design, with an expectation of improved outcomes relative to other approaches in the hierarchy of control strategies (Roland and Moriarty 1990, Sweeney *et al.* 2000). More specifically, it is argued that construction designers can substantially influence construction site safety by integrating safety considerations during the design process (Gambatese and Hinze 1999). Existing evidence suggests that a substantial fraction of injury-causing accidents stem from conditions ‘upstream’ of the actual construction process, at the stages of planning, scheduling, and design (Gambatese *et al.* 2005, Weinstein *et al.* 2005). Further, analysis by Hecker and Gambatese (2003) suggests that more than half of construction accidents can be eliminated, reduced, or avoided with more attention during design. Our approach described here is consistent with the safety in design concept, though modified to address ergonomic concerns.

Panelization (or panelized walls) refers to one example of the current trend in residential construction toward increasing use of premanufactured components. Panelized walls are in contrast to traditional ‘stick built’ walls, where the latter involves the familiar process of assembling and erecting walls starting from relatively raw lumber. Panels, in contrast, arrive at the work site more completely assembled. A panel designer, working from an architect’s drawing, specifies panel sizes (typically lengths) and several aspects of pre-assembly (i.e. from wood only to complete with sheathing, conduit, insulation, etc.). A carpentry crew transfers and erects the panels at required locations on site.

Previous work (Wakefield *et al.* 2001) has documented the present and fairly rapid shift among residential U.S. production builders to panelized forms of construction. Panelization is also representative of other premanufactured construction materials, in that it tends to be a post-design activity undertaken by a subcontractor who ultimately provides fabrication and delivery services to a site erection subcontractor. This current trend toward panelization within the housing industry thus provides an opportunity to develop an ergonomic analysis tool, since the centralized panel designer can impact a large number of construction sites and workers.

In this paper, a sequential approach is described to yield a tool that allows panels designers to consider ergonomic risk when developing panel designs. Specifically, we intend for use of the tool to result in construction plans that reduce exposure to WMSD risks among residential carpenters who use panels. As described, ergonomics issues are incorporated along with more traditional production aspects (e.g. staffing needs, costs, time requirements), in order to increase the likelihood of and decrease impediments to adoption of the tool, and to facilitate a larger-scale optimization of the design-build process. Along with an overview of the approach, preliminary results from several of the steps are provided.

Approach

Our objective is to develop a computerized decision support system (DSS) for residential construction using panelized walls. Given the building plan (blueprint) for a home, we can divide the required decision-making into two phases: design and planning. The design phase is concerned with establishing the *panelization design*: what panels to employ (dimensions, quantity of and location of openings) and the layout (arrangement) of panels. Given a panelization design, the planning phase then establishes the *construction plan*: how panels are to be delivered to the site, what construction tasks are necessary, and when these tasks are performed and by whom (i.e., construction schedule).

A field study of mechanical installation work has shown that over 50% of the total time observed on construction sites is nonvalue-adding time in terms of interruption, disturbance, communication and preparation (Vedder and Carey 2005). A good *construction schedule* can reduce nonvalue-adding time in construction, and thus improve efficiency. To establish how good a particular solution (panelization design and construction plan) is, three measures are suggested: some aggregate measure of overall ergonomic risk β , the quantity of workers used W , and the total construction time T . The overall objective in design and planning will be to minimize one of the three measures, subject to specified constraints on the other two. Thus, ergonomics aspects are considered directly in formulating the panelization design and construction plan, an approach that should contribute to improving worker health, safety, and performance (van der Molen *et al.* 2005). Previous efforts to develop computer-aided software tools for construction planning (e.g., Chantawit *et al.* 2005) have separated ergonomics aspects from construction planning and scheduling. As previously stated, our goal is to address ergonomics from the design stage, since such early integration of ergonomics aspects is likely to be most effective (Fadier and Garza 2006).

We assume a finite set of alternative materials and configurations are available for panelization, and that a finite set of generic construction tasks can be identified and quantified, via laboratory-based experiments, with respect to ergonomic risk and performance (i.e., task

time). Furthermore, the generic construction tasks and laboratory-based data can be used to generate reasonably-accurate, stochastic predictions of ergonomic risk and performance for any particular construction task and panel definition. Additional assumptions are as follows: (i) all workers are identical with respect to risk and performance (to keep the problem manageable), (ii) no defective panels (extremely low defect rates are readily attainable via lean and six sigma programs at panel manufacturers), (iii) negligible setup time for all tasks, and (iv) all construction tasks have 100% likelihood of being completed successfully on the first try (i.e., no rework). Each of these assumptions can be relaxed, if appropriate data are available.

The assumptions of finite panelization materials/configurations and quantifiable construction tasks allow panelization design and construction planning to be modeled as discrete optimization problems. In each case, a finite quantity of solutions is possible and the objective is to find the 'best' (i.e., optimal) solution. The problems are too large to solve optimally, however, so heuristic (approximate) methods are employed. Different heuristics will result in different solutions (i.e., panelization designs and/or construction plans) for a given problem. To establish performance (β , W , or T) for a given solution, the entire construction process – from panels arriving at the drop-off locations through completion of panelized construction – is simulated. Simulation has been shown to be an effective technique to evaluate decision-making on construction sites (Shi 2003). Here, the simulation will provide not only performance (β , W , or T), but also detailed output concerning ergonomic risk, worker utilizations, etc. Additionally, a low-fidelity simulation animation will be possible, allowing the designer to 'see' the construction process in action and get a feel for how the workers must work together, whether some workers appear busier than others, etc.

While the construction tasks for each panel and construction schedule are established as part of construction planning, it is anticipated that simply providing these items to workers and expecting them to follow will not always be feasible. Workers may be unable and/or unwilling to work in this manner, tasks may be short and numerous enough that too much time is wasted checking the schedule, etc. Additionally, emphasizing adherence to a rigid construction schedule can result in reduced productivity and quality, such that the actual schedule benefits may be barely worth the effort (Nepal *et al.* 2006). An alternative approach will be to provide workers with *construction rules* which, when followed, ideally result in the desired assignment of construction tasks and construction schedule. This approach also has the advantage that it allows workers to react to changes and unplanned contingencies that might quickly invalidate plans made in advance.

Based upon the above, the DSS will operate as follows (Figure 5.1):

1. The designer first selects the overall (global) objective for the construction problem: minimize overall ergonomic risk β , quantity of workers W , or total construction time, T . Constraints are then specified for the other two variables.
2. The designer inputs values for the design parameters (e.g., possible panel drop-off locations).
3. The designer selects the desired solution methodology (i.e., particular combination of solution methods) to be used. This is explained in detail in Section 6.

4. The DSS then outputs (i) the panelization design and construction plan, and (ii) the value of the selected objective variable (β , T , or W). The designer can then view a simulation animation of the construction process, if desired. Additional output (e.g., ergonomic risks and worker utilizations) is also available for in-depth analysis.
5. If desired, the designer changes the solution methodology (i.e., one or more solution methods) and re-runs the problem through the DSS.
6. The designer evaluates all solutions generated and selects the most appropriate one.

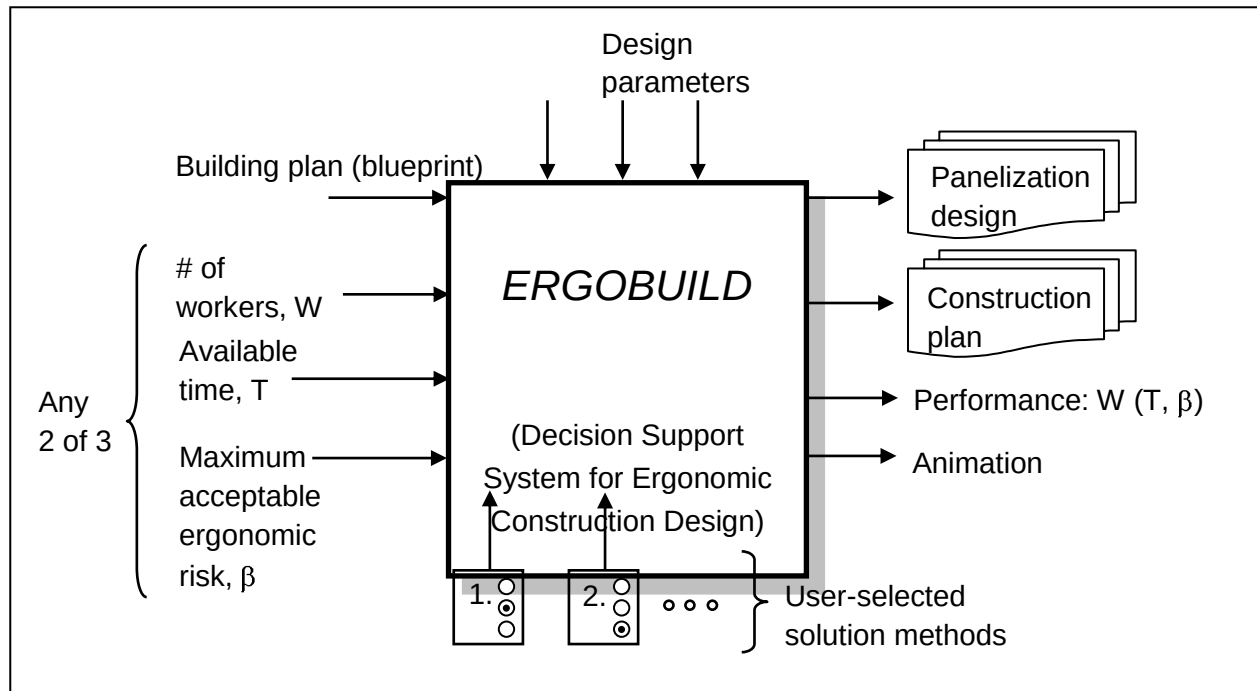


Figure 5.1: Top-level input/output diagram for decision support system. Once the above process is complete, the results are used as follows. The panelization design, panel drop-off locations, and panel stacking order at each location are provided to the panel manufacturer and transport company (if an external agent is used), so the panels can be manufactured and delivered accordingly. If deemed practical, the construction tasks for each panel and construction schedule can be forwarded to the construction site for the workers to follow in building the house. Otherwise, the construction rule employed for the chosen solution is provided to the job site and communicated to the workers, who then perform their own decision-making during the building process.

To implement the above approach, several tasks are necessary. Broadly speaking, the tasks can be divided into three categories:

- i) generic modeling of construction tasks (lift panel, move panel, etc.) and laboratory-based generation of ergonomic and performance data for such tasks.
- ii) modeling and solution of the panelization design and construction planning problems, via the generic construction tasks and ergonomic/performance data from (i).
- iii) implementation of (i) and (ii) via the DSS.

In the following sections, a summary is first provided of input obtained from designers that will be used to guide DSS development. An overview is then given of our approach to generic modeling and laboratory-based data collection, followed by a description of how the panelization design and construction planning problems are addressed.

Input from End Users

As defined by Gambatese (2000), most design-bid-build project delivery efforts include a 'designer' who is a professional with expertise in one of several disciplines (e.g. architecture, structural or mechanical engineering, etc.). Given our focus on a proactive (design-based) approach, versus one that relies on the behaviors of workers, and given that designers are ultimately the individuals who can ensure that delivered construction materials can be safely assembled into end products, we consider the *residential construction designer* (in particular the panel designer) as our end user. This is not to ignore the on-site construction worker, as their health and safety is our end goal (see Section 4.3 for results concerning worker perceptions of physical demands).

We seek to take advantage of the knowledge and experience of panel designers, and to ensure that the end product is both usable and useful. Given our intent to incorporate ergonomics in panel design, there was thus a need to determine the following among panel designers: knowledge of ergonomics; perceived barriers to including ergonomics into design; and opinions regarding whether ergonomics has a role in design. In addition, current practices needed to be identified, including whether there are existing panelization design rules, principles, and practices.

We recently completed an investigation into these issues (Kim *et al.* In Press) with a sample of panel designers in the eastern U.S. They reported having little knowledge about ergonomics or the potential impact of their panel designs on the ergonomic risks incurred by construction workers. As a whole, they were neutral or slightly resistant to incorporating ergonomics in their designs, primarily due to a perceived lack of responsibility for worker health, limited potential influence, and an anticipation of increased workload and costs and decreased flexibility. They were also neutral to slightly negative regarding the feasibility of including ergonomics in their designs, yet most agreed on the necessity to reduce health and safety risks. Any software tool that incorporates ergonomics must address and/or overcome these perceptions and beliefs.

Results from this investigation also highlighted that software must also accommodate or address current design practices. Panel designers indicated that transportation and stacking issues were key in driving decision making, and that panel weight and crew size were low in

importance. The latter two would appear to be of greatest consequence for ergonomic exposures. Panel manufacturers also have standard panel dimensions, which are based on shipping costs, trucking capacity, standard lumber dimensions, etc. These must be accommodated, in order to avoid excessive increases in manufacturing costs.

Taxonomy and Task Identification

Even with the relatively narrow scope of panelized wall construction, the discrete tasks used and variability of methods employed are likely extensive. In order to ergonomically assess panelized construction methods, a descriptive approach is first required, to yield an understanding of the process and the specific tasks involved. Findings from such a descriptive approach can then guide more detailed investigations, as hazard identification should precede exposure measurements (Schneider and Susi 1994).

Therefore, this step had three objectives. The first was to develop a taxonomy of the panel erection process. A broad or taxonomic approach permits more complete hazard identification, by characterizing the process and identifying frequently performed tasks with high risk exposures (Moir *et al.* 2003). The second objective was to provide a descriptive basis for detailed lab-based biomechanical analysis of identified tasks, specifically the characteristics of panel erection tasks involving manual material handling. The third objective was to obtain preliminary indications of which tasks involved the highest levels of physical demands, in order to focus the subsequent lab-based simulations.

Wall panels are delivered to a work site as pallets, containing 15-40 panels, with a height of 1-3 meters. Panel erection involves a relatively consistent set of procedures. Prior to panel erection, workers draw panel layout lines and mark panel numbers on the floor, according to panel layout drawings that come with panel stacks. The layout lines indicate the actual location of each panel, and the panel number matches with the number labeled on the panel. Afterwards, panel stacks are placed either on the floor or near the floor using a forklift, and workers erect panels in designated locations.

Taxonomic description and assessment of task characteristics were based on video recordings obtained during the framing phase of 10 different home building sites in the Washington, DC area. Both single family and town homes were visited, and crew sizes ranged from three to eight workers. Panel erection was recorded for the first or second floor, depending on the site and status. Prior to any video recording, an informed consent procedure was completed, that was approved by the local IRB.

Hierarchical Task Analysis

Hierarchical task analysis (HTA) was used to develop a taxonomy of the panel erection process. HTA is a broad approach that can effectively organize diverse subtasks of the task of interest (i.e., operations), and can establish conditions that determine when subtasks are carried out to achieve operating goals (Kirwin and Ainsworth 1993). Overall, HTA is a hierarchical tool used to develop a description of the task in terms of operations and conditions. Operations are simply referred to as subtasks that constitute a task of interest (hereafter the term task is employed instead of operation for simplicity). A series of conditions is, in general, referred to as

a plan. In the current taxonomy, two conceptual levels (i.e., tasks and subtasks) were used, and two functional categories were introduced (fundamental and supplemental) as described below.

Tasks are central to developing an HTA. Tasks can be defined as a sequence of subtasks and/or activities performed by an individual or a group of workers to accomplish a specific purpose (Moir *et al.* 2003). Tasks in the panel erection process were identified by review of the video recordings. The name of each task was selected to conform to an operational goal of the task. A task was further divided into subtasks, and multiple levels of subtasks were defined, depending on the level of detail required (or of interest). Separate tasks could share the same subtask.

Here, subtasks were considered equivalent to activities defined by Moir *et al.* (2003). Subtasks were characterized by a series of physical actions (e.g., lifting, lowering, twisting, etc) that an individual worker performs to attain a simple work goal and that are transferable from one worker to another. Subtasks were identified when an important change in a series of physical actions was observed. In the panel erection process, a group of workers usually performs a subtask that includes multiple activities. For example, when nailing down a panel, one worker performs a hammering activity while other workers perform a holding activity to keep the panel in position.

Tasks, including their subtasks, were categorized into *fundamental* tasks and *supplemental* tasks, in order to discriminate tasks that are sequential and commonly observed on every site from tasks that are non-sequential and not commonly observed. That is, *fundamental* tasks are defined as required tasks that are sequentially completed for panel erection. In contrast, *supplemental* tasks are conditionally done during the course of panel erection, depending on house type, builder practice, etc.

Primary handling techniques for lifting, carrying, erecting, moving and lowering activities were identified from review of the video records. Table 5.1 shows the coding system used, and also specifies and describes alternative techniques employed. Panel erection could be comprehensively represented by four fundamental and 10 supplemental tasks (a hierarchical diagram of which is given in Figure 5.2). The fundamental task plan is represented as a flowchart (Figure 5.3), indicating the order in which fundamental tasks are performed and how the supplemental tasks are interrelated. Similar plans were derived for each of the fundamental and supplemental tasks, and subtasks.

Table 5.1: Coding and descriptions of primary panel handling techniques.

Activity	Technique	Description	Notes
Lifting	L1	• Lift panel while it is oriented horizontally	Eight initial hand positions
	L2	• Lift panel while orientating it vertically, so that panel is held vertically at completion of lifting	
Carrying	C1	• Carry panel while in a horizontal orientation	
	C2	• Carry panel while in a vertical orientation	
	C3	• Carry panel oriented vertically while held slanted over the shoulder	
	C4 _{A/B/C}	• Only for a single worker, while other carrying techniques may be done by a single or multiple workers	
		1. C4_A: worker carries unsheathed panel or panel with opening on one shoulder with the arm around the opening of a panel 2. C4_B: worker carries panel by holding panel over the shoulder 3. C4_C: worker carries panel by grasping one side of panel	
Moving	M1	• Push/pull panel while it rests on the deck in a vertical orientation	
	M2	• Push/pull panel by holding up one side of the panel while the other side rests on the deck	
	M3	• Push/pull panel without lifting	
Erecting	E1	• Lower one side of panel to touch the deck and push upward on the panel until it stands vertically	Five initial hand positions
	E2	• Rotate panel to a vertical orientation without touching the deck	
Lowering	LW	• Lower panel onto the floor	

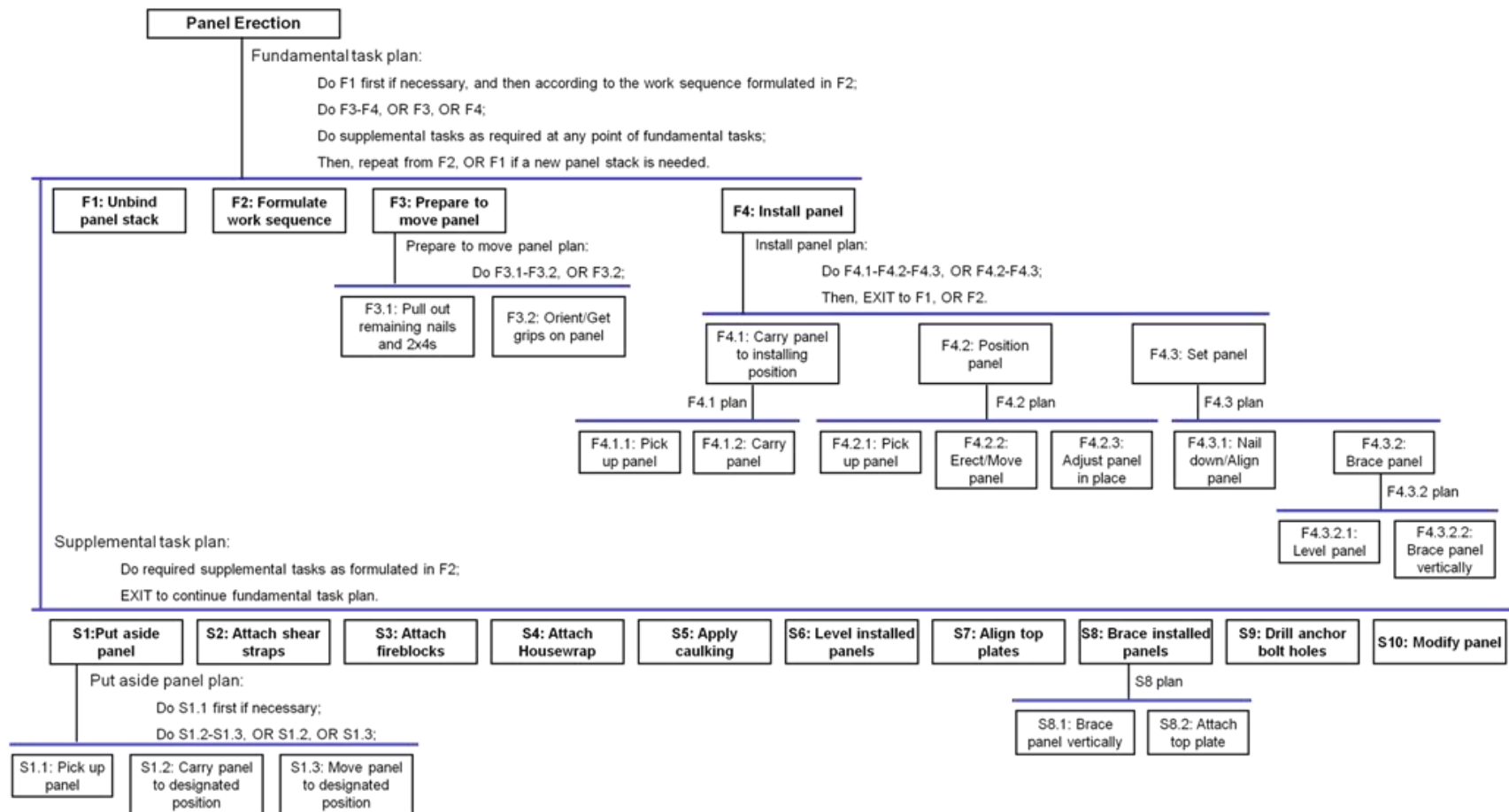


Figure 5.2: Hierarchical diagram for panel erection.

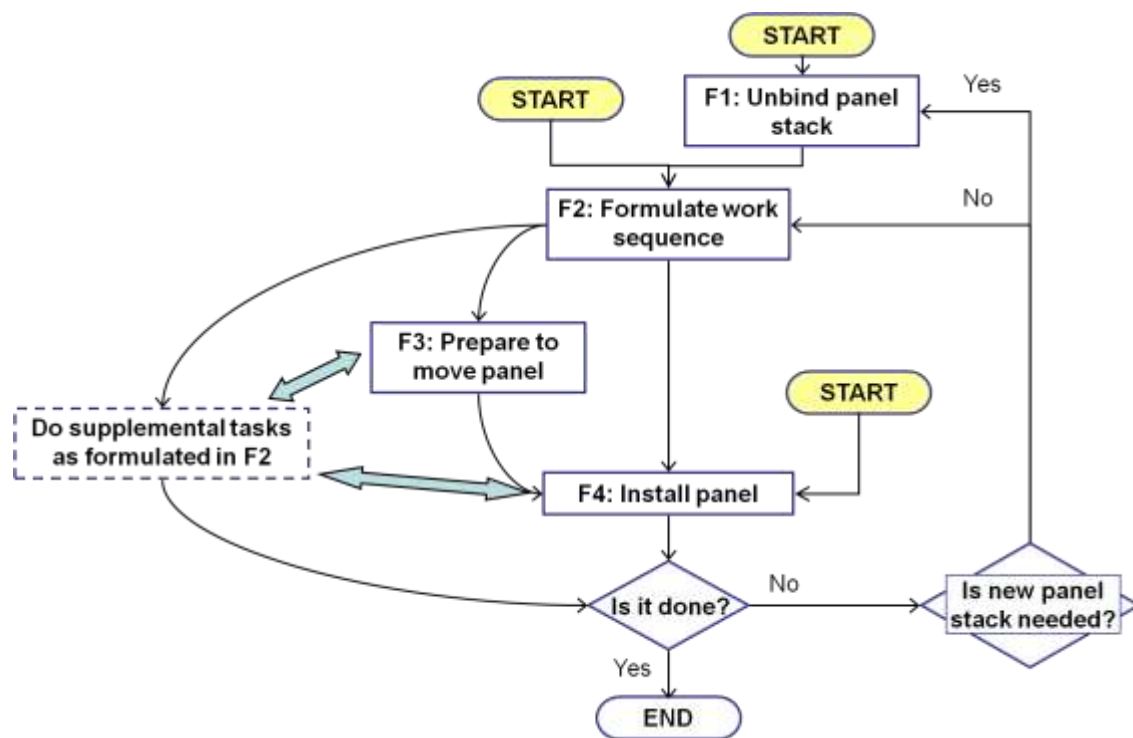


Figure 5.3: Flowchart of fundamental task plan. Panel erection can be completed by beginning the process from three different starting points.

Task Characteristics

While an HTA can describe how and what activities workers actually perform to accomplish the given task, it does not provide detailed quantitative data on how often or how long a certain task, subtask, or activity is conducted. In order to facilitate a better identification of exposures to ergonomic risk factors and guide subsequent lab-based analyses, additional measures were obtained from MMH tasks: primary panel handling techniques, the number of workers, type of panel, time duration, and frequency of each of the identified tasks and subtasks. These were obtained after the HTA was completed; in essence, the HTA served as a framework for the assessment of task characteristics. Primary panel handling techniques and associated activity duration were identified for *lifting*, *carrying*, *moving*, *erecting*, and *lowering* activities. Task characteristics were determined separately by two investigators, and cross-checked to ensure consistency and minimize errors.

Time duration was recorded (from review of the videotapes) only for actual physical efforts; the time required to formulate a work sequence or to interpret a panel layout drawing was not taken into account. In addition, time duration for two work activities were not measured: simple tape measurements without handling of panels or hand tools, and cutting a lumber plate or a piece of lumber to a certain length. The former did not involve any physically demanding activities, and the latter was excluded due to difficulties in tracking all the workers on site. In addition, the time involved in descending a ladder was disregarded because workers were frequently observed to stay on a ladder after completing a job or task.

A total of 1443 panel handlings were recorded, and frequencies identified for alternative techniques, panel types, and other relevant dimensions (e.g. initial hand position, transfer distances, etc.). Examples of two lifting techniques observed are provided in Figure 5.4. Results for lifting, erecting, and lowering are summarized in Table 5.2, while those for carrying and moving are in Table 5.3. Overall, the dominant technique for each handling activity was different according to panel type. A review of the video records, however, showed that lifting and carrying techniques tended to change as the panel erection process advanced. For example, techniques using a vertical panel orientation are more often employed in the later phases, since working space becomes limited by panels already installed.



Figure 5.4: Illustration of two lifting methods (Top: L1, Bottom: L2). Carrying techniques (C1 and C2) are extensions of lifting methods L1 and L2, respectively.

Table 5.2: Primary panel handling techniques (Lifting, Erecting, and Lowering).

Activity	Technique	Panel type*	Initial hand position	Number of workers Mean (min, max)	Total observations
Lifting	L1: 191 (50.7%)	A: 63 (33.0%) B: 47 (24.6%) C: 81 (42.4%)	Ground: 58 (30.4%)	2 (1, 4)	377
			Knee: 48 (25.1%)	2 (1, 3)	
			Knuckle: 37 (19.4%)	2 (2, 4)	
			Elbow: 34 (17.8%)	2 (1, 5)	
			Shoulder: 10 (5.2%)	2 (1, 3)	
			Above shoulder: 4 (2.1%)	2 (1, 3)	
			Below ground: 1 (0.5%)	1 (1, 1)	
	L2: 186 (49.3%)	A: 29 (15.6%) B: 23 (12.4%) C: 134 (72.0%)	Ground: 60 (32.3%)	1 (1, 3)	
			Knee: 19 (10.2%)	1 (1, 2)	
			Knuckle: 15 (8.1%)	1 (1, 2)	
			Elbow: 44 (23.7%)	1 (1, 3)	
			Shoulder: 27 (14.5%)	2 (1, 3)	
			Elbow-Waist/Knee ⁺ : 20 (10.8%)	2 (1, 3)	
Erecting	E1: 165 (81.7%)	A: 54 (32.7%)	Ground: 35 (21.2%)	2 (1, 4)	402

	B: 37 (22.4%)	Knee: 12 (7.3%)	2 (1, 4)	
	C: 74 (44.8%)	Knuckle: 43 (26.1%)	2 (1, 4)	
		Elbow: 49 (29.7%)	2 (1, 4)	
		Shoulder: 26 (15.8%)	2 (1, 3)	
E2: 37 (18.3%)	A: 5 (13.5%)	Knuckle: 5 (13.5%)	2 (1, 3)	
	B: 4 (10.8%)	Elbow: 22 (59.5%)	2 (1, 3)	
	C: 28 (75.7%)	Shoulder: 10 (27.0%)	1 (1, 2)	
Lowering	A: 33 (26.8%)		2 (1, 5)	123
	B: 25 (20.3%)			
	C: 65 (52.8%)			

* Type A: exterior wall with opening

Type B: exterior wall without opening

Type C: interior wall

+ One hand placed at elbow height, the other at waist or knee height

Table 5.3: Primary panel handling techniques (Carrying and Moving).

Activity	Technique	Panel type*	Transfer distance (m) Mean ± s.d.	Duration (sec) Mean ± s.d.	Number of workers Mean (min, max)	Total observations
Carrying	C1: 165 (41.0%)	A: 59 (35.8%)	3.8 ± 2.7	11 ± 7	2 (2, 5)	402
		B: 44 (26.7%)				
		C: 62 (37.6%)				
	C2: 46 (11.4%)	A: 2 (4.3%)	3.3 ± 2.3	9 ± 5	2 (2, 3)	
		B: 3 (6.5%)				
		C: 41 (89.1%)				
	C3: 85 (21.1%)	A: 3 (3.5%)	4.2 ± 3.0	9 ± 7	2 (2, 3)	
		B: 3 (3.5%)				
		C: 79 (92.9%)				
	C4 _A : 51 (12.7%)	A: 3 (5.9%)	3.9 ± 2.0	9 ± 4	1 (1, 1)	
		B: 3 (5.9%)				
		C: 45 (88.2%)				
	C4 _B : 39 (9.7%)	B: 3 (7.7%)	3.6 ± 2.4	9 ± 7	1 (1, 1)	
		C: 36 (92.3%)				
		A: 1 (6.3%)				
	C4 _C : 16 (4.0%)	B: 3 (18.8%)	4.6 ± 3.7	7 ± 4	1 (1, 1)	

		C: 12 (75.5%)				
		A: 55 (21.8%)				
	M1: 252 (74.3%)	B: 34 (13.5%)	1.9 ± 1.85	8 ± 8	2 (1, 4)	
		C: 163 (64.7%)				
		A: 29 (36.2%)				
Moving	M2: 80 (23.6%)	B: 16 (20.0%)	1.7 ± 1.2	6 ± 4	2 (1, 3)	339
		C: 35 (43.8%)				
		A: 5 (71.4%)				
	M3: 7 (2.1%)	B: 1 (14.3%)	1.5 ± 1.2	7 ± 6	1 (1, 2)	
		C: 1 (14.3%)				

* Type A: exterior wall with opening

Type B: exterior wall without opening

Type C: interior wall

Time durations were obtained from 1321 fundamental and 614 supplemental tasks. Summary statistics for the fundamental tasks are given in Table 5.4, with similar results available for the supplemental tasks. In some cases, tasks were inseparable, in that they are done simultaneously, or the time duration of one task is extremely short compared to the other task. For example, F4.1.1 (Pick up panel) + F4.1.2 (Carry panel) indicates that workers carry a panel after lifting the panel off the floor. A transition from lifting to carrying often could not be clearly identified. In these cases, a '+' sign is used in Table 5.4, and time duration is considered an aggregated duration for the completion of both tasks.

Table 5.4: Time durations for fundamental tasks (see text for note regarding '+' signs).

Fundamental task	Time duration (sec.)	Minimum	Maximum
	Mean $\pm$ SD	duration (sec.)	duration (sec.)
<i>Unbind panel stack (F1)</i>	144 $\pm$ 76	57	253
<i>Prepare to move panel (F3)</i>			
F3.1	39 $\pm$ 24	7	88
F3.2	29 $\pm$ 37	9	135
<i>Carry panel to installing position (F4.1)</i>			
F4.1.1 + F4.1.2	16 $\pm$ 5	6	23
F4.1.2	14 $\pm$ 6	7	26
<i>Position panel (F4.2)</i>			
F4.2.1 + F4.2.2	36 $\pm$ 21	17	88
F4.2.2	18 $\pm$ 6	10	26
F4.2.3	38 $\pm$ 12	23	64
<i>Set panel (F4.3)</i>			
F4.3.1	47 $\pm$ 20	20	80
F4.3.2.1 + F4.3.2.2	67 $\pm$ 56	23	130
F4.3.2.2	31 $\pm$ 32	13	85

Worker Questionnaires

A questionnaire was developed to gather opinions of construction workers regarding the physical demands associated with panel erection tasks. Illustrations of the fundamental and supplemental tasks identified above were provided, and participants rated their perceptions of the overall physical difficulty of each task using a 5-point scale (1: not demanding – 5: extremely demanding). In addition, participants indicated which three tasks were thought to be the most physically demanding. Additional questions asked which tasks/subtasks could lead to injuries during installation, in which body parts they experienced soreness or pain during or after panel installation, and aspects of a panel that increased physical demands. Field managers in residential home building companies in the Washington, D.C. area distributed the questionnaire to individual carpenters (both an English and a Spanish language translation were made available), and 18 responded.

Across the different tasks, carrying a panel and modifying a panel on site were rated the most difficult, with mean responses of 3.7 and 3.6, respectively. Carrying (78%) and modifying (39%) panels were also selected as the most and second most frequently as most physically demanding, with erecting a panel selected third most frequently (33%). Carrying (78%) and erecting (57%) panels were most frequently indicated as potentially leading to injury. Body parts most frequently identified were the lower back (50%), upper back (22%), and arms (22%). Several aspects of panels were identified as increasing physical demands, the most frequent being the large size of panels (83%), high weights (50%), panels that don't fit properly (33%), and difficulty in handling (17%).

Laboratory-Based Task Simulation, Exposure Assessment, and Risk Assessment

From the HTA, identified task characteristics, and worker questionnaires, information is available regarding necessary and optional tasks, task sequencing, differences and relatively frequencies of alternative techniques, and the relative physical demands related to primary wall erection tasks. This information, though somewhat crude, can be used to develop higher-fidelity lab-based simulations. Doing so allows for more detailed measurements of exposures, which would otherwise be difficult to obtain in the field.

The design of such lab-based simulations should achieve two goals. First, the tasks should be simulated with a reasonable level of detail and accuracy. Wall erection at a construction site can involve material spread widely and rising multiple stories, yet few labs have such available space. We thus plan to simulate only elemental tasks, specifically those identified from the field observations. Further, the simulations will include alternative methods used (e.g. horizontal and vertical lifting, Figure 4). As not all tasks and alternatives can be feasibly examined, a limited set of simulations will be achieved by identifying combinations that involve apparent physical demands and occur with some frequency. Second, the simulations and exposure assessment should facilitate subsequent ergonomic risk assessment. Below, we indicate a set of risk assessment tools that have been identified. Lab-based measurements must provide the necessary data as input to these tools. Further, it would be prudent to obtain measures for more advanced tools, as well as for future tools that may be developed. A set of measures are planned to achieve these goals, and that can be broadly categorized as anthropometric, kinematic, kinetic, and electromyography (EMG). In all cases, methods to obtain these are fairly standardized, and no fundamentally novel approaches seem needed.

Anthropometric descriptions allow both for comparisons of experimental and worker populations, and serve as input for determining subsequent measures. Kinematic measures (posture and motions) will be obtained to represent the body as a system of linked segments. External kinetics (forces and moments) will be obtained using a combination of load cells (attached to panels) and force platforms. From these data, inverse dynamics analyses will be used to estimate 3-D dynamic external moments at major joints (ankle, knee, hip, lumbar spine, shoulder, elbow, wrist). Finally, activity of major torso muscles will be monitored from surface EMG, to allow for estimates of spinal loading.

Multiple and diverse ergonomic assessment methods are available. We have selected a subset to achieve three ends, specifically ease of implementation, common use, and relevance to panelized wall erection. These methods are not intended as complete, but rather as broad and representative, with each providing distinct output for ergonomic evaluation. Psychophysical limits and two rapid assessment tools will be used to obtain overall evaluations of the lifting tasks. Psychophysical limits (e.g. Snook and Ciriello 1991) are based on studies in which participants determined maximal acceptable levels of physical effort. RULA (McAtamney and Corlett 1993) and REBA (Hignett and McAtamney 2000) allow for assessments of limb postures and loads. Although alternative methods exist, and there is limited validation of these methods to predict injury risks, they are selected based on common use and incorporation of generic injury risk factors.

more quantitative approaches will be based on joint strength demands and an existing guideline for manual lifting. Strength demands refer to the external moments imposed by the panel erection tasks, relative to population capacity (strength). The former is obtained during the lab-based simulation, while the latter is available in software (e.g. The University of Michigan 3DSSPP™). The NIOSH lifting equation (Waters *et al.* 1993) will be used to assess lifting tasks, based on widespread use and incorporation of primary risk factors.

Preliminary results have been obtained using the NIOSH lifting equation applied to 174 observed panel lifts. Both one- and two-person lifts were analyzed, for two types of lifts (L1, panel held horizontal; L2, panel held vertical). Video records, along with panel layout drawings, were used to estimate distance-related multipliers. Asymmetry was estimated by observation, while coupling was set as 'fair'. Frequency multipliers were all set equal to one. Panel masses were estimated from the panel dimensions, and data provided by O'Brien *et al.* (2000). This report, however, did not provide estimates of masses for exterior walls with openings; masses were thus conservatively approximated assuming no openings. Actual masses were likely only slightly overestimated, as header material adds additional mass when openings are present. Results indicated that Lifting Indexes were often quite high, and <1 only for a small proportion of small panels (Figure 5.5). A given panel mass also resulted in a significantly higher lifting index when a vertical lift was performed.

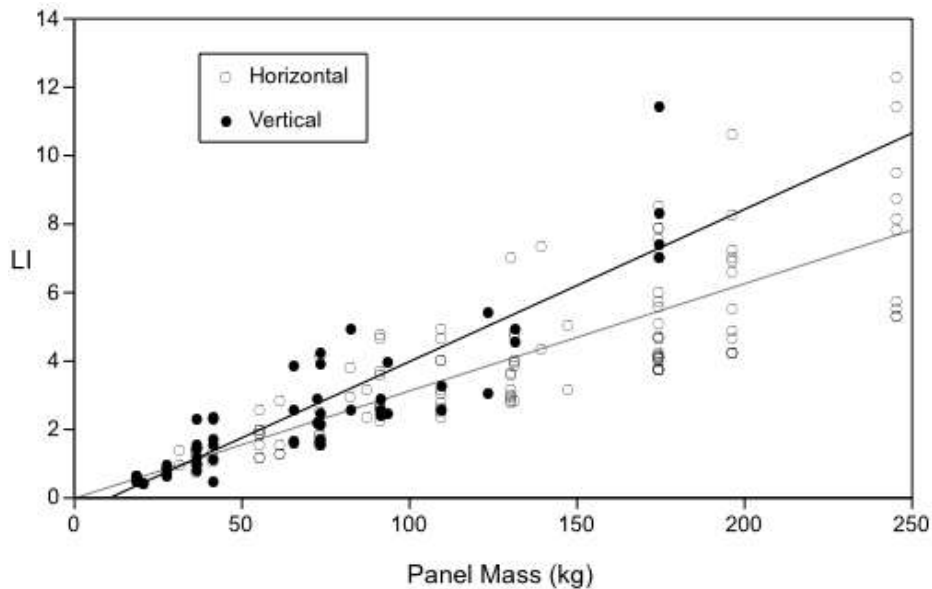


Figure 5.5: Lifting indexes (LI) as a function of panel mass, using two different lifting methods. Linear trends are illustrated for the two lifting methods.

An EMG-based model (e.g. Cholewicki *et al.* 1995, Nussbaum and Chaffin 1998, Staudenmann *et al.* 2007) will be employed to obtain more refined estimates of low back loading and injury risk (i.e. compression and shear forces). An EMG-based approach can directly account for individual differences, and is feasible since EMGs are obtained in the lab-based studies. A final model will be employed to assess postural stability. Falls are the leading cause of death, accounting for roughly a third of all worker fatalities (Hinze 1997; OSHA 1990). In construction, a large fraction of falls are directly related to material handling (Pertulla *et al.* 2003, Fredericks *et al.* 2005). Loss of balance is considered an important causal factor (Hsiao and Simeonov 2001), and our own preliminary work suggests that workers are frequently exposed to fall hazards during panel erection (Kim *et al.* 2006). Though postural stability is a broad construct, it can be operationally defined as the fraction of the base of support traversed by the body center of mass (e.g. Holbein and Redfern 1997, Chow *et al.* 2005) or by the control of linear and angular momentum (e.g. Commissaris and Toussaint 1997).

Modeling and Solution of Panelization Design and Construction Planning Problems

As outlined in section 2, the decision-making required for residential construction using panelized walls can be divided into panelization design and construction planning phases. To improve tractability (i.e. ease of solution), construction planning itself can be decomposed into several smaller problems. The result is six separate sub-problems for residential construction using panelized walls, summarized as follows:

1. *Panelization Design* – panel specifications (dimensions, openings, etc.) and layout.
2. *Panel Stacking* – how panels are arranged into stacks for delivery to the construction site.
3. *Stack Locating* – drop-off location for each stack at the construction site.

4. *Stack Delivery Sequencing* – precedence constraints specifying which stacks must arrive before which other stacks at the construction site.
5. *Construction Task Planning* – construction tasks (lift, move, tilt, etc.), and their sequence, for each panel.
6. *Construction Task Scheduling* – which construction tasks are to be done when, and by which worker(s).

The decomposition approach improves tractability, but has a drawback. Even if an optimal solution is found for each sub-problem, there is no guarantee that the combination of local optimal solutions will result in a global optimum. Thus, while each sub-problem is addressed independently (sequentially), the resulting solution cannot be completely evaluated at that stage; we can only evaluate how good the global (overall) solution is once all sub-problems have been solved. Furthermore, because global optimality cannot be guaranteed, it is desirable to have alternate solution methods (heuristics) available for each sub-problem. A particular combination of solution methods – one for each sub-problem – constitutes a *solution methodology*. For a given construction problem, many solution methodologies are possible. The end user must evaluate the appropriateness of the solution (panelization design and construction plan) and adjust the solution methodology as deemed necessary, as described in section 2. A brief overview of the modeling and solution approaches for each sub-problem now follows.

Sub-Problem 1 Panelization Design

While there is no clear-cut objective in designing panels, the impact of panelization design is obvious: employing larger-size panels means fewer trips but panels are heavier, and vice-versa. The decision logic for panelization can be established based upon user input (section 3) and detailed analysis of the problem. For example, panel lengths are to be in increments of 4' whenever possible, panel breaks must be some minimum distance from corner joints and openings such as walls and doors, and openings should be placed in large panels (as opposed to small) to reduce weight where most beneficial. A choice of design parameters can then be established to specify the panelization procedure exactly. Example design preferences include selection of maximum panel size (12', 16' or 20'), preferred panel size (8', 12', 16' or 20') and where to place remainder panels (left end, right end, or middle of wall).

Sub-Problem 2: Panel Stacking

Once panels are produced, they are stacked together for delivery to the job site. We must establish (i) how many stacks, (ii) the panels in each stack, and (iii) the stacking order for each stack. The panelization plan is divided into *construction zones*, where all panels within a zone form a continuous build structure. The panels comprising each zone then form a different stack. Next, the build sequence for the panels in each zone is established: panels are then placed in this same order in the stack to allow for continuous flow during construction. A build sequence is feasible if (i) each panel connects to at least one panel already in place, (ii) no panel blocks the path needed for a subsequent panel (i.e., no 'traps'), and (iii) no panel goes in-between panels already in place (i.e., no 'squeeze fits'). The objective is to minimize *stack start delay*:

the time workers must wait, once a subsequent stack arrives, before it can be started. If a panel is to connect to another panel already in place, there is increasing delay if the panel is farther down the stack. To help study this problem, a preliminary integer programming (IP) model has been developed (see Appendix). Trapping and squeeze fits are not considered in this simple model. Even so, the model is far too difficult to solve optimally. Heuristics are thus under development.

Sub-Problem 3: Stack Locating

At any site, the ease of access to the structure will vary. For example, a road may lead directly to the south edge of a structure, while trees prohibit access to the north edge. We assume all stacks will be dropped along the same edge of the structure, which is input by the user. The problem is then to establish where along that edge each stack should be placed. This can easily be found in order to minimize total material handling distance.

Sub-Problem 4: Stack Delivery Sequencing

To construct an entire house via panels, many stacks will be necessary. It may not be physically possible to deliver all stacks together (or one right after the other), however, since drop-off locations may result in stacks which physically overlap if present at the same time. Additionally, we must ensure that the stack arrival sequence results in a feasible build process (e.g. if panels are dropped at the structure's south edge, we must start with the north construction zones). As many different stack delivery sequences will be feasible, only stack precedence constraints are established, giving the panel manufacturer flexibility in establishing the actual delivery sequence.

Sub-Problem 5: Construction Task Planning

This problem consists of establishing the sequence of construction tasks needed to get each panel from its initial location/orientation to its final location/orientation in the panelized house. As described in section 4, a generic taxonomy of construction tasks has been developed. For each panel, a sequence of these generic tasks must be established, then parameterized as required (e.g., variable quantity of workers for a carrying task). Because different task types may be possible for a given action (e.g., various carrying tasks can be used to move a panel) and the selected tasks may need to be parameterized, many possible task sequences may be possible for a given panel.

One approach being explored for construction task planning is to simply employ the global objective for the overall panelization design/construction planning problem. For example, if the global objective is to minimize ergonomic risk β , tasks that create the lowest risk are chosen, and then workers assigned accordingly. This may lead to infeasibility, however. Minimizing β , for example, may result in the maximum quantity of workers for all tasks, which could result in fewer panels being worked on in parallel and thus increasing the total time required (and cost) until construction cannot be completed within time/budget. Further work is underway to establish how to address this sub-problem.

Sub-Problem 6: Construction Task Scheduling

The construction task scheduling problem is that of determining which construction tasks are performed when and by which worker(s). The problem closely resembles *job shop scheduling*, where a set of jobs must be processed on a set of machines and each job can visit different machines and in a different order. Job shop scheduling problems are notoriously difficult to solve, and despite extensive research, optimal methods are seldom available (Askin and Standridge 1993). Similarly, deterministic project scheduling for construction projects is also difficult (Ahuja and Thiruvengadam 2004). One widely used and well-studied heuristic approach for job shop scheduling is to employ *dispatching rules*: whenever a job is completed at a machine, a simple rule is used to select the next job to run (e.g., select the job having the shortest processing time). We employ this same approach via the use of *construction rules*: whenever a construction task has been completed by one or more workers, a simple rule can be used by each worker to select the next panel to work on. For example, the rule could be of the following form:

if (tasks where an additional worker can help are available)
 and (one or more of these is $\leq$ a distance x away)
 and (one or more of these $\leq y\%$ complete)
 then from the set of such tasks, select (closest task, task with lowest ergonomic risk, most time remaining, etc.)
 else (go to the nearest panel drop-off site having one or more panels remaining).

Ergonomic and performance (i.e., task time) data are required to execute such rules, and these data are available as described above. By changing one or more parameters, different construction rules are possible. Discrete simulation is then used to determine how construction proceeds, and the resulting construction schedule, for a given construction rule. An example of this overall approach can be seen in Mizark and Bayhan (2006), who compared the performance of dispatching rules in an actual job shop environment and provided guidance for schedulers to determine effective dispatching rules for that type of system.

Simultaneous Solution of Sub-Problems 5 and 6

Analysis of the construction task identification and scheduling problems shows that they are not independent. Some tasks require a certain number of construction workers, so the number of workers available must be known. But this is cannot be determined until the construction schedule is established, which in turn requires knowledge of the construction tasks. Because of this dilemma, both construction task identification and scheduling (sub-problems 5 and 6) should ideally be solved simultaneously. This approach can easily be easily implemented via the use of construction rules (see sub-problem 6). Such rules can be extended so that the next panel and corresponding construction task to employ are chosen together.

To implement the overall approach described above via a decision support system, various software packages are required. These include applications for relational databases (so information on ergonomics exposures and risks, and performance data, can be maintained),

discrete simulation, and discrete optimization. These will all be integrated within a Web-based application, developed using ASP.NET.

Discussion

Residential carpentry is a relatively high-risk occupation in terms of morbidity and mortality. Given the potential for design impact in safety (and arguably ergonomics), however, what accounts for the lack of more substantial designer involvement (Hinze and Wiegand 1992)? Several explanations are apparent from the work of Gambatese and colleagues (Gambatese *et al.* 1997, Gambatese and Hinze 1999; Hecker and Gambatese 2003). Construction designers have limited education and experience related to construction safety, and we have found comparable results with respect to ergonomics (Kim *et al.* In Press). In addition, there is a pervasive attitude that construction work is inherently unsafe and that design has a minimal impact on safety. Compounding this is the traditional construction model, in which there is a strict financial and legal separation between the design process and people and the contractors/constructors. Additional barriers include the range of stakeholders involved, large numbers of often small companies (subcontractors), limited resources, and limited control of workplace conditions by subcontractors (van der Molen *et al.* 2005).

Despite these barriers, enhancing construction safety through design is becoming more common, often via legislation (Lin and Mills 2001, Hecker and Gambatese 2003, Gibb 2004, Lam and Chen, 2004). In the U.S., there appears to be at least a willingness to implement safety in construction design (Gambatese *et al.* 2005). To capitalize on this willingness, and to achieve the potential benefits of ergonomics in construction design, the barriers identified above must be overcome. One particular barrier impeding the implementation of safety in design is the lack of tools or guidelines (Gambatese *et al.* 2005). Our efforts to facilitate ergonomics in residential construction design are focused on the development of a DSS as described above. This tool is intended to enable designers to incorporate ergonomics issues in their design process, specifically for panelized walls.

Most residential construction is a craft-based enterprise, driven by a design, but disconnected from the actual method of assembly and its impact on the human workers. Modern residential designers are typically removed from most on-site production activity, and rely heavily on a distribution of subcontractor construction and installation knowledge associated with the diverse systems that comprise a home. These subcontractors are provided with little or no guidance on acceptable construction methods associated with the design, other than material specification and schedule expectations. The lack of consideration given to the effects of panel design on the construction process or the on-site labor (O'Brien *et al.* 2002), is representative of residential construction processes in general, where fragmentation and sub-optimization are typical.

Our DSS can overcome some of these barriers, but clearly not all. Several advantages, though, are inherent to the DSS. Use of the software will facilitate a more proactive approach to ergonomics in one aspect of residential construction. It also addresses the need expressed by designers for appropriate tools. By addressing ergonomics aspects early in the construction process, and facilitating input by designers, the overall impact is expected to be more efficient and effective than more reactive, site-based interventions. The DSS is scalable, and can incorporate a range of additional tasks or processes involved with panelized wall construction,

assuming requisite input data is available. Use of laboratory-based tasks simulations will provide quite detailed and extensive information on exposures. Such data allows for ergonomic risk assessment using a range of contemporary tools, but the DSS can also be easily adapted in the event that more advanced tools are developed. We suggest also that a primary advantage in our approach is the inclusion of both ergonomics and productivity as basic components. Thereby, a designer (or other user) can quantify the effects of modifications on both fundamental aspects, perhaps by determining a weighting or balance between the two.

It is important to note that the proposed approach is not without cost, however. Different panel sizes and quantities may take more or less time/cost to build at the factory, and changes to stacking and loading of trucks may result in additional loading effort and trips. As this upstream work is expended in the factory, however, where working conditions are controlled and modern equipment and practices employed, substantial time/cost savings in the field can be realized for relatively little time/cost in the facility. Additionally, while ergonomic risk is reduced in the field, it does not increase at the facility, as the same modern equipment and practices (designed to address ergonomics) can be used.

The DSS is a novel attempt to address a fairly difficult problem. As such, a number of limitations are involved. It is being developed with a somewhat narrow scope, that of panelized wall construction. Within this, only a subset of worker tasks are actually incorporated, specifically those that represent relatively larger physical demands (e.g. lifting, carrying, etc.). Laboratory-based measurements are necessarily also narrow in scope, in that only a subset of potential variables and levels can be tested. This results in a need to estimate exposures and associated risks for some tasks. Furthermore, for those tasks modeled, all workers are considered identical with respect to risk and performance to keep the problem manageable. Finally, the eventual usability and utility of the DSS is difficult to anticipate. While initial input from designers is being used to drive development, substantial testing and refinement will be necessary, and is planned, to accommodate a majority of end users.

Several directions for future work on and extensions to the DSS can be envisioned, primarily to address the noted limitations. In particular, model validity can be greatly improved by recognizing that workers are in actuality far from identical with respect to ergonomic risk and performance. A method for incorporating this variability is needed. In addition, the underlying concepts and methods described here might be used to develop similar tools in other areas of construction, such as roofing, drywall, masonry, finish carpentry, etc. Application to other occupational sectors may also be feasible, yet is it likely that some aspects of the fundamental approach will differ. Providing such tools, however, that can address ergonomic (or safety) concerns proactively, that integrate ergonomics with other business concerns, that generate quantitative assessments, and that allow for rapid simulation of alternatives, can be envisioned as having a substantial benefit over a range of occupations.

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6. Laboratory-based Ergonomic- and Risk-Assessment

Using the information obtained from the prior steps, we created relatively high-fidelity lab-based task recreations (mock-ups). By assessing exposures in the lab, we obtained detailed measures of exposure that would have been quite difficult to gather in the field. Note that exposures here refer to contact with risk factors associated with WMSDs (e.g., postures, forces). The lab study was designed to achieve two goals. First, tasks were reproduced with a reasonable level of detail and accuracy. We included only the fundamental tasks identified from the field observations, as these were consistent and identified as the most physically demanding. Alternative methods used by actual workers were included (e.g., horizontal and vertical lifting), with the final set of tasks based on observed frequencies. Second, exposures were measured to facilitate subsequent ergonomic risk assessment. Lab-based measurements provided the necessary input to these tools, but also fairly extensive additional information to anticipate future risk assessment tools. Results from the lab study are the first formal ergonomic assessment of construction tasks using wall panels. A broad set of measures was obtained: anthropometric, psychophysical, kinematic, kinetic, and electromyographic (EMG). In all cases, the methods to obtain these measures were fairly standardized, and no fundamentally novel approaches or invasive instrumentation were needed. The lab study has been completed, and initial data analysis, reduction, and modeling are nearing completion. Results are summarized below, but additional analyses will be performed at a later time.

Multiple and diverse ergonomic risk assessment methods are available. Note that by risk assessment we mean the qualitative or quantitative value of risk associated with a given task. We have incorporated a set of existing tools in the DSS to achieve three ends, specifically ease of implementation, common use, and relevance to panelized wall erection. These methods are not intended as complete, but rather as broad and representative of both application-oriented and research-based tools.

Each method provides distinct output toward ergonomic risk assessment. For each, we categorize the output (which in most cases is a continuous value) using the common traffic light analogy (RED/YELLOW/GREEN). This categorization is common in industry, and we use generally accepted criteria. As examples, categorization of the lifting index (LI) from the NIOSH equation ($LI \leq 1$ = GREEN; $1 < LI < 3$ = YELLOW; $LI \geq 3$ = RED) and of compressive forces (F_C) in the lumbar spine ($F_C \leq 3400N$ = GREEN; $3400N < F_C < 6400N$ = YELLOW; $F_C \geq 6400N$ = RED) are both commonly used. Categorizing the output (vs. continuous output) is necessary both to ease interpretation of the diverse results and to simplify the algorithms within the DSS. It is also required by the lack of good integrative tools in ergonomics (i.e., across exposure domains or body parts). While methods have been proposed to integrate exposure and/or risk across diverse jobs or tasks, none are widely accepted or well validated. Since our existing risk assessments are based on a subset of all possible tasks, we use a linear interpolation or extrapolation for tasks not included in the lab study or directly measured in the field. Within the DSS, we aggregate the number of RED/YELLOW/GREEN instances (i.e., across workers in a crew and tasks) for an entire construction job. (Note, however, that the DSS provides the detailed underlying data and can easily integrate new methods that may be developed). These aggregates are then converted into frequencies based on job duration. Frequencies are used to account for differences between building instances and because use of the DSS can reduce construction time. Our approach to risk assessment is essentially task-based and assumes that

risks are comparable for each worker doing a given task. Such task-based assessments are commonly used when individual exposures are difficult to assess.

6.1 Effects of Panel Size, Panel Mass, and Additional Worker on Ergonomic Risks

1.Introduction

The nature of residential building construction entails exposure to risk factors for work-related musculoskeletal disorders (WMSDs) – rapid work pace, forceful exertion, and non-neutral postures among others (Bernard, 1997; Punnett & Wegman, 2004). Within this occupational sector, one third of all carpenters (~ 0.2% of total national employment) are involved in residential building construction (BLS, 2009a; Mullins, 2006). However, compared to the general workforce, carpenters and construction laborers have a high prevalence of occupational injuries. For example, in the U.S. they had the second longest median days away from work (10 days) among all industries (BLS, 2009b). Overexertion and repeated motion accounted for > 20% of days away from work cases.

Previous studies have indicated an increasing adoption of prefabricated components among U.S. residential builder (NAHB, 2009; Toole & Gambatese, 2008), and specifically the use of panelized construction (Wakefield, et al., 2001). Panelized walls (or panels) are one example of such prefabrication. Contrary to traditional ‘stick-built’ walls (assembled on-site), the production of panels is performed off-site, wherein a panel designer develops panels from an architect’s drawing. The off-site production of panels can elicit improvements in many aspects such as cost, time, speed of assembly, and the number of code violations (National Association of Home Builders, 2009; Toole, 2001; Toole & Gambatese, 2008). More importantly, with off-site production, panel designers can play an important role in the control of WMSDs on-site, since they can affect a large number of construction sites and workers with their design choices. The involvement of central panel designers yields a unique opportunity to control exposures to WMSD risks, in that WMSD risks can be “designed out” or minimized early in the product/project lifecycle (i.e. in the design phase), consistent with the “safety through design” and “prevention through design” concepts (Gambatese & Hinze, 1999; Gambatese, et al., 1997; Hecker & Gambatese, 2003; Toole & Gambatese, 2008). Based on these concepts, our group has undertaken the development of a decision support system (DSS) that enables designers to assess ergonomic and productivity concerns early in design phases (Nussbaum, et al., 2009). Therein, a detailed description of the DSS development process was presented along with preliminary results from several completed steps.

To complete the initial development of the DSS for designing panels, WMSD risks involved in common panel erection tasks need to be determined quantitatively. To the authors’ knowledge, no formal risk assessment has been performed on common panel erection tasks with respect to panel design factors (e.g., mass, size, and number of workers). Note that by risk assessment we mean the qualitative or quantitative value of risk associated with a given task; i.e., compliance assessment (Dempsey, 1999). Multiple and diverse ergonomic risk assessment methods are available. We have, at this time, incorporated a set of existing tools in the DSS to achieve three ends, specifically ease of implementation, common use, and relevance to panelized wall erection. These methods are not intended as complete, but rather as broad and representative of both application-oriented and research-based tools.

2. Methods

A convenience sample of 24 participants (19 males and 5 females) was recruited from the university and local community. The mean (SD) age, stature, and body mass were 24.2 (4.8) yrs, 174.2 (8) cm, and 71.4 (12.8) kg, respectively. All participants reported being physically active and having no illnesses, injuries, or musculoskeletal disorders within the past year that restricted their daily activities. Prior to participation, they completed informed consent procedures approved by the Virginia Tech Institutional Review Board.

2.1 Experimental Design and Protocol

A set of biomechanical, psychophysical, and surface electromyography (sEMG) measures were obtained in a balanced incomplete block design with block size = 2. Four independent variables (IVs) were experimentally manipulated: panel Size [small, medium and large], panel Mass [sheathed (light) vs. unsheathed (heavy)], use of an Additional worker (with vs. without) and Task type (eight levels of lifting, carrying, erecting and moving). These IVs were determined based on extensive field and video observations. Panel specifications are presented below (Table 6.1).

Table 6.1: Panel Mass and Size.

	Small (1.2 m x 2.4 m)	Medium (2.4 m x 2.4 m)	Large (3 m x 2.4 m)
Heavy (kg)	53	87	108
Light (kg)	30	44	54

Each experimental session lasted ~3 hours and involved a different panel size. A pair of participants completed all the combinations of panel mass, use of an additional worker, and task type in the given session (Table 6.2). The order of combinations of IVs was controlled such that the order of panel mass was first randomized, and the order of use of an additional worker and task type were randomly assigned within each panel mass.

Table 6.2: Overview of balanced incomplete block design with block size = 2.

Small			Medium			Large		
Task	Heavy	Light	Task	Heavy	Light	Task	Heavy	Light
L1G	P1 & P2		L1G	P1 & P2		L1G	P5 & P6	
L1K	P3 & P4		L1K	P3 & P4		L1K	P7 & P8	
L2G	P9 & P10		E1G _{Top}	P5 & P6		E1G _{Top}	P9 & P10	
E1G _{Top}	P11 & P12		E1G _{Side}	P7 & P8		E1G _{Side}	P11 & P12	
E1K _{Side}	P13 & P14		E1K _{Top}	P13 & P14		E1K _{Top}	P17 & P18	
M1	P15 & P16		E1K _{Side}	P15 & P16		E1K _{Side}	P19 & P20	
C1	P21 & P22		M1	P17 & P18		M1	P21 & P22	
C2	P23 & P24		C1	P19 & P20		C1	P23 & P24	

• P1 – P24 are participant IDs.

The nominal number of workers was one or two for the small panel, one or three for the medium panel, and two or three for the large panel; these were determined based on field observations and each participant's physical competency. Experimenters (including the authors) performed tasks with the participant as additional workers according to each experimental condition. Each task lasted ~10-20 seconds and was repeated twice with ~ 2 min rest between trials. For the small panel, task types included (Figure 1):

- Two levels of lifting type L1: Lift panel horizontally. Panel initially placed on the floor (L1G) or at knuckle height (L1K), using jack stands.
- Lifting type L2: Lift panel off the floor such that it is oriented at roughly 45 degrees to the floor at completion of lift.
- Two levels of erecting E1: Erect panel off floor until it stands vertically while participant stands at panel top-plate (E1G_{Top}), or erect panel until it stands vertically, with panel initially held at a knuckle height and participant stands at panel side (E1K_{Side}).
- Moving M1: Push vertically placed panel forward along long axis.
- Carrying type C1: Carry panel in horizontal orientation.
- Carrying type C2: Carry panel while holding it at roughly 45 degrees to the ground.

For E1, L2 and C2, use of an additional worker condition was not performed because adding an additional worker was physically impractical with the small panel. For the medium and large panels, task types included:

- L1G, L1K, M1, and C1.
- Two levels of erecting type E1G: Erect panel off floor until it stands vertically, while participant stands at the top-plate (E1G_{Top}), or at panel side (E1G_{Side}).

- Two levels of erecting type E1K: Same as above except that panel is initially held at knuckle height; i.e. E1KTop or E1KSide.

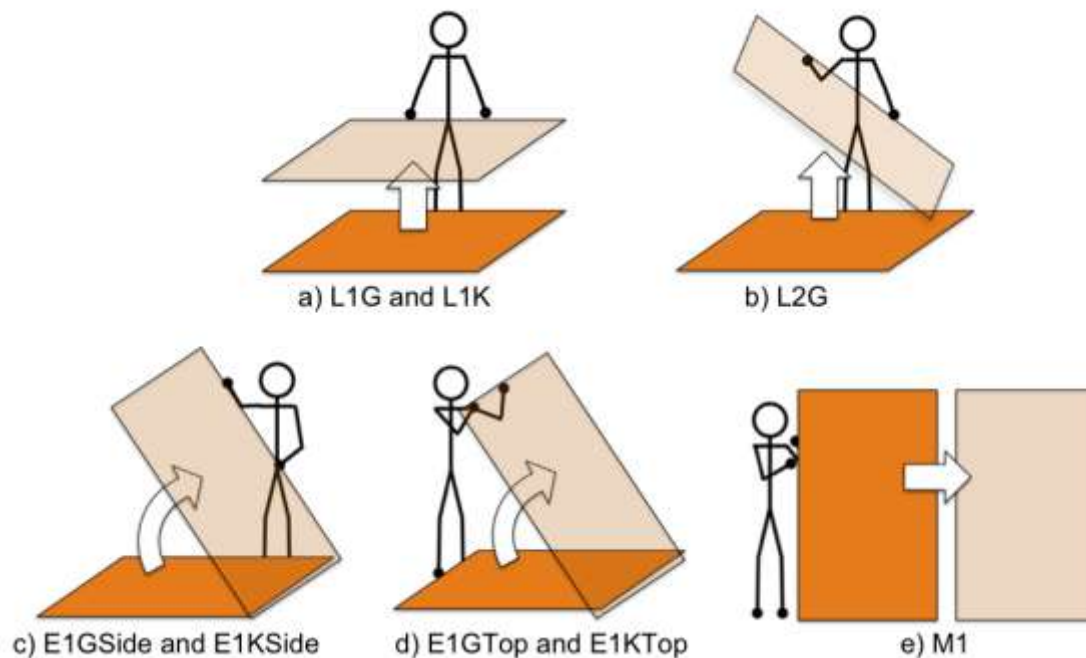


Figure 1. Illustrations of task types. The letters G and K respectively indicate origin heights of ground and knuckle. For the latter, the panel is initially held at knuckle height. The white arrow indicates the direction of panel movement.

During data collection, the participant stood initially on two force platforms (AMTI OR6-7-1000, Watertown, Massachusetts), placing one foot on each force platform. Then, they were asked to practice the given task and to find their preferred hand positions on the panel. At these locations, two load cells (AMTI MC3A-6) were attached to collect tri-axial hand forces. While the participant performed a given task, muscle activity (electromyography), force platform, and load cell signals were collected at 1080 Hz. Passive marker data were collected at 120 Hz using a 6-camera system (Vicon 524, Vicon system, Los Angeles, CA). Afterwards, force platform and load cell signals were low-pass filtered with a cut-off frequency of 12 Hz, and passive marker positions were low-pass filtered with a cut-off frequency of 9 Hz.

2.2 Instrumentation

To obtain surface electromyographic (sEMG) signals, pairs of pre-gelled bipolar Ag/AgCl electrodes with a 2.5 cm inter-electrode distance were bilaterally placed over eight accessible abdominal and trunk muscles (Potvin, et al., 1996; van Dieën, 1997): internal oblique, external oblique, rectus abdominis, iliocostalis lumborum pars lumborum, latissimus dorsi, multifidus, longissimus thoracis pars lumborum, longissimus thoracis pars thoracis. Before electrode placement, the skin was shaved, lightly abraded and cleaned with 70% isopropyl alcohol.

Several pre-experimental trials were conducted to calibrate an EMG-based model (described below). sEMG signals were collected using two 8-channel telemetered systems (Telemetry 900, Noraxon, Scottsdale, AZ). Resting sEMG signals were collected for the abdominal and back muscles in the supine and prone positions, respectively. Isometric maximum voluntary contractions (MVC) of the torso were performed, during which the participant was asked to stand in a custom frame attached to a tri-axial force platform (Bertec 4550-08, Worthington, OH). The participant performed three MVC trials, with a 1 min rest between trials, for each of six tasks involving the torso: flexion, extension from a 20° forward flexion angle, right/left lateral bending, and right/left axial rotation. A passive trial was then performed during which the participant stood on a force platform (AMTI OR6-7-1000, Watertown, Massachusetts) with their feet together in a fully flexed posture while holding a 6.5 kg mass in the hands.

In order to track body-segment positions and orientations, passive markers were attached bilaterally or in the mid-sagittal plane over anatomical landmarks, using double-sided and surgical tapes. Anatomical landmarks for each body segment were: the calcaneus, 2nd and 5th metatarsal heads of the foot, lateral and medial malleolus, lateral and medial tibial epicondyles, acromion, lateral and medial humeral epicondyles, radialis and ulnar styloid processes, the spinous processes of the 7th cervical (C7) and 8th thoracic (T8) vertebrae, incisura jugularis, xiphoid process, and anterior and posterior iliac superior spines. In addition, clusters of two or four markers were placed over the midpoint of C7 and T8, the lumbosacral joint location, lower legs, upper arms, lower arms and heels. Locations of clusters on the lower legs, upper and lower arms and the heel were adjusted for each participant to minimize obstruction of clusters by body movements.

Selected anatomical markers were removed prior to data collection after being referenced to corresponding clusters. Removed markers were reconstructed using clusters on the corresponding body segments (Challis, 1994). The joint coordinate system for each segment was defined, in large part, based on International Society of Biomechanics recommendations (ISB, 2002; Wu & Cavanagh, 1995; Wu, et al., 2005), and joint angles were calculated using the Z-X-Y sequence of Euler angles. For carrying tasks (C1 and C2), lower extremity angles were not calculated mainly due to obstruction of passive markers on the legs by movements and the panel. Obtained joint angles were low-pass filtered with a cut-off frequency of 5 Hz. All off-line data processing was completed using Matlab 7 (Mathworks™ Inc., Natick, MA).

2.3 Risk Assessments

Spinal loads: We have developed an EMG-driven model to estimate loads (compression and shear), based on existing models (Nussbaum & Chaffin, 1998; van Dieën, 1997; van Dieën & Kingma, 2005). For each participant, the model was calibrated based on normalized sEMG and muscle origins/insertions/nodes obtained from a three-dimensional musculoskeletal model of the spine (AnyBody™, AnyBody Technology, Denmark). The model scaled the muscles based on each participant's anthropometric data, and considered each muscle as a single segment from the origin to the insertion or the node.

As an input to the EMG-driven model, sEMG signals were first band-pass filtered between 20 and 400 Hz. Then, EMG signals were processed in the following steps: 1) high-pass filtering using a cut-off frequency of 300 Hz (zero lag, 1st order, Butterworth); 2) rectification; 3) 1st order Butterworth low-pass filtering at 2 Hz; 4) subtraction of resting sEMG levels; and 5) normalization to maximal sEMG values from MVC trials. After muscles forces were estimated, these were combined with postural and external kinetic data to estimate compressive and shear forces at L5/S1. The 95th percentile (max) compressive and shear forces served as dependent variables (DVs).

Rapid entire body assessment (Hignett & McAtamney, 2000): REBA is a postural analysis tool that considers most major body parts (trunk, neck, legs, upper arms, lower arms and wrists) using a scoring system that associates postures with numerical values, similar to the related rapid upper limb assessment (McAtamney & Corlett, 1993). Using joint angles and load cell data from each task, a REBA score was obtained at every 10% of the task duration. During data collection, neck and wrist angles were not monitored, hence scores for the neck and the wrist were conservatively set to be = 1. In addition, for carrying tasks, the leg score was set to be = 2 by assuming that knee flexion angles were 30° ~ 60°. The maximum REBA score served as a DV.

Lumbar risk model (Marras, et al., 1993): This multiple logistic regression model is a method used to predict the probability of membership in a high risk group (P_{Risk} , risk of low back disorder) for a given manual material handling task. The model includes five factors describing trunk motion and workspace factors: lift rate, average twisting velocity, maximum moment at L5/S1, maximum sagittal flexion, and maximum lateral velocity. For each task, the maximum moment at L5/S1 was obtained using the AnyBodyTM modeling system. Though the regression model is rather insensitive to the lift rate, it was conservatively set to be 12 lifts/hr.

Revised NIOSH lifting equation (Waters, et al., 1994; Waters, et al., 1993): The revised NIOSH lifting equation is a well-known analytical tool specifically designed to assess risks during two-handed manual lifting tasks, so that details are not included here. Passive marker positions and load cell data from each task were used to calculate the lifting index (LI), while the frequency multiplier and the coupling type were set to be 1 and fair, respectively.

Ratings of perceived exertion using Borg CR-10 scale (Borg, 1990): At the completion of two replications of each task, the participant provided ratings of their perceived exertion for the whole body, lower back, and shoulders, arms and legs. Ratings were collected using a modification of the Borg CR-10 scale. This instrument is a 10-point category scale and was provided along with a human body schematic with graphical descriptors anchored at selected body regions. Whole body (WB_{RPE}) and lower back (LB_{RPE}) scores served as DVs.

2.4 Statistical Analyses

Statistical analyses largely consisted of two parts. First, the effects of three IVs (Mass, Size and Task) were examined by excluding the additional worker condition. Second, statistical analyses focused on the effects of Additional worker. Details of each part are below.

2.4.1 Effects of Mass, Size and Task

Repeated measures analyses of variance (ANOVA) were performed on the risk assessment measures to evaluate the effects of three IVs (Mass, Size and Task), using the SAS PROC Mixed procedure (Littell, et al., 2006). Due to the experimental design (balanced incomplete block), not all of the interactions among IVs could be included in an ANOVA model.

Alternatively, separate analyses were performed on a given risk measure with following sets of interactions: 1) Mass x Size and Mass x Task and 2) Mass x Size and Size x Task. Spine loads (compression and shear) were normalized by the participant's body mass (Hof, 1996). Further, all risk measures except RPE scores were log-transformed prior to statistical analyses to achieve normally distributed residuals. Significant effects were followed by post-hoc pairwise comparisons (Bonferroni-adjusted t tests). All statistical analyses were performed with SAS 9.2 (SAS Institute Inc., Cary, NC), and statistical significance was determined at $p < 0.05$. All summary data are presented as means (SD).

2.4.2 Effects of Additional worker

Repeated measures ANOVAs were performed on all IVs using the SAS PROC Mixed procedure. These analyses were used to evaluate the benefits of Additional worker with respect to panel design factors. To this end, initial analyses were performed on a given risk measure with Additional worker x Mass and Additional worker x Size interactions. Prior to the analyses, risk measures were normalized and/or log-transformed as needed. Significant effects were followed by post-hoc pairwise comparisons (Bonferroni-adjusted t tests).

3. Results

The results from each part of the statistical analyses are presented separately.

3.1 Effects of Mass, Size and Task

ANOVA results for all risk measures are summarized in Table 3, with interaction effects obtained from separate analyses incorporated. Significant results of each risk measure are detailed below.

Table 3: ANOVA results [*F* value (*p*)] of effects of IVs on risk measures. Results are highlighted in bold if significant.

	Mass	Size	Task	Mass x Size	Mass x Task	Size x Task
Anterior/posterior shear force (Fx)	10.7 (0.0011)	1.21 (0.3)	32.47 (< 0.0001)	0.39 (0.68)	1.42 (0.17)	2.44 (0.0042)
Compressive force (Fy)	20.04 (< 0.0001)	6.1 (0.0024)	57.24 (< 0.0001)	0.12 (0.88)	0.98 (0.45)	2.95 (0.0005)
Lateral shear force (Fz)	9.98 (0.0017)	7.31 (0.0007)	17.31 (< 0.0001)	2.24 (0.11)	0.69 (0.71)	1.58 (0.091)
Max. REBA	4.36 (0.013)	6.18 (0.013)	195.97 (< 0.0001)	0.52 (0.59)	2.69 (0.0044)	3.5 (< 0.0001)
P _{Risk}	26.95 (< 0.0001)	4.59 (0.01)	420.38 (< 0.0001)	0.72 (0.49)	2.35 (0.013)	4.78 (< 0.0001)
LI	66.59 (< 0.0001)	47.48 (< 0.0001)	153.08 (< 0.0001)	13.54 (< 0.0001)	5.74 (< 0.0037)	1.67 (0.19)
LB _{RPE}	55.88 (< 0.0001)	1.48 (0.26)	20.76 (< 0.0001)	1.06 (0.35)	0.62 (0.78)	2.27 (0.009)
WB _{RPE}	59.47 (< 0.0001)	1.66 (0.2)	17.08 (< 0.0001)	0.45 (0.64)	0.48 (0.89)	2.82 (0.0011)

3.1.1 Spinal Loads

Significant main effects of Mass showed that anterior/posterior shear (Fx), compressive (Fy) and lateral shear (Fz) forces generally increased in the heavy condition [Fx: 932 (452) N > 841 (496) N; Fy: 3261 (1279) N > 2900 (1217) N; Fz: 175 (212) N > 149 (197) N]. Further, Fx and Fy were significantly affected by the Size x Task interaction (Figure 2). Lateral shear force was affected by main effects of Size [medium (199 (208) N) > large (141 (238) N) = small (146 (157) N)], and Task (C1 = C2 = E1GSide > E1G = E1KSide = L1G = L2G > E1KTop = M1 > E1KTop = L1K).

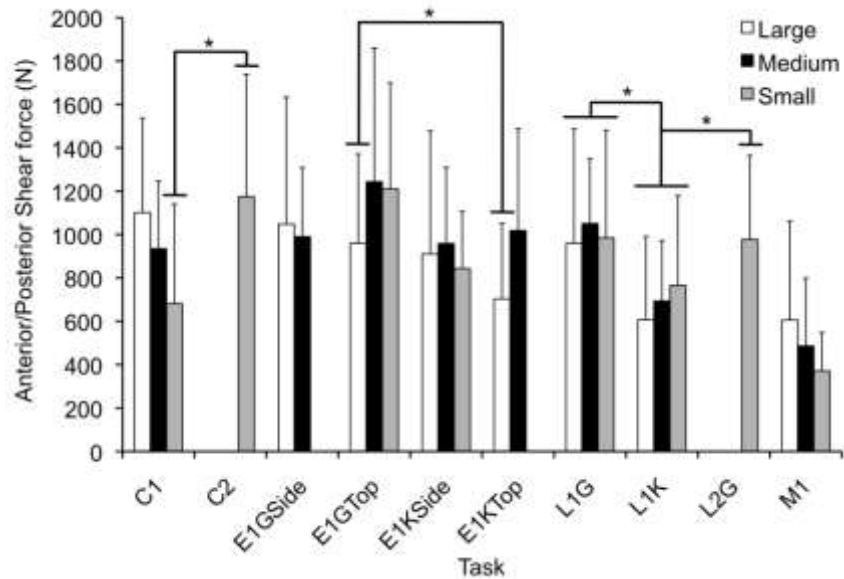
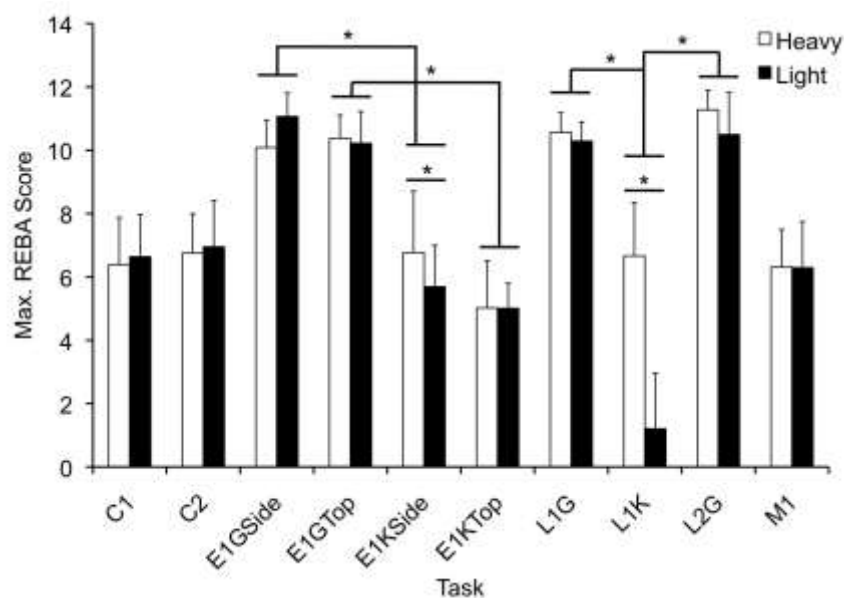


Figure 2. Size x Task interaction effects on anterior/posterior shear (top) and compressive force (bottom). Significant differences between panel sizes for the same and alternative tasks are indicated by *, and error bars indicate standard deviations.

3.1.2 REBA

Significant main and interaction effects of Mass, Size and Task (except Mass x Size interaction) were found on the maximum REBA scores (Figure 3). REBA scores were generally higher for the tasks that had a panel initially on the floor (E1GSide, E1GTop, L1G and L2G) versus other tasks. In addition, panel size and mass appeared to not significantly affect REBA scores for the same task, excepting that E1KSide was affected by Mass and Size and L1K by Mass.



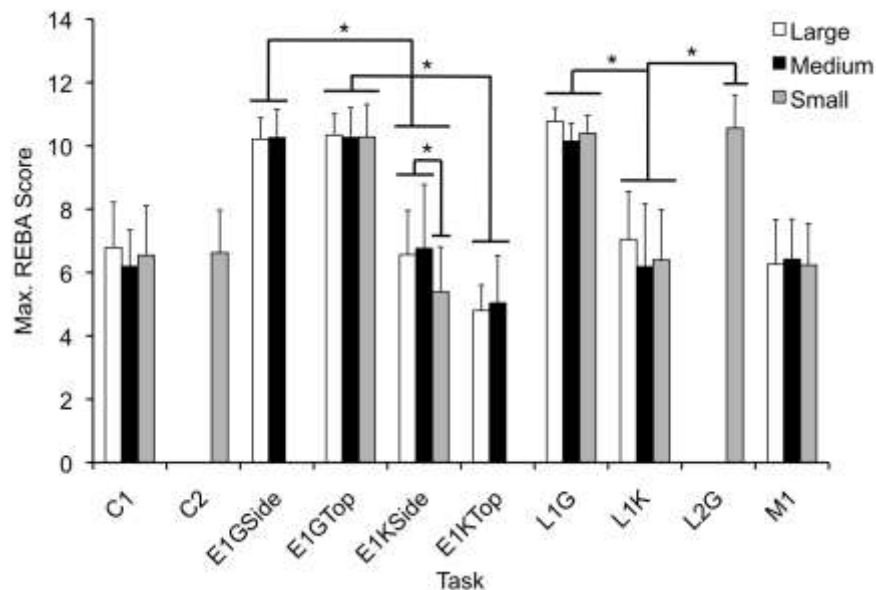


Figure 3. Significant Mass x Task (top) and Size x Task (bottom) interaction effects on maximum REBA score. Significant differences between panel sizes or masses for the same and alternative tasks are indicated by *.

3.1.3 Lumbar Risk Model

Main and interaction effects of Mass, Size and Task (except Mass x Size) significantly affected the probability of high-risk group membership, P_{Risk} (Figure 4). Similar to REBA results, P_{Risk} values were higher for E1GSide, E1GTop, L1G and L2G than other tasks. In addition, within the same task, only E1KSide was significantly affected by Mass and Size, and M1 was affected by Mass.

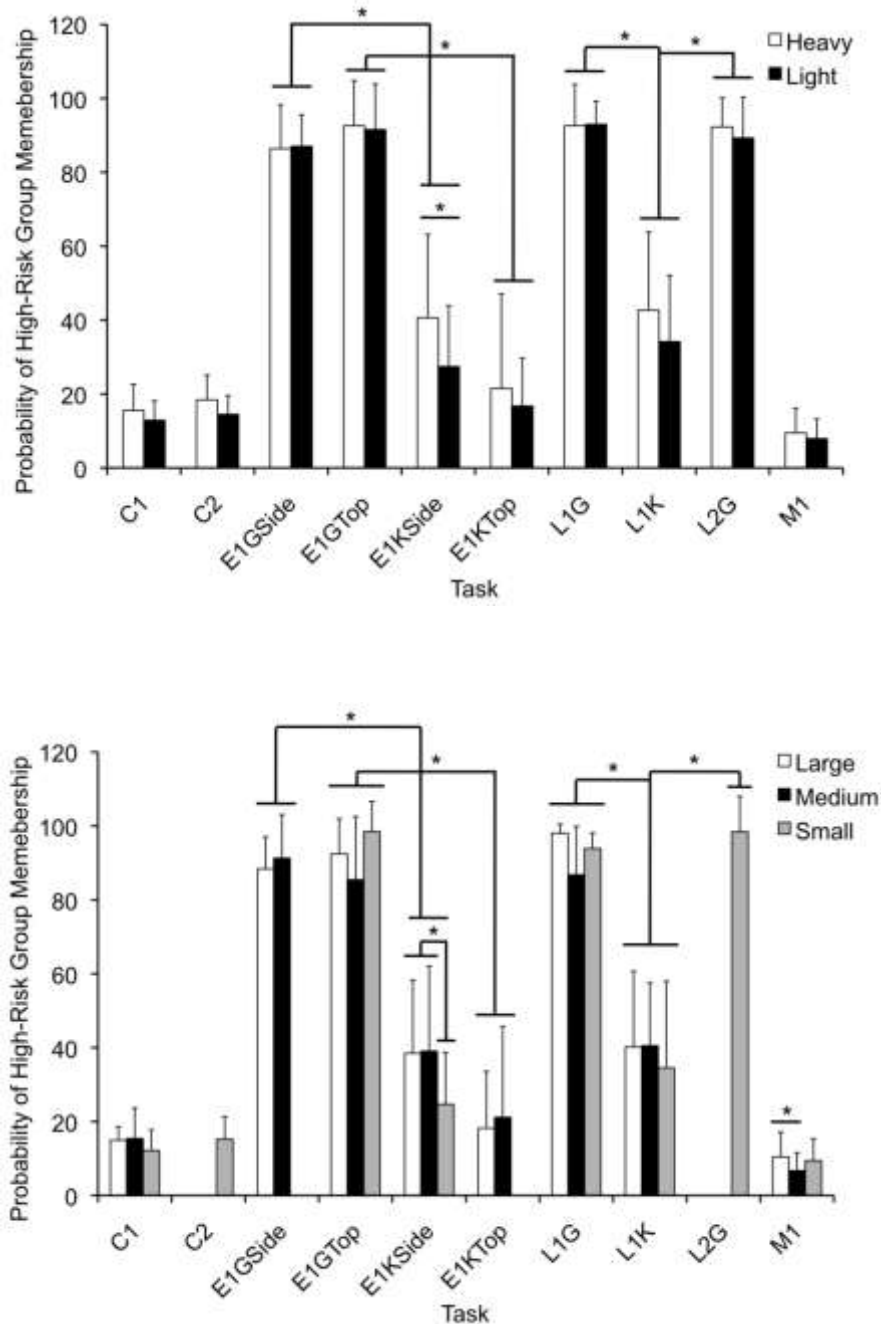


Figure 4. Significant Mass x Task (top) and Size x Task (bottom) interaction effects on the probability of high-risk group membership. Significant differences between panel sizes or masses for the same and alternative tasks are indicated by *.

3.1.4 Revised NIOSH Lifting Equation

LI values were significantly affected by main and interaction effects of Mass, Size and Task (except Size x Task). Large and medium panels generally led to higher LI values than the small panel (Figure 5). Except for the large panel, LI values were significantly higher for the heavy

condition than for the light condition. In addition, L1G and L2G showed higher LI values [2.22 (0.73) and 2.44 (0.43), respectively] than L1K [1.5 (0.49)], regardless of Mass. LI values for L1G and L2G were comparable, yet L2G under the heavy condition resulted in higher LI values [2.76 (0.27)] than L1G [2.39 (0.85)].

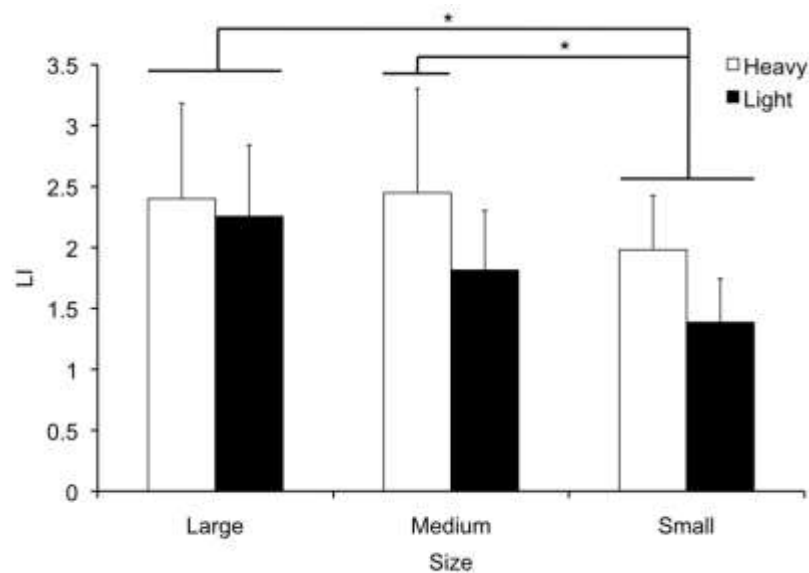


Figure 5. Significant Mass x Size interaction effects on LI values. Significant differences between panel sizes are indicated by *.

3.1.5 RPE

Whole body and lower back RPE scores were significantly affected by main effects of Mass and Task, as well as the Size x Task interaction. RPE scores were generally higher for the heavy condition than the light condition [WB_{RPE} : 2.7 (1.5) > 2 (1.2); LB_{RPE} : 2.5 (1.6) > 1.8 (1.3)]. The Size x Task interactions had comparable effects on WB_{RPE} and LB_{RPE} , so this interaction effect on WB_{RPE} is only presented in Figure 6.

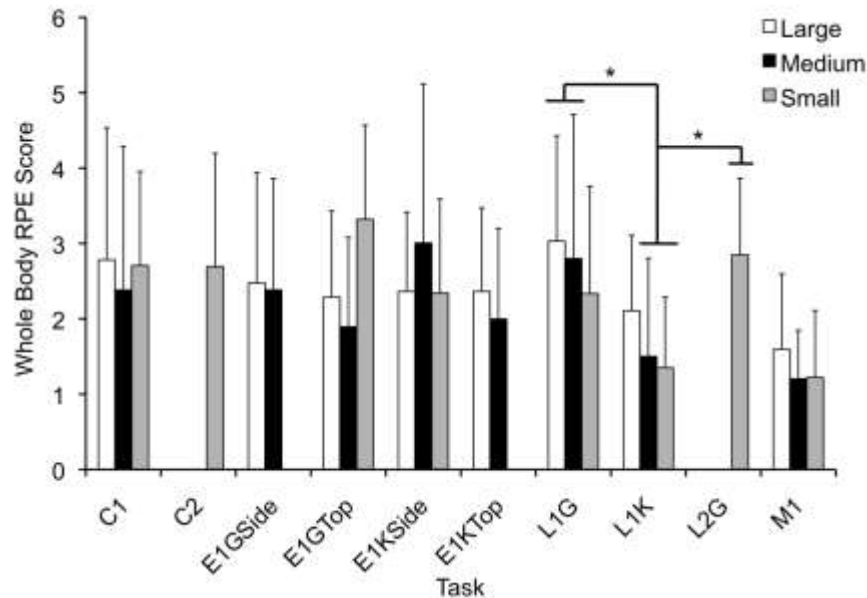


Figure 6. Significant Size x Task interaction effects on whole body RPE scores. Significant differences between panel sizes for the same and alternative tasks are indicated by *. Note that the score “1” indicates a “very weak” level of exertion, “3” indicates “moderate” and “5” indicates “strong”.

3.2 Effects of Additional worker

ANOVA results for all risk measures are summarized in Table 4. There were significant main effects of Additional worker on all risk measures excepting the maximum REBA score, such that risk levels were reduced when an additional worker was available (Table 5). In addition, LI values were significantly affected by the Additional worker x Mass and Additional worker x Size interactions. Specifically, within each mass condition, LI values were larger without use of an additional worker [Heavy: 2.2 (0.71) > 1.76 (0.55); Light: 1.7 (0.56) > 1.25 (0.48)]. The light condition with an additional worker had significantly smaller LI values than other conditions. In addition, Additional worker x Size interaction showed, in each mass condition, that LI values were larger without use of an additional worker as follows: Large: 2.2 (0.7) > 1.78 (0.57); Medium: 2.1 (0.76) > 1.48 (0.54); Small: 1.68 (0.5) > 1.27 (0.5).

Table 4: ANOVA results [F value (p)] of effects of IVs on risk measures. Results are highlighted in bold if significant.

	Additional worker	Mass	Size	Task	Additional worker x Mass	Additional worker x Size
Anterior/posterior shear force (Fx)	18.21 (< 0.0001)	35.66 (< 0.0001)	2.56 (0.078)	56.01 (< 0.0001)	1.51 (0.22)	0.39 (0.68)
Compressive force (Fy)	28.87 (< 0.0001)	68.22 (< 0.0001)	7.9 (0.0004)	95.78 (< 0.0001)	0.7 (0.4)	0.76 (0.47)
Lateral shear force (Fz)	6.05 (0.014)	11.25 (0.0008)	17.81 (< 0.0001)	29.03 (< 0.0001)	0.83 (0.36)	0.89 (0.11)
Max. REBA	0.01 (0.93)	10.05 (0.0016)	7.15 (0.0008)	371.67 (< 0.0001)	0.69 (0.41)	0.35 (0.72)
P _{Risk}	19.74 (< 0.0001)	61.26 (< 0.0001)	6.9 (0.001)	732.98 (< 0.0001)	0.13 (0.71)	1.42 (0.24)
LI	193 (< 0.0001)	213.68 (< 0.0001)	56.83 (< 0.0001)	221.95 (< 0.0001)	8.09 (0.0047)	4.05 (0.018)
LB _{RPE}	45.95 (< 0.0001)	94.07 (< 0.0001)	1.93 (0.15)	34.14 (< 0.0001)	1.47 (0.23)	0.39 (0.68)
WB _{RPE}	69.86 (< 0.0001)	134.57 (< 0.0001)	3.2 (0.042)	28.83 (< 0.0001)	0.72 (0.4)	0.53 (0.59)

Table 5: Summary statistics of spine loads, P_{Risk} and RPE scores.

		Fx (N)	Fy (N)	Fz (N)	P_{Risk} (%)	LB_{RPE}	WB_{RPE}
Additional worker	With	754.73	2696.62	142.43	45.44	1.59	1.71
		(400.45)	(1074.54)	(174.27)	(35.12)	(1.24)	(1.17)
	Without	886.74	3080.79	162.24	50.82	2.1	2.3
		(477.03)	(1260.92)	(205.31)	(35.99)	(1.5)	(1.42)

4. Discussion

This study was designed to assess the WMSD risks involved in common panel erection tasks with respect to different panel masses, sizes, and use of an additional worker, using multiple existing ergonomic assessment tools. Based on spinal loads, LI values and RPE scores, the effects of panel mass are straightforward compared to the effects of panel size, in that each of these measures generally decreased in the light condition. Yet, results from the Lumbar Risk Model and REBA showed that different mass conditions yield similar risk levels for a given task with a few exceptions (Figure 3 and 4). Similarly, all ergonomic assessment tools indicated that risk levels are comparable for a given task with different panel sizes, excluding a few of the tasks. In the case of use of an additional worker, the results of most ergonomic assessment tools clearly demonstrated that risk levels imposed on workers decrease if an additional worker is available (Table 5).

Reducing panel mass potentially lowers WMSD risk levels imposed on workers performing common panel erection tasks. For a given task, reduced risk levels with lighter mass can be expected from prior studies; e.g., decrease in spinal loads (Fathallah, et al., 1998; Granata, et al., 1999). In this study, the difference of the mass between the light and the heavy condition was 23 kg (77%) for the small panel, 43 kg (97%) for the medium panel and 54 kg (100%) for the large panel. The heavy condition caused 11% ~ 17% increases in peak spinal loads [Fx: 91 N; Fy: 361 N; Fz: 26 N], 11% ~ 43% (or 0.2 ~ 0.6) in LI values, as well as ~35% (0.7) in RPE scores. However, for a given task, P_{Risk} values and REBA scores appeared to be practically insensitive to the mass condition (Figure 3 and 4). This suggests that body movements do not differ enough between the mass conditions to yield different P_{Risk} values and REBA scores because the Lumbar Risk model and REBA largely consider body kinematics in assessment. Existing studies have also report similar inconsistencies among ergonomic assessment tools (Lavender, et al., 1999; Mirka, et al., 2000).

In general, the effects of panel size seem to be small within the same task, according to the ergonomic assessment tools applied. Only the revised NIOSH lifting equation indicated that the small panel has significantly lower LI values than the medium and large panel (Figure 5). However, the present results regarding the effects of panel size should not be simply interpreted as suggesting that the size of an object has no practical impact on risk level for a given task. This study did not aim to assess the “true” effects of size, but rather to assess risk levels of panel erection tasks with panel design factors commonly used in reality. Thus, the effects of

size may not have been pronounced due to other factors that were also varied (e.g., the number of nominal workers).

Initial vertical panel placement affected risk levels, in that risk levels for a given task were higher if a panel was initially placed on the ground rather than at knuckle height. The Lumbar Risk model and REBA showed that tasks having a panel initially on the ground (E1GSide, E1GTop, L1G and L2G) resulted in P_{Risk} of > 90% and REBA scores of > 10 (high risk level), whereas tasks with panels initially at knuckle height (E1KSide, E1KTop and L1K) had P_{Risk} of < 45% and REBA scores of < 7 (medium risk level). This trend regarding initial placement was less obvious with spinal loads, the revised NIOSH equation, and RPE. Spinal loads indicated that many tasks yield shear and compressive forces larger than or close to the spine shear tolerance of 1000 N (McGill, 1996) and the NIOSH action limit of 3400 N of compression (NIOSH, 1981), regardless of panel mass and size (Figure 2). In particular, carrying tasks (C1 and C2) exhibited relatively high spinal loads and RPE scores, compared to risk levels estimated using other assessment tools.

Considering the magnitude of the effects of mass and size, and the large variability in the derived risk measures, modification of panel mass and/or size may not be viewed as an important objective criterion for solving the designing and planning problems within the DSS. However, panel design factors can be considered not only to determine panel specifications, but also to plan the panel stacking order and drop-off locations problems. For example, heavy and/or large panels can be stacked close to the top of a stack to raise the initial panel height, while minimizing or eliminating double handling of panels during the entire panel erection process. Our results showed that risk levels are generally high if a panel is initially placed on the ground. This emphasizes the importance of minimization or elimination of double handling, in that workers would experience an avoidable exposure when sorting panels from a stack to get to the one they need. In addition, alternative work processes might be introduced, such that sheathing can be partially installed on-site to reduce the total mass of a panel.

Use of an additional worker generally yields a reduction in risk levels, even though simulated tasks nominally require team manual material handlings. The magnitude of such reduction was 14% ~ 17% in spine loads [F_x : 132 N; F_y : 384 N; F_z : 19 N], 12 % in P_{Risk} , ~ 33% (or ~ 0.55) in RPE scores, and 24% ~ 42% (or 0.41 ~ 0.62) in LI values. As summarized above, modulation of panel mass yielded a similar degree of benefits in risk levels. In the case of spine compression, previous studies, however, have reported a larger reduction with symmetric two-person simple lifting, compared to individual lifting; e.g., ~ 20% (Dennis & Barrett, 2002) or ~ 660 N decrease (Marras, et al., 1999). The benefits of team lifting during heavy lifting tasks can be confounded by many factors such as different statures or standing height (Dennis & Barrett, 2003; Lee & Lee, 2001), coordination of body kinematics and synchronization among team members (Marras, et al., 1999), to list a few. Thus, the observed smaller degree of benefits from using an additional worker can be attributable to the complexity of simulated tasks, the size of team members, and the lack of control over individual differences. Nevertheless, the benefits of using an additional worker are clear, such that work crews should seek to capitalize on available additional workers when performing panel erection tasks.

A few limitations of this study should be acknowledged. First, the participants had no formal experience in panel erection tasks, though some participants had experienced general carpentry. All participants were required to watch video recordings of panel erection tasks

during the preliminary session, and had opportunities to practice each task during data collection sessions. Physical competency and perceptions of the participants, however, could differ from those of experienced carpenters. Second, due to constraints in the laboratory equipment, participants' movements were somewhat restrained, and they were asked to keep their hands on load cells attached to the panels. Though efforts were taken to avoid discomfort and to provide sufficient familiarization, limitations such as these may nonetheless limit external validity. In addition, we did not consider less than optimal working conditions (less stable footing due to cluttered floor, uneven surfaces, etc). This study did not control participants' movements strictly, however, which lends some level of generalizability to the results. Finally, this study did not provide quantitative descriptions of WMSD risks associated with common panel erection tasks in extreme conditions.

The present work addressed WMSD risks involved in common panel erection tasks for different panel masses, sizes and use of an additional worker, and discussed the findings within the context of the DSS. Though there are some inconsistencies in predicted risk levels among the ergonomic assessment tools, they showed that use of an additional worker or a reduction in panel mass can lead to a decrease in spinal loads, LI values and RPE scores, and that manipulated panels from the ground results in high risk levels. Further, spinal loads suggested that workers are likely to be exposed to excessive levels of spinal shear and compression while handling panels. Given the existence of centralized designers in off-site panel production, information on risk levels can be exploited by a system like the DSS to proactively control WMSD risks without compromising or (ideally) maximizing on-site productivity.

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7. Panelization Construction Design and Planning Algorithms

The overall design and planning process for panelized residential construction can be divided into three closely related problems: panelization, stacking, and construction planning. Few researchers have examined these problems in depth. Related works pertain primarily to higher level planning issues or areas such as construction process planning. Our approach, based upon lean manufacturing, is summarized here and stems from several fundamental concepts:

- Stacking is based upon build order. In other words, the “top” panel of each stack is always the next one needed/used. Workers no longer slide panels off to the side or onto the floor to get to the panel they need. Only those panels being worked on are out of the stack, and the work area is kept neat and tidy (lean principle: 5S). This accelerates construction and also eliminates safety hazards resulting from panels left lying on the ground or tipped against walls.
- Once a panel is removed from a stack, it is processed in one continuous operation (barring a change of workers) until it is fixed at its final position (lean principles: one-piece flow, minimize setups).
- Workers involved with a given panel can change between construction tasks (e.g., from lifting the panel off the stack to carrying it) to best suit the requirements of a given panel/task combination (lean principle: shojinka).
- Connectivity is maintained to the extent possible – each panel, save the first, is preceded by ≥ 1 connecting panels. This simplifies positioning and minimizes the need for temporary bracing of stand-alone panels; thereby panels are installed quickly and correctly the first time (lean principle: jidoka).
- A single *build direction* is used (e.g., left-to-right and front-to-back), to avoid workers being trapped or boxed-in.
- Upon delivery, all stacks are dropped off along the same edge of the structure (“dropping edge”).

Panelization

Panelization consists of “breaking up” the walls or dividing them into panels. The process employs three parameters: stud spacing (12 or 16 in), preferred panel length (e.g., 8 ft), and maximum panel length (e.g., 16 ft). Based upon these parameters, walls are divided into panels. The build direction is taken into consideration to ensure smooth construction in the field and to minimize ergonomic impact. Of note is that the panelization plan (and hence stacking formulation, construction sequence, etc.) varies with build direction. Thus, a panelization plan is created for each feasible build direction (input by the user). The remaining problems are then solved for each panelization plan, and the best overall solution is selected.

Stacking

A heuristic method employing a staged approach has been developed for stacking. In brief, we divide the building into zones running parallel to the dropping edge. Each zone has an unload

area along the dropping edge – where panels can be unloaded from a stack without interfering with any finished panels – and one or more associated build areas. Stacks are dropped off at each unload area in turn. Panels within the associated build areas then form a continuous build sequence (and connect with the previous build areas). Once zones are established, the corresponding build area panels are assigned to stacks by moving through the build areas according to the build direction and selecting panels based upon their final location in the build area. This approach ensures that panel connectivity is maintained as much as possible and that a feasible build sequence results. Stack locations and delivery sequence are automatically generated, and the results minimize move distances for panels within each stack. Delivery of select stacks can be overlapped, if desired, to allow two stacks to be worked on simultaneously. Compared to the traditional approach (fill stacks as much as possible to minimize trips to the worksite), our methods can yield a larger quantity of stacks, each filled to a lesser extent. More trips are not a necessary outcome, however, as multiple, partially filled stacks can be loaded onto the same truck.

Construction Planning

The stacking heuristic assigns panels to stacks to maintain connectivity and provide a feasible build sequence. Thus, no on-site construction sequencing is necessary. To get each panel from its initial location/orientation on a stack to its final location/orientation in the building, a sequence of construction tasks is required. These are based upon our construction task taxonomy (Section 4.3). In addition, there is a set of possible task sequences, along with the allowable worker quantities for each task. As previously described, we allow the workers involved with a panel to vary from one task to the next.

The construction task planning, scheduling, and worker assignment problems are difficult to solve. Construction scheduling alone closely resembles traditional job-shop scheduling; as such, the three problems together will be at least as hard to solve as job-shop scheduling problems. One widely-used and well-studied approach for job shop scheduling is the use of dispatching rules: whenever a job is completed at a machine a simple rule (e.g., shortest processing time) is used to select the next job to run. We employ this same approach via the use of construction rules that can be easily employed by workers in the field. Such rules are needed to establish (i) what panel to work on next, when a worker becomes available, (ii) how many workers to use for each panel task, and (iii) *which* workers to use for each panel task once the quantity has been established. For example, we may elect for a worker to always go to the nearest panel being worked on, select the maximum quantity of workers for each panel task, and then select the actual workers to use to balance workload (utilization).

7.1 Panel Stacking

Guo C, Shewchuk JP: [2009] Panel stacking in residential construction using prefabricated panel: a lean approach. Submitted to the Journal of Construction Management.

Abstract

A current trend in residential construction is the use of prefabricated wall panels. Panels are constructed at a factory, then arranged into one or more stacks for transporting to the worksite, where they are assembled. Current approaches to stacking are focused on making the stacking and transport procedure efficient, with little consideration given to how construction will proceed once the stacks are delivered. This results in excessive material handling during construction, increased construction lead time, and increased risk of worker overload and/or injury. This paper proposes a lean approach to the panel stacking problem, where panels within each stack form a continuous build structure and are erected via continuous flow. Mathematical models are presented, along with a heuristic procedure for solving the stacking problem. Computational experiments show the proposed heuristic can greatly reduce on-site material handling and construction time, with little or no impact on panel transportation costs.

Introduction

Residential construction using prefabricated walls is becoming an established trend in the United States and abroad. In this approach, wall sections ('panels') are fabricated at a factory, then transported to the worksite for assembly. The approach offers many advantages over traditional, 'stick-built' construction. Quality is vastly improved, as panels can be fabricated in manufacturing facilities using tools, techniques, jigs, and fixtures unavailable at the worksite. Additionally, both the time to produce panels and the on-site construction time can be decreased dramatically, as can the amount of material needed. A study by the Building Systems Council (2009) reports that construction of a 2,600 sq. ft. home with trusses and panels took just 37% of the man-hours needed for a stick-built home, and also used 26% less lumber and generated 76% less waste. Panelized construction also reduces the need for skilled labor and the risk of on-site theft of materials (Shepherd, 2000).

An important aspect of the panelized approach is that of determining how to get the panels to the work site. Panels are arranged into one or more *stacks* at the panel manufacturer (Figure 7.1), each of which must then be transported to the work site and dropped on (or near) the floor of the building structure. Current approaches to stacking are focused on making the stacking and transport procedure efficient, with the objective typically being to minimize the quantity of trips to the construction site. Little consideration is given to the how construction will proceed once the stacks are delivered. Stacks are typically dropped off at the easiest location to get to at the work site, even though that location may significantly increase the distance workers must move panels. The construction foreman or lead hand must determine the sequence in which the panels will be assembled (construction sequence), with little more to go on than his/her own experience. Whatever sequence is selected, the arrangement of panels in the stack invariably causes problems. Workers must routinely remove one or more panels from a stack to get to the one they need: removed panels are moved off to the side (necessitating additional material handling) or simply left on the floor (creating a safety hazard). Further material handling is incurred walking around panels left on the floor. In other cases, panels that

do not connect with any completed (i.e., erected) panels, but are easily accessible in the stack, are moved directly to their final location and temporarily braced. This bracing activity is not required (or is significantly reduced) if each panel connects with one or more completed panels. Overall, the current stacking method result in not only excessive construction time, but also increased safety hazards and risk of worker injury and overload.

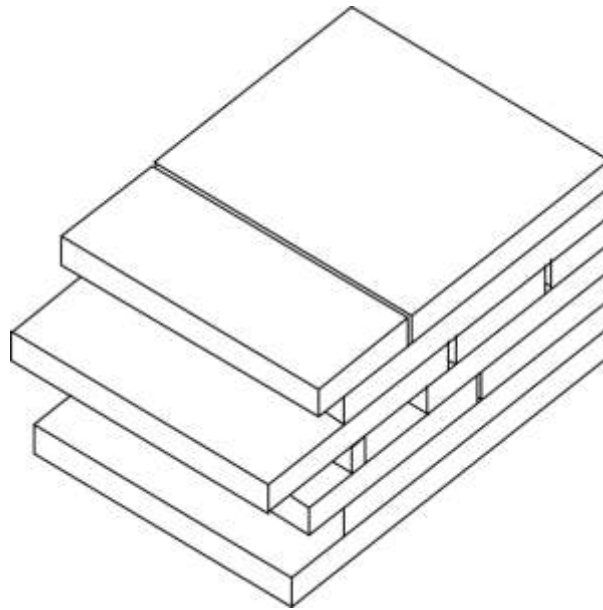


Figure 7.1: Example stack for panelized residential construction.

In this paper, we propose an approach to panel stacking aimed at addressing these problems. The approach is based upon lean manufacturing, which has revolutionized manufacturing worldwide (Womack and Jones, 2003) and has more recently made inroads into the construction field (e.g., Construction Industry Institute 2005, Sharma *et al.* 2006, Watkins *et al.* 2009). The approach will assign panels to stacks as well as the arrangement of panels within each stack. Additionally, the drop-off location for each stack is also established. Section 2 provides a review of related literature. The approach is outlined in Section 3, followed by the development of mathematical models in Section 4. A heuristic procedure for solving the stacking problem is presented in Section 5, with computational experiments to establish performance described in Section 6. Concluding remarks are provided in Section 7, along with a discussion of where additional research is needed.

Literature Review

A review of the literature has found no papers that directly tackle the stacking problem for residential panelized construction. The most closely-related papers are those dealing with layout planning, lean construction, and construction process planning. Jang *et al.* (2007) propose a floor-level construction material layout to minimize repositioning construction materials, using a genetic algorithm to tackle the problem. They report that their approach reduces material handing time. But they consider elements such as crane location only: the

issues of panel stacking and stack locations are not addressed. Hegazy *et al.* (1999) present a model and genetic algorithm for layout planning which “places facilities” at a construction site. They assume that panels are stacked when they are delivered to construction site, and hence do not address the panel stacking problem.

In the area of lean construction, Beary and Abdelhamid (2005) developed a production planning model based on Lean Construction production planning concepts and Six Sigma techniques. It was reported that Lean Construction aims at identifying and eliminating waste and that continuous improvement is needed. The issue of panel stacking, however, is not addressed. Choo *et al.* (1999) created a database program that implemented several lean construction techniques to help crew foreman to allocate available and equipment resources. But again, the panel stacking problem was not examined. Zhang *et al.* (2005) propose replacing the traditional management approach for residential construction site operation with a management philosophy that has as its sole and unifying objective the elimination of process waste. But this paper does not consider stacking at all: waste refers only to missing or broken tools/equipment, missing information, improperly staged material, and incomplete prior work.

Several authors have investigated automatic generation of construction process plans. Hu (2005) presented a model based on geometric reasoning, which reverses the disassembly process to obtain the construction process. The model provides a graph of precedence constraints, thus allowing feasible construction sequences to be established. But the related issue of how the panels should be stacked (for any given sequence) is not addressed: this is left for construction workers in the field. Nguyen and Oloufa (2001) developed a building design methodology, via a solid modeling platform, which can generate complex building information. Nguyen (2005) then proposes a framework that can generate sequences of construction activities automatically. But the framework is limited to the use of spatial information to establish construction sequences: other factors such as work spaces and panel stacking are not taken into consideration.

In summary, several related papers provide useful background for tackling the stacking problem, but none address the problem directly.

Approach

Before investigating how panel stacking can be performed, we must establish the basic nature of the stacks themselves. We first assume that all panels within each stack are similarly oriented, i.e., each panel's bottom plate is along the same edge of the stack. Second, stacks are placed directly on the sub-floor of (as opposed to being placed beside) the structure. This is necessary for workers to safely move panels from the stack to a location within the structure. Third, all stacks are dropped off along the same edge of the structure: we refer to this as the *dropping edge*. Finally, all stacks are dropped off with their length dimension parallel to and one length edge (e.g., bottom plate) flush with the dropping edge. Each of these assumptions reflects current practice, as verified through discussion with panel manufacturers and/or observations of actual panelized wall construction processes.

Our approach to panel stacking is then based upon the following lean principles:

- i) Panels are erected in the order in which they appear in the stack. In other words, the top panel of each stack is always the next one needed. Workers no longer slide panel

after panel off to the side, onto the floor, etc., to get to the panel they need. Only those panels being worked on are out of the stack, and the work area is kept neat and tidy (lean principle: 5S). This not only accelerates construction: it also eliminates the safety hazards resulting from panels left lying on the ground, tipped against walls, etc.

- ii) Once a panel is removed from a stack, it is processed in one continuous operation until it is fixed at its final position in the structure (lean principle: continuous flow).
- iii) *Connectivity* is maintained at all times during construction, i.e., each new panel (except the first) is preceded by at least one connecting panel. This simplifies positioning and minimizes the need for temporary panel bracing, ensuring panels are installed quickly and correctly the first time (lean principle: *jidoka*).

Mathematical Models

The basic stacking problem is formulated as follows. We are given a set of N prefabricated wall panels: let L_i and T_i denote the length and thickness of panel i , $i = 1, \dots, N$, respectively. All panels are of the same height. The N panels must be divided into one or more stacks for transporting to the construction site. Each stack will consist of one or more layers, each having one or more panels. Define

$$x_{ijk} = \begin{cases} 1, & \text{panel } i \text{ placed in layer } j, \text{ stack } k \\ 0, & \text{otherwise} \end{cases}$$

Panels within the same layer may have different thickness (e.g., interior vs. exterior panels): in such cases spacers are used in the stack as necessary to ensure layers remain parallel. Let C_{jk} denote the (maximum) thickness of layer j , stack k . The overall height of each stack and length of each layer are constrained both by the dimensions/carrying capacity of the delivery truck and worker considerations (e.g., maximum height workers can safely remove panels from a stack). Let $H_{\max}$ be the maximum stack height and $S_{\max}$ be the maximum stack length. Furthermore, define $L_{\min}$ ($L_{\max}$) as the minimum (maximum) possible panel length and $T_{\min}$ ($T_{\max}$) as the minimum (maximum) panel thickness.

As previously mentioned, the traditional emphasis in stacking is to minimize the quantity of stacks. Define

$$y_k = \begin{cases} 1, & \text{at least one panel assigned to stack } k \\ 0, & \text{otherwise} \end{cases}, \quad k = 1, \dots, K_{\max}$$

where an upper bound on the quantity of stacks can easily be found via

$$K_{\max} = \left\lceil N / \left(\left\lfloor \frac{S_{\max}}{L_{\max}} \right\rfloor \cdot \left\lfloor \frac{H_{\max}}{T_{\max}} \right\rfloor \right) \right\rceil$$

We can similarly define an upper bound on the quantity of layers in any stack:

$$J_{\max} = \left\lfloor \frac{H_{\max}}{T_{\min}} \right\rfloor$$

The traditional approach to panel stacking can then be formulated as follows:

$$\text{Minimize } \sum_{k=1}^{K_{\max}} y_k$$

$$\text{subject to } x_{ijk} \leq y_k \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{MaxStacks} \quad (1)$$

$$\sum_{j=1}^{J_{\max}} \sum_{k=1}^{K_{\max}} x_{ijk} = 1 \quad \forall i \in \text{Panels} \quad (2)$$

$$\sum_{i=1}^N L_i x_{ijk} \leq S_{\max} \quad \forall j \in \text{Layers}, k \in \text{MaxStacks} \quad (3)$$

$$\sum_{j=1}^J C_{jk} \leq H_{\max} \quad \forall k \in \text{MaxStacks} \quad (4)$$

$$C_{jk} \geq T_i x_{ijk} \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{MaxStacks} \quad (5)$$

where $\text{Panels} = \{1, 2, \dots, N\}$, $\text{Layers} = \{1, 2, \dots, J_{\max}\}$, and $\text{MaxStacks} = \{1, 2, 3, \dots, K_{\max}\}$. The objective function serves to minimize the total quantity of stacks. Constraint (1) establishes whether each possible stack k is used or not, while constraint (2) ensures each panel appears in exactly one layer of one stack. Constraints (3) and (4) ensure that the length and height of each stack does not exceed the specified limits. Constraint (5) ensures that the height of each layer equals that of the thickest panel assigned to that layer.

In formulating stacks, the above model does not consider connectivity: workers may end up having to move one or more panels to get to the next one they need. Additionally, stack drop-off locations are not considered: these are at the discretion of the truck and/or forklift driver. Thus, this simple model accurately represents the traditional case.

In contrast to the traditional approach, the proposed approach seeks to minimize the total panel move distance during construction. For each panel, we consider rectilinear distance from the panel's starting location (i.e., panel centroid, panel in its stack) to the final location in the structure. To simplify, we consider the starting location of each panel to be the same as the stack location (centroid). Let the x axis be parallel to the dropping edge and the y axis perpendicular to the dropping edge. As stacks always have their length dimension parallel to

(and one length edge flush with) the dropping edge, the y -coordinate is constant for all stacks and hence the y -component of the move distance will be the same for any stack location. Thus, we need only consider move distance along the x axis, i.e., from the stack's x location to the final location of each panel that has been assigned to that stack. Let

q_i = x coordinate, final location of panel i (finished structure)

u_k = x coordinate of stack k

A mathematical model for the proposed approach, where the quantity of stacks K is given, is as follows:

$$\text{Minimize } \sum_{i=1}^N \sum_{j=1}^{J_{\max}} \sum_{k=1}^K E_{ijk}$$

$$\text{subject to } E_{ijk} + F_{ijk} \geq x_{ijk} q_i \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (1)$$

$$E_{ijk} - F_{ijk} \geq -x_{ijk} q_i \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (2)$$

$$F_{ijk} \leq u_k + M(1 - x_{ijk}) \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (3)$$

$$-F_{ijk} \leq -u_k + M(1 - x_{ijk}) \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (4)$$

$$F_{ijk} \leq M x_{ijk} \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (5)$$

$$-F_{ijk} \leq -M x_{ijk} \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (6)$$

$$\sum_{j=1}^{J_{\max}} \sum_{k=1}^K x_{ijk} = 1 \quad \forall i \in \text{Panels} \quad (7)$$

$$\sum_{i=1}^N L_i x_{ijk} \leq S_{\max} \quad j \in \text{Layers}, k \in \text{Stacks} \quad (8)$$

$$\sum_{j=1}^J C_{jk} \leq H_{\max} \quad k \in \text{Stacks} \quad (9)$$

$$C_{jk} \leq T x_{ijk} \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (10)$$

$$x_{ijk} \leq \sum_{n \in P[i]} \sum_{m=1}^j x_{nmk} + \sum_{q=1}^{k-1} \sum_{m=1}^{J_{\max}} x_{nmq} \quad \forall i \in \text{Panels}, j \in \text{Layers}, k \in \text{Stacks} \quad (11)$$

where *Panels* and *Layers* are as before and $Stacks = \{1, 2, \dots, K\}$. E_{ijk} is the move distance for panel i , layer j , stack k . Constraints (1)-(2) force E_{ijk} to be positive, where F_{ijk} is the x coordinate of the stack to which panel i is assigned. Constraints (3)-(6) ensure that F_{ijk} is set correctly: they will ensure that $F_{ijk} = u_k$ if $x_{ijk} = 1$ (otherwise $F_{ijk} = 0$). In these constraints, M is a large positive value, at least as large as the length of the dropping edge. Constraints (7)-(10) are equivalent to Constraints (2) - (5) in the traditional model. Constraint (11) ensures that panel connectivity is maintained. To solve stacking problems via the above model, we first set $K = K_{min}$ = minimum possible quantity of stacks. The lower bound can easily be found via

$$K_{min} = \left\lceil \frac{N}{\left\lfloor \frac{L}{L_{min}} \right\rfloor J_{max}} \right\rceil$$

If the problem is infeasible, K is increased until a feasible solution is obtained.

Each of the above mathematical models is a variation of the generalized assignment problem, which is NP-hard.

Algorithm

Preliminary work using the preceding mathematical models and a commercial solver (CPLEX) indicated that realistic problem instances could not be solved in reasonable time (e.g., a 17-panel problem required more than 15 hours run time). Thus, a heuristic algorithm is proposed for minimizing the total panel move distance.

The algorithm is based upon the idea of assigning panels to stacks based upon a pre-specified *build direction*, so that workers cannot become ‘trapped’ (i.e., install a panel which then prevents them from being able to return to the stack). The build direction is established by the dropping edge. For example, if the south edge of the structure is the dropping edge, the build direction is north-south. Connectivity must again be maintained between all panels following the first. After all panels have been arranged into stacks, the drop-off location for each stack is determined. To account for the fact the larger panels are more difficult for workers to handle, we multiply panel move distance by panel length. The problem then becomes a traditional weighted mini-sum location problem, with weight corresponding to panel length. We use an iterative algorithm (Appendix A) to solve the drop-off location problem. Let

A = set of all panels.

I = set of panels already assigned to a stack.

C = set of candidate panels for the next panel.

D_i = distance from the center of panel i to the dropping edge.

B_i = distance from the center of panel i to the left side of the structure (i.e., blueprint rotated until dropping edge at the bottom of the figure).

$A_{ij} = \begin{cases} 1, & \text{panels } i \text{ and } j \text{ connect} \\ 0, & \text{otherwise} \end{cases}$

S_{rem} = length capacity remaining for the current layer.

H_i = height of panel i in the stack (i.e., from ground level).

H_{rem} = height capacity remaining for the current layer.

Using the above notation (and that established previously), the algorithm is shown in the flowchart of Figure 7.2. Note that the proposed algorithm solves the stacking problem for a single dropping edge. In practice, the algorithm should be used for each accessible dropping edge for the structure, and the stacking solution (and dropping edge) having the minimum total weighted panel moving distance selected.

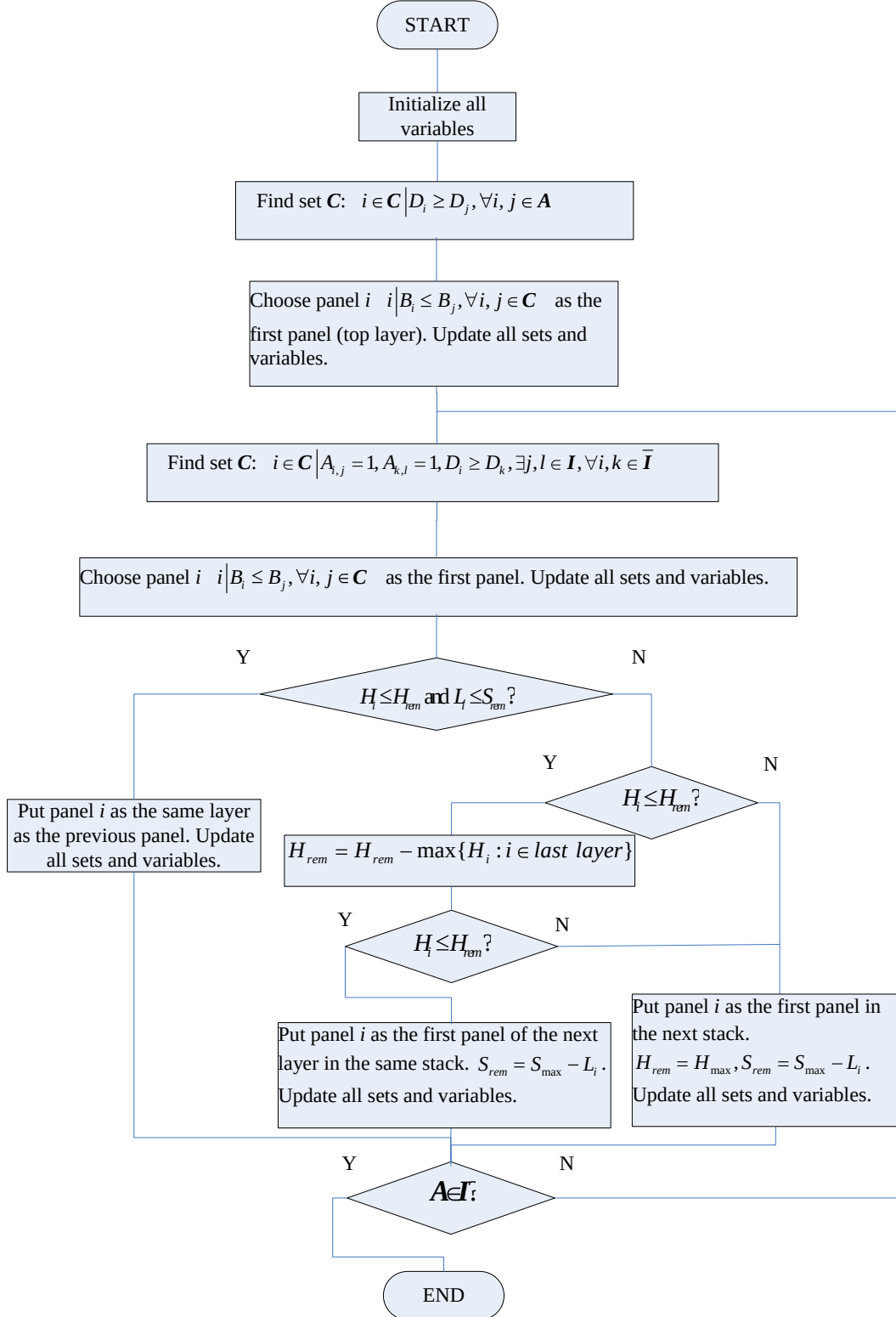


Figure 7.2: Flow chart of proposed panel stacking algorithm.

Computational Experiments

Experimental Design

A set of computational experiments was performed to establish the performance of the proposed panel stacking algorithm. Three sizes of residential home designs were investigated – small (one bedroom, one bath), medium (two bedrooms, one or one-and-one-half baths), and large (3 bedrooms, 2 or more baths). For each scenario, five home plans were randomly chosen from an online database of housing plans (The Home Plan Group, 2009), giving fifteen problems. For each problem, the corresponding set of panels were found by ‘breaking up’ walls one-at-a-time into panels, assuming 12-in. stud spacing and a preferred panel length of 8 feet. Panel lengths were adjusted as required to account for door and window openings, with a maximum panel length of 12 ft. observed.

Stacking was then performed using both the traditional approach and proposed stacking algorithm. The traditional approach requires an algorithm for the corresponding mathematical model (presented previously). As outlined in the literature review, however, no published algorithm for the panel stacking problem has been found. The problem of minimizing the quantity of stacks, however, is actually a two-stage, fixed-orientation two-dimensional cutting stock problem. This is a variant of the constrained two-dimensional cutting stock problem (Hifi *et al.*, 2006). If all panels have the same thickness, the problem is reduced to the one-dimensional cutting stock problem, for which algorithms and software are available. Thus, we assume that panel thickness is constant for all experiments, and employ a commercially-available business cutting stock software program (Astrokettle, 2009) for solving problems using the traditional approach.

Solutions were compared in terms of (i) quantity of stacks, K , (ii) total weighted panel move distance, and (iii) the percentage of panels for which connectivity is maintained (when panels are installed in the order they appear in the stack). In practice, it is much more difficult to install a panel when it does not connect with any completed panels: additional bracing is required, a panel may need to be force-fit in between existing panels, etc. This additional work cannot be determined, however, without detailed modeling and simulation of the construction process. The connectivity value is meant to provide a simple indication of the extent to which such problems would be encountered.

Results

Experimental results are presented in Table 7.1. In all cases, the proposed approach significantly reduces the total weighted move distance. Except for one case having a reduction of 18% (Small-1: 105,184.48 vs. 86,225.67), the reduction was at least 25% and as high as 63% (Big-2). Connectivity was of course 100% for all cases with the proposed algorithm (the algorithm ensures connectivity is always maintained). It ranged from 26-59%, however, using the traditional approach. Finally, we see that in all cases except one (Med-5), the proposed approach resulted in the same quantity of stacks. In terms of solution speed, the proposed algorithm solved each problem in less than one second.

Table 7.1: Computational results for proposed stacking algorithm vs. traditional approach.

Case	# of panels	Traditional Approach			Proposed Algorithm		
		# of stacks	Total weighted move distance, in.	Connectivity, %	# of stacks	Total weighted move distance, in.	Connectivity, %
Small-1	27	2	105,184.48	26	2	86,225.67	100
Small-2	26	2	138,260.16	34	2	101,890.50	100
Small-3	21	2	942,61.14	47	2	535,25.12	100
Small-4	25	2	161,175.59	56	2	922,40.68	100
Small-5	27	2	139,655.54	44	2	696,57.55	100
Med-1	35	3	234,974.23	57	3	149,360.68	100
Med-2	54	5	559,626.06	28	5	238,791.78	100
Med-3	27	2	100,414.73	41	2	540,19.01	100
Med-4	40	3	287,542.84	40	3	114,592.17	100
Med-5	44	3	298,833.56	39	4	140,189.27	100
Big-1	60	5	500,616.38	43	5	188,650.61	100
Big-2	47	4	317,892.59	49	4	115,180.05	100
Big-3	49	4	407,698.56	33	4	164,985.28	100
Big-4	52	4	429,029.03	42	4	318,366.78	100
Big-5	46	4	349,447.44	59	4	112,304.65	100

Discussion of Results

The computational results indicate that the proposed approach to stacking can dramatically decrease the amount of material handling workers must perform in erecting panelized structures. Additionally, it will always reduce the amount of additional bracing, fitting, etc., required when panels are installed in the given stack order (as indicated by the connectivity values), as the proposed approach guarantees connectivity. While the computational results showed significant gains are possible in this area, we must keep in mind that the algorithm used for the traditional approach did not consider connectivity at all. In practice, we have observed that some panel manufacturers do in fact consider connectivity in some limited fashion during

stacking, but it is never to the extent provided by the proposed algorithm. Thus, it is safe to say that the proposed approach will always be better in this respect, though the actual level of improvement depends upon the actual stacking method used in the traditional approach.

In terms of the quantity of stacks required, it is critical to note that the proposed approach resulted in additional stacks in only one of the fifteen cases examined. This indicates that the gains in construction efficiency obtained via the proposed algorithm do not necessarily result in increased costs upstream, i.e., during panel stacking and transport.

Conclusions

This paper has addressed the problem of panel stacking problem in residential construction, using a lean approach to reduce construction workload and the possibility of worker injury. A mathematical model was developed, along with a heuristic algorithm which can solve real stacking problems quickly. Computational experiments indicate that the proposed approach can greatly reduce the construction workload when compared to the traditional approach to stacking, which simply aims to minimize the quantity of stacks. At the same time, the proposed approach appears to have little impact on the quantity of stacks. This indicates that for any given stack quantity, many stacking arrangements are possible and due emphasis should be placed on finding a solution which reduces the workload at the construction site as much as possible. The proposed algorithm provides but one manner in which such solutions can be generated.

Additional research is needed on several fronts. The computational experiments were performed for a single panelization strategy only (8 ft. panels): the impact of stacking when other panelization strategies are utilized should be explored. Additionally, the experiments assumed that all panels were of the same thickness. In practice, external (and some internal load-bearing) walls are often of increased thickness: varying wall thickness can also be investigated.

At a more fundamental level, however, the validity of the mathematical model and algorithm can be improved. In particular, the issue of panel move path feasibility must be considered. For any panel in a stack, a Euclidean path from the stack to the panel's final location was assumed feasible. In practice, however, the actual path a panel takes can vary dramatically, due to the need to clear the stack, move around finished panels in structure, etc. Additionally, clearance is needed for the workers: this can be significant when as many as five or six workers may be required for large panels. Finally, the stack itself may interfere with one or more panel locations in the completed structure, making installation of such panels impossible. Such issues are extremely difficult to model mathematically, yet alone identify and develop suitable heuristics for. Detailed discrete-event simulation, coupled with simulation optimization techniques, may be necessary to successfully tackle the panel stacking problem when such items are considered.

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7.2 Design and Planning

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**Received “Best Paper” Award, in the Construction track of the IERC.*

Abstract

A current trend in residential construction is the use of panelized walls. In this approach, wall sections (panels) are fabricated at a factory, then transported to the worksite for assembly. While the approach provides substantial reductions in construction lead time, waste, etc., it also results in greatly increased risk of worker overload and injury. This paper briefly describes how designing and planning for panelized residential construction can be done taking ergonomic considerations into account. The goal is to be able to develop construction plans which result in an acceptable level of overall ergonomic risk and construction lead time.

1. Introduction

A current trend in residential construction is the use of panelized walls. In this approach, wall sections (panels) are fabricated at a factory, then transported to the worksite for assembly. The overall design and planning process for panelized residential construction can be broke down into six steps as follows:

1. Panelization (panel design): divide walls into panels.
2. Stack formation: arrange panels into stacks, for delivery to the worksite.
3. Stack location: determine where each stack is to be delivered at the worksite.
4. Stack delivery: determine when each stack is to be delivered to the worksite.
5. Construction sequencing: determining the construction sequence for the panels.
6. Construction task planning, scheduling, and worker assignment: determining how each panel will be processed, when, and by whom (i.e., which workers).

A study performed by the Building Systems Council [1] found that construction of a 2,600 sq. ft. home with trusses and panels not only took just 37% of the man hours as compared to a traditional ‘stick-built’ home; it also used 26% less lumber and generated 76% less waste. Additionally, panelized construction reduces the need for skilled labor and the risk of theft on-site [2]. While the panelized approach provides unmistakable savings in many areas, the present methods being employed also result in greatly increased risk of worker overload and injury. As panels are produced in a factory, production-related objectives (minimize production lead time, cost, setups, etc.) are typically employed. This may result in panels which are too large for workers to handle comfortably or too small, resulting in an excessive quantity of panels and hence increased material handling. The objective in stack formation is usually to minimize the quantity of stacks (and subsequent transportation costs): little attention is paid to the

sequence in which the panels in each stack will be used. As a result, construction workers must routinely remove one or more panels from the stack to get to the one they need: the removed panels are moved off to the side (requiring additional handling) or simply left on the floor (creating a safety hazard). Stacks are typically dropped off at the easiest location to get to at the worksite, even though that location may significantly increase the distance workers must move panels. The construction sequence is determined by the lead hand or foreman based upon experience: ergonomic considerations are seldom considered. Finally, construction task planning, scheduling, and worker assignment are almost always ad-hoc: workers have little guidance as to how to properly handle panels, when additional workers should be used, how tasks should be spread to minimize overall ergonomic risk, etc.

This paper presents an overview of how design and planning for residential panelized construction is being tackled by a prototype software tool under development at Virginia Tech. The tool will provide automated routines for each design/planning step described above: workers are explicitly considered in each case.

2. Approach

A large portion of injury-causing accidents in residential construction result from conditions established upstream of the actual construction process [3, 4]. With this in mind, we consider the entire design and planning process, dividing the steps into three independent problems: panelization, stacking (stack formation, stack location, and stack delivery) and construction (construction sequencing, followed by construction task planning, scheduling, and worker assignment). Few researchers have examined these problems in depth: related works pertain primarily to higher-level planning issues [5] or areas such as construction process planning [6, 7]. The solution methods under development for the three problems are all based upon the following fundamental concepts:

- Panels are always stacked in build order, such that every panel can be moved from its stack directly to its final location in one continuous operation. This is the lean concept of *one-piece flow* [8]: each panel is handled only once (i.e., all tasks are done sequentially, without interruption). The present approach to stacking invariably results in *batching* of operations (e.g., panel unload) and each panel being handled multiple times. Note that this step alone eliminates the safety hazard resulting from panels left lying on the floor, tipped against walls, etc., prior to when they are needed.
- To employ one-piece flow, each panel (except for the first) must be preceded by at least one connecting panel. Thus, *connectivity* must be maintained, at all times, between the panels in each stack.
- To ensure that the build sequence is feasible (i.e., that workers don't get 'trapped' or boxed-in), a single *build direction* is employed for the structure. For any given build direction, panels are then erected via multiple 'rows' running perpendicular to the build direction. Exterior panels must always be done first (as they can only be approached from the inside of the building), and special accommodation must be made for panels at the end of a row or at the end of the build direction.

- All stacks are dropped off at a single *dropping edge* for the structure. This in turn establishes the build direction (e.g., panels dropped along south edge of structure: must start at north end and build south). We assume all stacks are dropped off with panel length orientation parallel to the dropping edge.

These concepts are illustrated in Figure 7.3. A hypothetical building structure is illustrated in (a), with door and window openings omitted for simplicity. The panelized structure and build sequence are then shown for a south (b) and east (c) build direction: the dropping edge is shown (bold line) in each case. A stack formation employing two stacks is shown for case (b) as well. Stack location and delivery are ignored in these simple examples.

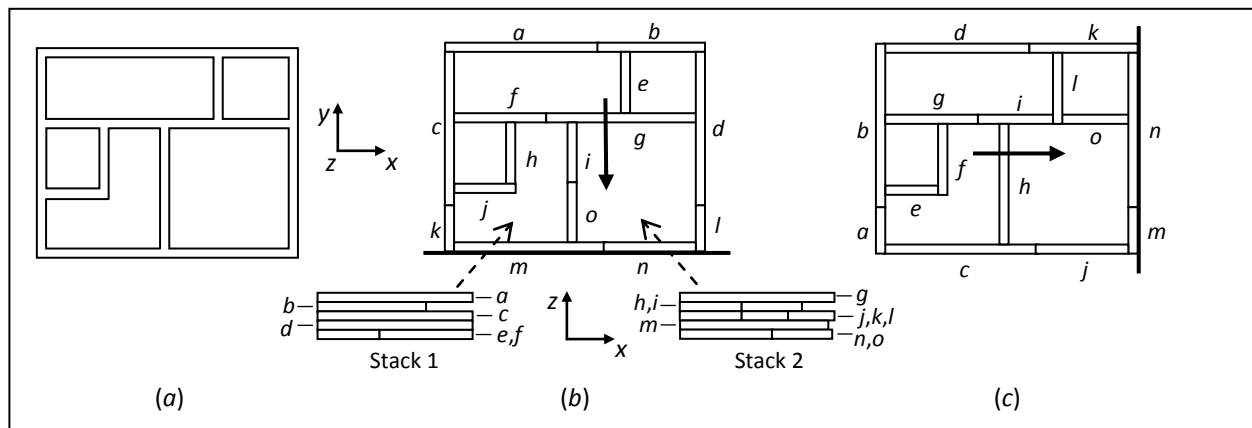


Figure 7.3: (a) Hypothetical building plan, (b) panelization plan, construction sequence, and stacks, south build direction, (c) panelization plan and construction sequence, east build direction.

3. Panelization

Panelization consists of ‘breaking up’ the walls comprising the structure into panels. The process starts with three parameters: stud spacing (12 in. or 16 in.), preferred panel length (e.g., 8 ft), and maximum panel length (e.g., 16 ft.). Based upon these parameters, walls are divided into panels, ensuring that panel breaks do not occur at wall openings (windows, doorways) and that some minimum distance is maintained between panel edges and openings. To ensure smooth construction in the field and minimize ergonomic impact, the build direction is also considered. Corner joints are established so as to follow the build direction: compare, for example, the joint between panels *a* and *c* (*h* and *j*) in Figure 7.3(b) with *d-b* (*f-e*) in Figure 7.3(c). Additional panel breaks and/or different joint configurations are then used when required to ensure construction is feasible. For example, consider panels *c*, *h*, and *i* in Figure 7.3(c). The build direction here (east) results in the construction sequence *c-h-i*, which is easily achievable. If the build direction were south, however, the construction sequence would be *i-c-h*, resulting in a severe *squeeze fit* for panel *h*, which is impractical. To alleviate this problem, panel *h* must be split, as shown in Figure 7.3(b), so that a minor (and acceptable) butt joint

squeeze fit results. In the case of panels *b*, *e*, and *g* in Figure 7.3(b), worker clearance is inadequate to install the panels resulting when panel *e* is split: an alternative solution is thus employed.

It is clear from Figure 7.3 that the panelization plan (and hence stacking formulation, construction sequence, etc.) varies with build direction. Thus, a panelization plan is created for each feasible build direction (input by the user): the remaining problems are then solved for each panelization plan and the best overall solution selected.

4. Stacking

Early attempts at Virginia Tech to address the stacking problem employed mathematical modeling. While the resulting mixed-integer linear programming (MILP) models provided valuable insight into the problem, their use for real problems was limited as they could not take into account the following issues:

- Considerable room may be needed to unload a panel from its stack – we must ensure that adequate clearance exists (and available space decreases as the structure progresses).
- Once unloaded, a clear path must be available for the panel (and workers), including room to rotate the panel 90° (xy plane: see Figure 7.3) if the panel is vertical (completed panel orientation on drawing).
- The stacks rest on the building floor and thus may overlap one or more final panel locations. The panels in these locations must therefore be assigned to some other stack, which in turn may change stack dimensions.

Consequently, a heuristic method was developed, employing a staged approach to panelized residential construction. In order to understand the process, it is first necessary to examine the ways in which panels can be unloaded from stacks. Nussbaum *et al.* [9] develop a taxonomy of tasks (activities) needed for panelized wall construction. Of concern here from this taxonomy is lift activity **L1**. Two additional lift activities – **L3** and **L4** – are required to implement the lean approach. These three activities are illustrated in Figure 7.4 (workers are omitted for clarity).

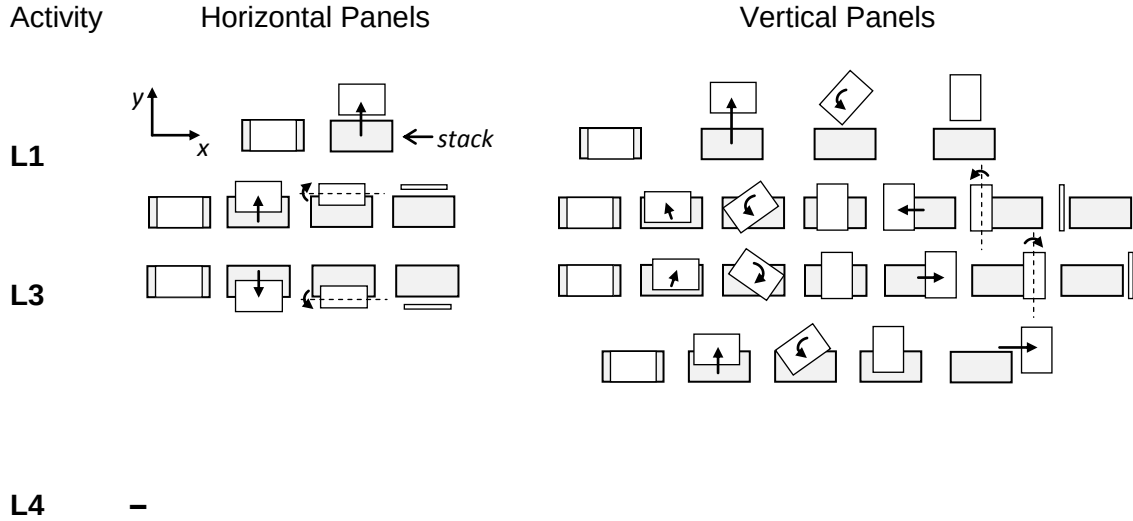


Figure 7.4: L1, L3, and L4 lift activities.

Consider a building plan oriented on paper such that the dropping edge is horizontal and at the bottom (Figure 7.4a). The building plan is divided vertically into $N_Z = \lfloor L_B/W_{nom} \rfloor$ zones, where L_B = building width (less exterior side panels) and W_{nom} = nominal zone width. The value W_{nom} is calculated such that any panel in any zone can be rotated 90° (i.e., vertical panels, using L1, L3 or L4) without crossing the sides of the zone. The width of each zone i is then found as $W_i = W_{nom}$, $i = 1, \dots, N_Z - 1$; $W_i = W_{nom} + (L_B - N_Z \cdot W_{nom})$, $i = N_Z$. Each vertical zone is then divided into a lower (unload) zone and upper zone, based upon unload zone height H^* . The value H^* is calculated such that any horizontal panel can be unloaded from the stack using L1, and any vertical panel using L4, without crossing H^* . In calculating both minimum zone width and H^* , adequate clearance is allowed for 1-4 workers handling the panels.

The staged approach to panelized construction is illustrated, for $N_Z = 3$, in (b)-(f) of Figure 7.5. Stacks are dropped off at each unload zone in turn, moving left-to-right, with a single stack in zone 1 and two stacks in each of the remaining zones. Panels from the first stack in each zone (type A stacks) fill the (upper) zone above the unload zone, plus provide any exterior panels as shown. If the panel is horizontal, L1 is guaranteed feasible (no interference with any completed panels) and is used. If the panel is vertical, L1 may be feasible: if so, this unload method is used. Otherwise, L4 is used for all zones but the last: L3 must be used (with the panel tipped off the right side of the stack) in this case. Panels from the second stack in each zone (type B stacks, zones 2, 3, ..., N_Z) fill the lower zone to the left of the unload zone (plus any exterior panels), using L3. If the panel is horizontal, the panel is tipped off the top or bottom of the stack; vertical panels are tipped off of the left side of the stack.

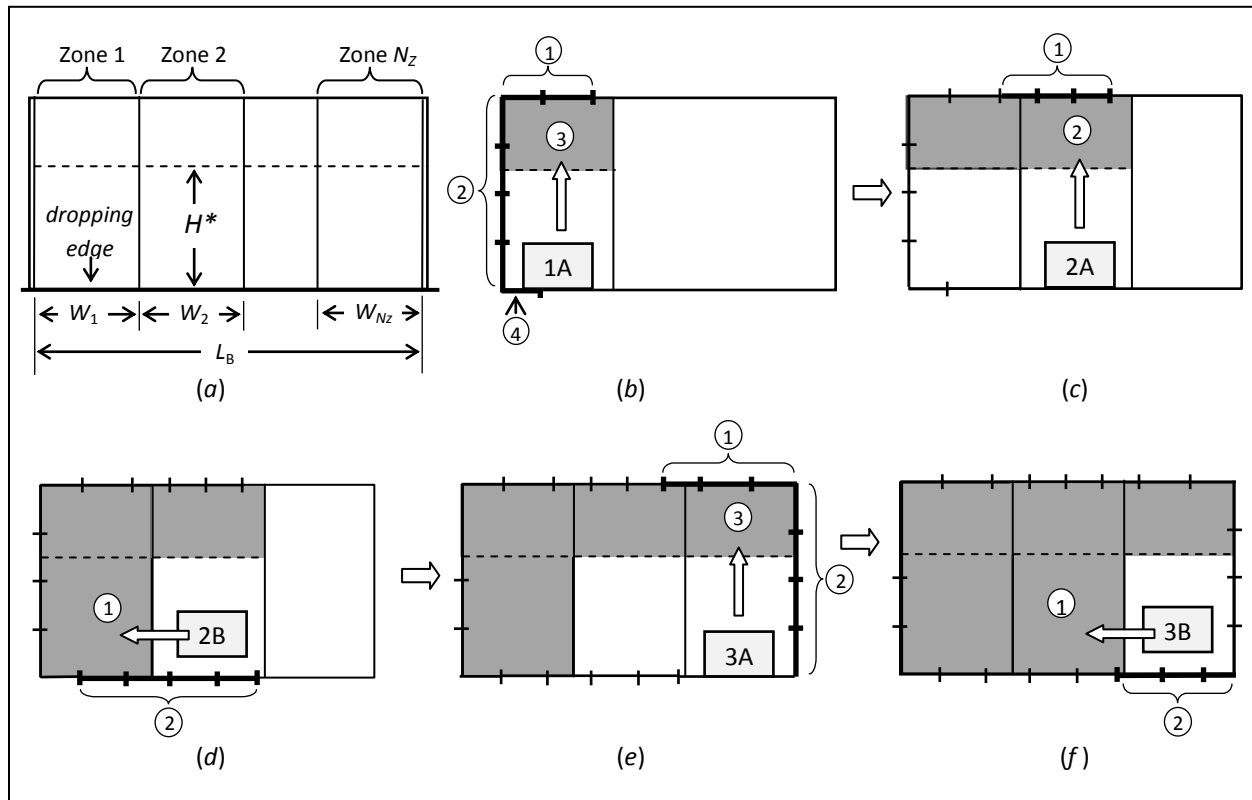


Figure 7.5: Staged approach to panelized residential construction.

Note that while Figure 7.5 shows type A stacks flush against and type B stacks near the dropping edge, these are minimum distances only. As panel length increases, the stack must move upwards in the zone (and hence H^* must increase) so that during panel rotation via **L3** or **L4**, (i) the location of the panel relative to the stack remains constant (necessary for worker positioning) and (ii) the panel does not cross the dropping edge. Additionally, note that the procedure can accommodate only a single panel having final location in the last unload zone (such a panel would be placed last in the type B stack). Additional panels must then be handled in ad-hoc manner, by the workers.

The above procedure minimizes move distance for the panels in each stack. The cost of this, however, is that more stacks are required. Unlike the current approach, where stacks are filled as much as possible to minimize trips to the worksite, stacks are only as full as necessary here to complete the panels assigned from the corresponding zone (The end result is not necessarily more trips, however, as it may be possible to load multiple partially-filled stacks on the same truck). To control the quantity of stacks, the user specifies a zone-width multiplier (parameter). A value of 1 uses W_{nom} as described above: this minimizes move distance, at the expense of the maximum quantity of stacks. As this parameter is increased, zone width increases, giving fewer stacks (and each stack filled to a greater extent), but increased move distance. Finally, note that the above procedure allows for multiple stacks to be worked on at the same time. In Figure 7.5, for example, stacks 2B and 3A can be worked on simultaneously, without any interference. This allows for higher productivity (at the expense of more difficult worker task scheduling).

4.1 Stack Formation

Once the zones have been established as above, panels can be assigned to stacks. Stacks are created in the order used (1A, 2A, 2B, 3A,...). For each stack, panels are assigned one layer at a time: the first layer will become the top layer of the stack (Figure 1). Panels are assigned to the current layer of a stack if total stack length (input parameter) is not exceeded; otherwise a new layer is started. The general procedure is as follows:

1. Add panels for any edges preceding the erect area, in the sequence shown in Figure 3. For horizontal edges, assign panels from left-to-right; for vertical edges, assign panels from top-to-bottom.
2. Select the panels from the erect area to assign to the stack. Go through the zone in build direction (left-to-right, top-to-bottom) to select panels for the stack, ensuring connectivity is maintained at all times. If a panel is entirely within the erect area, add it to the stack and continue. If a panel extends past the right edge of the zone, however, try to start another panel 'row.' If such a panel is found, continue as usual. Otherwise, stop: no more panels can be assigned to the stack from the erect area.
3. Add panels for any edges following the erect area, in the sequence shown in Figure 7.5. These edges are all horizontal, so assign panels from left-to-right.

4.2 Stack Locations and Stack Delivery

Stack locations and delivery sequence are automatically generated by the stacking heuristic. As previously explained, delivery of select stack pairs can be overlapped, if desired, to allow two stacks to be worked on simultaneously. The amount of overlap to employ is a parameter specified by the user.

5. Construction

5.1 Construction Sequencing

The stacking heuristic assigns panels to stacks to maintain connectivity and provide a feasible build sequence, so that one-piece flow is possible. Panels are unloaded from the stack, and moved to their final location and erected, in the order provided. Thus, no on-site construction sequencing is necessary.

5.2 Construction Task Planning, Scheduling, and Worker Assignment

In order to get each panel from its initial location/orientation on a stack to its final location/orientation in the building, a sequence of construction activities is required. Based upon the aforementioned construction task taxonomy [9], the following construction activities are defined:

- *Lift* activities: Unload panel from stack to angled orientation (**L2**), plus **L1**, **L3**, **L4** (Figure 2).
- *Carry* activities: move horizontally-oriented panel to end-of-carry point, tip down so bottom plate contacts floor (**C1**), move angled panel and tip down (**C2**), move vertically-oriented panel to erect point (**C3**).

- *Erect* activities: tip up panel carried via **C1** to vertical (**E1**); tip up panel carried via **C2** to vertical (**E2**).
- *Move* activities: move vertical panel to final location and fix (**M1**).

The possible activity sequences, along with the allowable worker quantities for each activity, are as follows:

- **L1** or **L4** (2, 3, or 4 workers) – **C1**(2,3,4) – **E1**(2,3,4) – **M1**(2,3,4).
- **L2**(2) – **C1**(2) – **E1**(2) – **M1**(2)
- **L2**(2) – **C2**(2) – **E2**(2) – **M1**(2)
- **L3**(2,3,4) – **C3**(2,3,4) – **M1**(2,3,4)

In order to provide the maximum opportunity for reducing ergonomic impact on workers, we allow the quantity of workers to vary from one activity to the next. So, for example, we may use two workers for **L1**, then have another worker join for **C1**, a fourth worker join for **E1**, then one worker less for **M1** (i.e., **L1**/2 – **C1**/3 – **E1**/4 – **M1**/3).

The construction task planning, scheduling, and worker assignment problems are all interdependent. Some activities require a certain quantity of workers, so the set of available workers must be known. But this cannot be determined until the construction schedule is established, which in turn requires knowledge of the construction activities. Thus, these three problems must be solved simultaneously. The construction scheduling problem alone closely resembles job-shop scheduling: as such, the three problems together will be at least as hard to solve as job-shop scheduling problems. One widely used and well-studied approach for job shop scheduling is the use of dispatching rules: whenever a job is completed at a machine, a simple rule (e.g., shortest processing time) is used to select the next job to run. We employ this same approach via the use of *construction rules*, which can be easily employed by workers in the field. Two rules are needed for construction activity planning:

- Panel start: if panel length $\leq L2\_length$ (parameter) use **L2**; otherwise use **L1/L4** (type 'A' stacks only).
- End of **L2**: if total panel move distance (Euclidean) $\leq C2\_distance$ (parameter), use **C2**; otherwise use **C1**.

For construction task scheduling and worker assignment, rules are needed to establish (i) the workers to use for the initial (lift) activity, (ii) the workers to use for subsequent activities (we assume that the first two workers must always remain, for continuity), and (iii) where idle workers should wait. A variety of rules are under development. The quantity of workers, for example, can be selected based upon some function of panel length, panel weight, etc., while the actual workers to use might be dependent upon worker utilization, proximity to the activity, cumulative ergonomic risk, etc. To employ rules utilizing ergonomic factors, a database of ergonomic data for the various construction activities is being developed, with data coming from

comprehensive lab-based experiments involving different panel sizes and different worker quantities. Details of this can be found in [6].

6. Implementation

As previously mentioned, a prototype software tool utilizing the above methods for design and planning for residential panelized construction is under development at Virginia Tech. Given a building plan, the user first specifies panelization parameters: the software then generates the corresponding set of possible panelization plans. Stacking parameters (e.g., maximum stack length, zone width multiplier) are specified next, following which the stacking plans are generated. Finally, the user specifies the quantity of workers and construction rules/parameters: the construction process is then simulated for each panelization and stacking plan. At the aggregate level, simulation output consists of total construction lead time and overall ergonomic risk. By modifying any of the rules and/or parameters, a different overall solution (simulation output) can be obtained. Once a suitable set of plans is obtained, the panelization plan and stacking plan are forwarded to the panel manufacturer and transport company (if an external agent is used). The construction rules/parameters are provided to the appropriate personnel at the job site, to be communicated to the workers.

Conclusions

Residential construction using panelized walls offers many advantages over stick construction. Because panels are large and cumbersome, however, the approach results in greatly increased risk of worker overload and injury. Current studies have shown that many injury-causing accidents are the result of problems which must be addressed upstream in the process, i.e., during design and planning. The methods described in this paper are an initial attempt to make panelized residential construction safer utilizing this 'prevention through design' approach. Because the work is ongoing, the extent to which the approach will be successful cannot yet be ascertained. Field studies and beta testing are planned, however, to quantitatively establish the validity and utility of the approach in practice.

References

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8. Software Development, Demonstration, and User Feedback

Software Development and Integration

A variety of software applications/programs are necessary to generate the DSS, and prototype versions of these have been developed, implemented, and integrated under Microsoft's Visual Studio environment. The panelization and stacking routines have been coded up using Visual Basic or C++. A generic residential panelized construction simulator, *ConstructionSIM*, has been developed in C++ using the object-oriented approach to discrete simulation. While we had planned initially to use a high-quality commercial simulation product (e.g., Flexsim, Flexsim Software Products Inc., Orem, UT), this proved infeasible as such products have insufficient modeling flexibility. An object-oriented approach, on the other hand, affords the highest possible level of modeling flexibility and has proven an excellent vehicle for our application. Animation capability is provided using PROOF3D (Wolverine Software Corporation, Alexandria, VA), a general-purpose, 3D animation package/language incorporating industry-standard DirectX graphics. We also use PROOF3D to generate building layouts and panelization plans, thereby eliminating any need for a third-party CAD package. Data input and output files are maintained as text, Excel, or Access files. The DSS itself has been implemented as an ASP.NET website. Users interact with the DSS through several web pages that in turn call and execute the various software programs. An example of how these programs work is provided below.

Generation of Ergonomic Risk

To determine ergonomic risk for a given panelization design, stacking plan, and construction plan, ConstructionSIM generates a task data text file that provides a complete list of all tasks performed during simulated building construction. Accompanying each task are factors needed for ergonomic analysis: the workers involved, panel involved, and panel size, weight, and translation/rotation (3 axes). Ergonomic data generated in our laboratory experiments has been compiled and stored in an "exposure and risk" database (MS Access™), and the risk assessment methods have been incorporated in a post-processor. Following simulation, the post-processor reads the task data text file, obtains the necessary ergonomic data from the Access database, and generates the ergonomic assessment measures. The latter are then provided to the user in summary format (see below).

Animation Capability

A simulation animation of the construction process is provided to the user. As the objective of this animation is purely visualization (vs. detailed analysis of postures, motions, etc.) low-fidelity human models and motion were proposed. Our initial plan was to create predefined frames of workers performing various tasks (lift, walk, etc.), with three to four frames created per task, then "play back" these frames to approximate human motion, complete with changes in posture and limb positions. This proved far too ambitious for a prototype software application, however, as even this crude level of detail is extremely laborious to obtain with commercial general-purpose simulation products. Such fidelity is possible using PROOF3D, but again difficult. Consequently, the low-fidelity human models in our prototype DSS are representative only – workers remain in a standing posture and limbs are not modeled. While not as detailed as first envisioned, this approach has proven sufficient for demonstrating proof-of-concept and thus

satisfies the requirements of our prototype DSS. Several workers modeled in this manner can be seen in the following software demo.

Software Demo

The following example illustrates how the prototype DSS is used and the various types of output which are provided. The example consists of a single-story, x sq. ft. house to be constructed using panelized walls.

Figure 8.1 shows the home page for the DSS website. The panel designer clicks 'Continue to Main Menu', which opens the main menu of Figure 8.2. Here, the user establishes the manner in which the DSS is to be employed:

1. *Particular scenario.* The user specifies all required parameters for panelization, stacking, and construction. The DSS generates the corresponding panelization and stacking plans, then simulates construction.
2. *Optimization.* The user specifies the objective (minimize construction time, overall ergonomic risk, or quantity of workers) and constraints on the remaining two variables (plus other parameters as required). The DSS then generates all possible panelization plans, stacking plans, and construction plans, then selects the first optimal set of plans found.

In this example, the user selects for a particular scenario, then clicks 'Continue.' The web page for designing and planning panelized construction for a given scenario then appears (Figure 8.3). Panelization, stacking, and construction planning are all done via this single web page.

The first step is panelization. The user browses a directory on his/her machine to locate the desired building plan, then clicks on 'Upload' to retrieve the it. The building plan can then be viewed ('View Plan'), as shown in Figure 8.4. Panelization parameters are then selected (or uploaded from a file, if desired) and saved, following which the user clicks on 'Panelize' to run the panelization algorithm. The algorithm generates four panelization plans, one for each possible drop-off edge of the structure (north, south, east, and west). The user clicks on 'View/Save Results' to view the panelization plans and/or save a copy of the plans to his/her machine (Figure 8.5). Here, we see the panelization plan for a south drop-off edge both as a drawing (Figure 8.6) and a text file (Figure 8.7).

The second step is stacking. The user inputs the stacking parameters (or uploads from a file, if desired), saves the parameters, then clicks on 'Stack' (Figure 8.8). The stacking algorithm then generates one stacking plan for each accessible drop-off edge (stacking parameter #1), and selects the plan having the minimum total weighted move distance (distance from each panel's stack location to its final location). The user can then view and/or save the results as before, as shown in Figure 8.8. The stacking plan comparison shows the total weighted move distance for each stacking plan generated. Figure 8.9 shows the stacking plan for the single south drop-off edge panelization plan generated previously.

The final step is construction planning. The user inputs the construction parameters (or uploads from a file, if desired), saves the parameters, then clicks on 'Simulate', as shown in Figure 8.10. The DSS then executes ConstructionSIM, using the panelization plan, stacking plan, and construction parameters just established. The simulator runs and creates three output

files: (i) an animation trace file, (ii) simulation output, and (iii) a task data text file. Once the simulation is complete, a dialog box opens with three selections:

1. *View Animation.* Starts PROOF 3D running, with the animation trace file as input. This provides a 3D animation of the entire construction process, from stacks arriving to the site to building completion. Figures 8.11 – 8.15 show some screen shots of the construction animation for the example provided.
2. *View Simulation Results.* Provides standard observation-based and time-persistent statistics for the simulated construction process. This is still under development: the simulation results currently generated for the example are shown in Figure 8.16.
3. *View Ergonomic Results.* Causes the DSS to generate summary measures of ergonomic risk as previously described (p. 103). Figure 8.17 shows the first portion of the task data text file generated for the example. This is still under development: the ergonomic results currently generated for the example are shown in Figure 8.18.

It should be noted that while panelization, stacking, and construction planning were all performed sequentially in this example, this need not always be the case. The user can upload an existing panelization plan, for example, and start with stacking (see Figure 8.3). Alternatively, the user can upload both panelization and stacking plans and start with construction planning. This ability to start at different stages of the process, as desired, facilitates the use of the DSS by multiple parties.

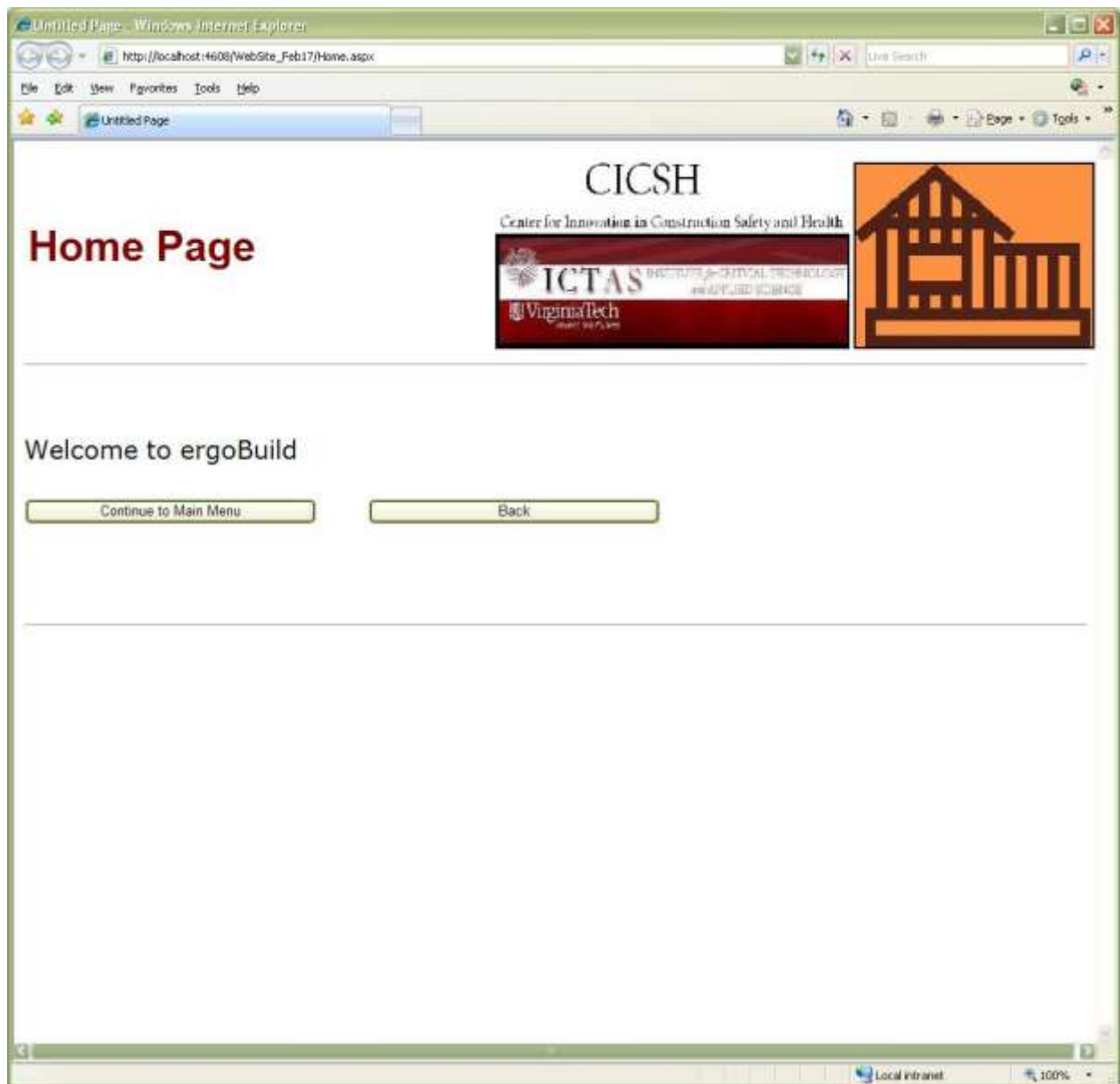


Figure 8.1: Prototype DSS home page.

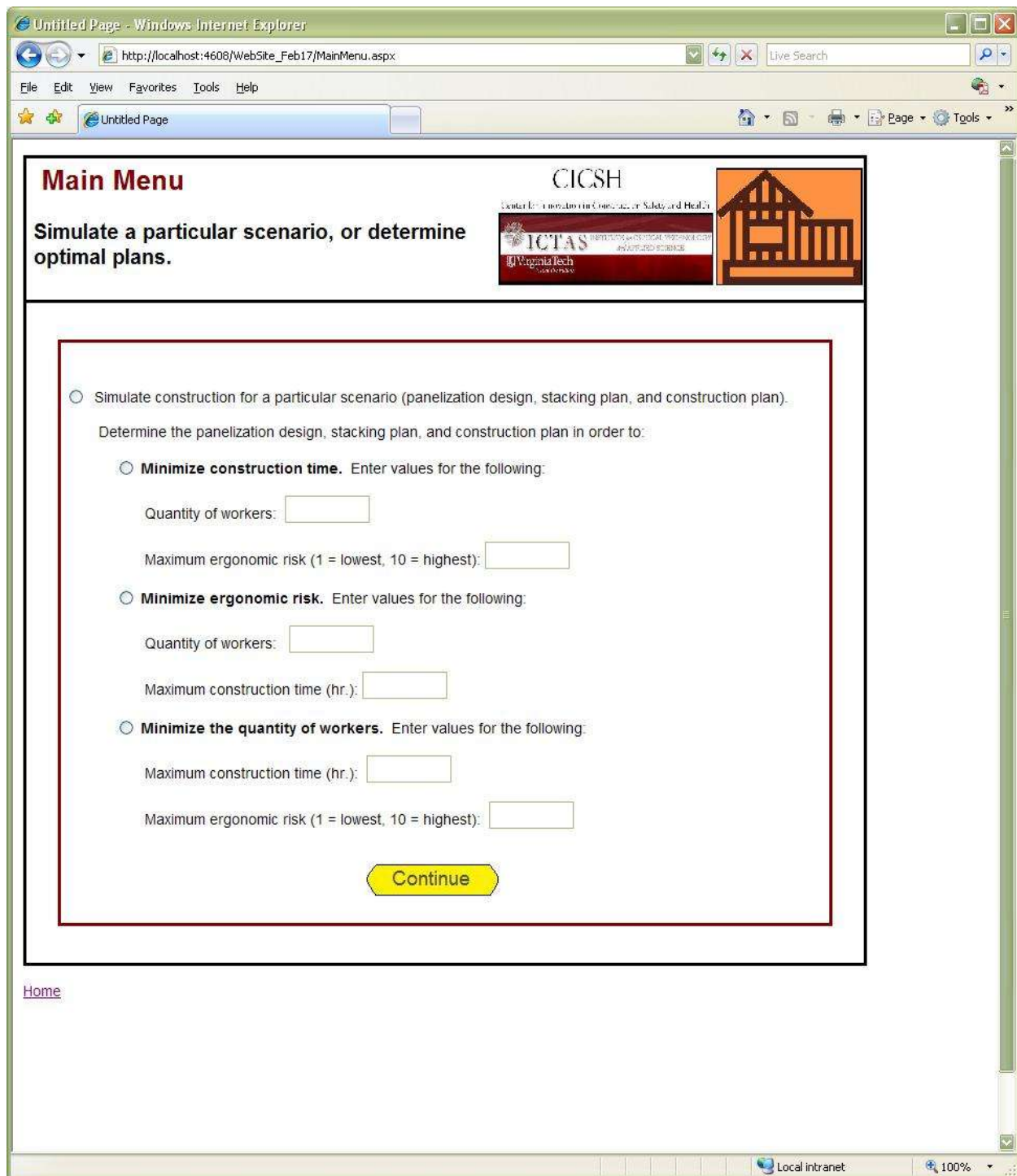


Figure 8.2: Selection of decision support approach: particular scenario or optimization.

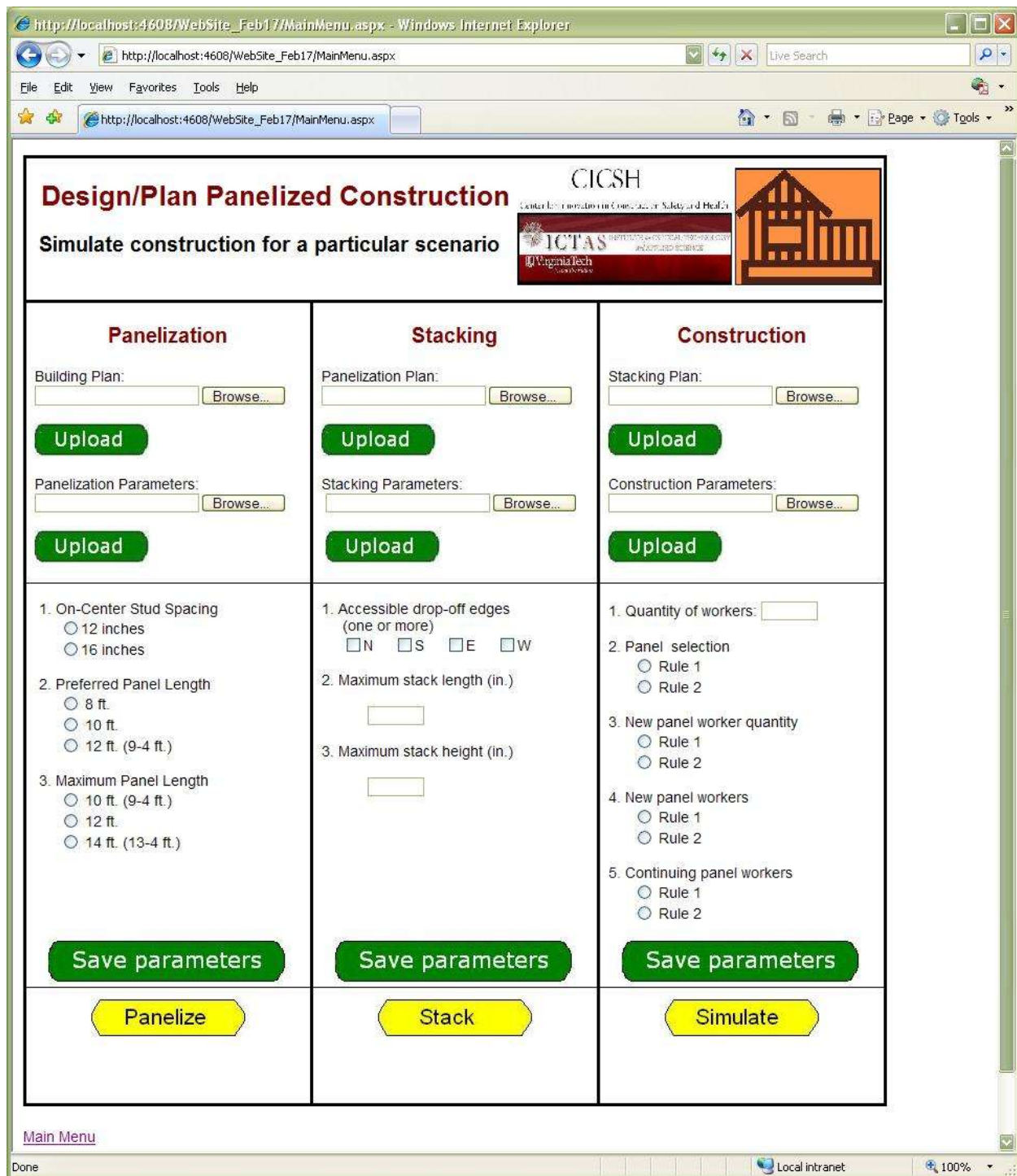


Figure 8.3: Main web page for designing/planning panelized construction for a particular scenario.

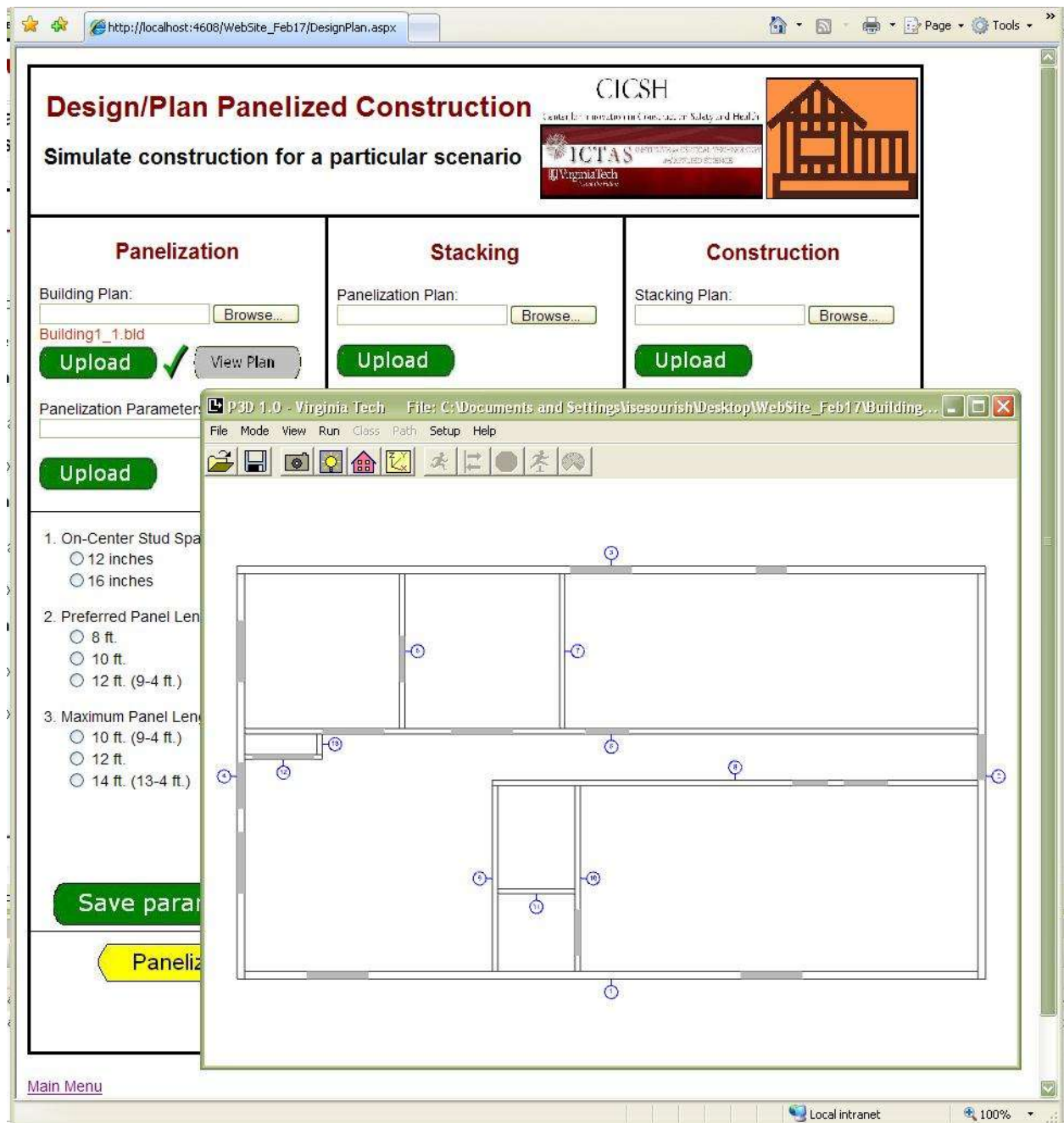


Figure 8.4: Selection and uploading of building plan, then viewing of plan.

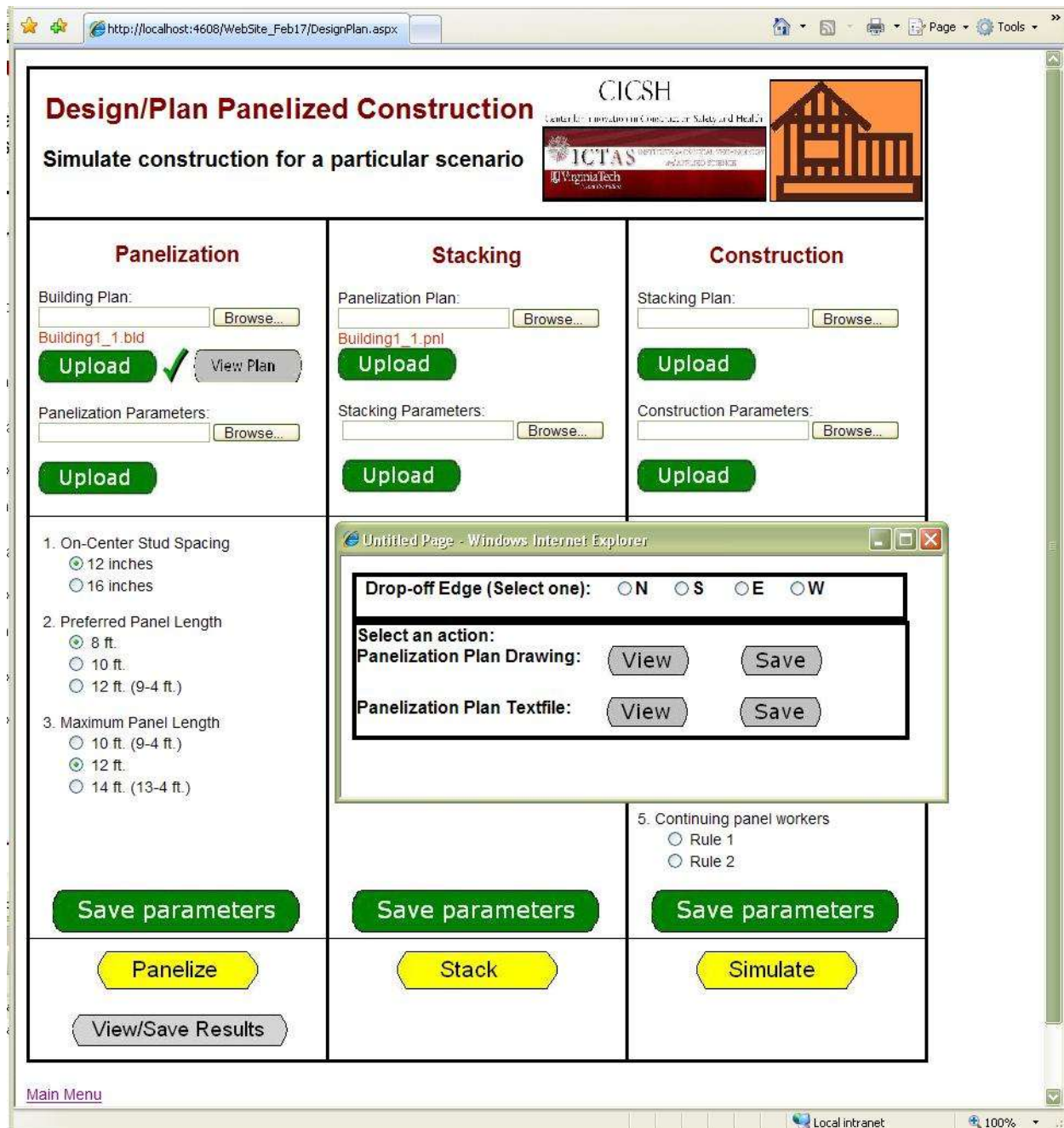


Figure 8.5: Panelization: specification of parameters, generation of panelization plan, and selection of plan (via drop-off edge) to view and/or save.

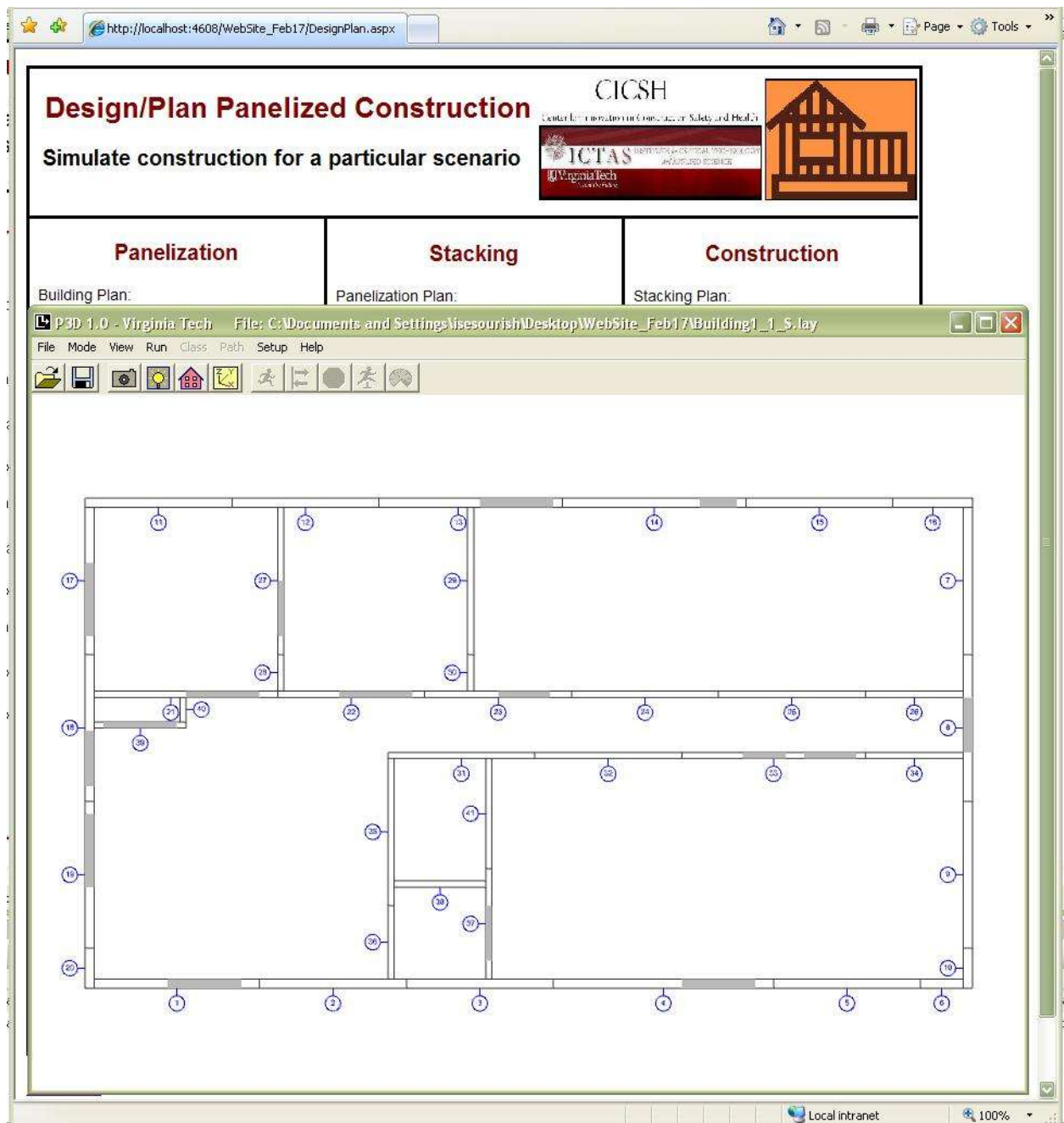


Figure 8.6: Panelization plan, provided as a drawing (PROOF 3D) – compare to Figure 8.3.

http://localhost:4608/WebSite_Feb17/DesignPlan.aspx

Design/Plan Panelized Construction

Simulate construction for a particular scenario

CICSH
Center for Innovation in Construction Safety and Health

ICTAS
INSTITUTE FOR INTELLECTUAL TECHNOLOGY AND SCIENCE
VIRGINIA TECH



Panelization

Building Plan:

Building1_1.bid ☒

Panelization Parameters:

Stacking

Panelization Plan:

Building1_1.pnl

Stacking Parameters:

Construction

Stacking Plan:

Construction Parameters:

Building1_1_S - Notepad

```

File Edit Format View Help
*** Panelization Plan
*** File: Building1_1_S.pnl

*** Panel Height ***
96

*** quantity of panels ***
41

*** panel panel panel sheath # of openings ***
*** length thkns type type openings # length height x-loc y-loc ***
*** # ***
1 108 6 1 1 1 1 48 60 48 18
2 96 6 1 1 1 0
3 96 6 1 1 1 0
4 144 6 1 1 1 1 48 48 84 24
5 96 6 1 1 1 0
6 28 6 1 1 1 0
7 96 6 1 1 1 0
8 96 6 1 1 1 1 36 74 28 0
9 96 6 1 1 1 0
10 26 6 1 1 1 0
11 96 6 1 1 1 0
12 96 6 1 1 1 0
13 120 6 1 1 1 1 48 48 66 24
14 120 6 1 1 1 1 24 36 90 38
15 96 6 1 1 1 0
16 52 6 1 1 1 0
17 96 6 1 1 1 1 48 48 36 24
18 96 6 1 1 1 1 36 74 50 0
19 96 6 1 1 1 1 48 60 8 18
20 26 6 1 1 1 0
21 120 4 2 2 2 1 48 74 60 0
22 96 4 2 2 2 1 48 74 40 0
23 96 4 2 2 2 1 34 74 48 0
24 96 4 2 2 2 0
25 96 4 2 2 2 0
26 64 4 2 2 2 0
27 96 4 2 2 2 1 36 74 48 0

```

[main menu](#)

Local intranet 100%

Figure 8.7: Panelization plan, provided as a text file.

http://localhost:4608/WebSite_Feb17/DesignPlan.aspx

Design/Plan Panelized Construction

Simulate construction for a particular scenario

CICSH
Center for Innovation in Construction of Architecture & Building

ICTAS
Institute for Technology and Architecture Simulation

Panelization

Building Plan: Browse...
Building1_1_bld
Upload ☒ **View Plan**

Panelization Parameters: Browse...
Upload

1. On-Center Stud Spacing
☒ 12 inches
☐ 16 inches

2. Preferred Panel Length
☒ 8 ft.
☐ 10 ft.
☐ 12 ft. (9-4 ft.)

3. Maximum Panel Length
☐ 10 ft. (9-4 ft.)
☒ 12 ft.
☐ 14 ft. (13-4 ft.)

Save parameters

Panelize

View/Save Results

Stacking

Panelization Plan: Browse...
Building1_1_pnl
Upload

Stacking Parameters: Browse...
Upload

1. Accessible drop-off edges (one or more)
☐ N ☒ S ☐ E ☐ W

2. Maximum stack length (in.)
 150

3. Maximum stack height (in.)
 50

Save p

Stack

View/Save Results

Construction

Stacking Plan: Browse...
Building1_1_stk
Upload

Construction Parameters: Browse...
Upload

1. Quantity of workers:

2. Panel selection
☐ Rule 1
☐ Rule 2

3. New panel worker quantity
☐ Rule 1
☐ Rule 2

Simulate

View/Save Results

Untitled Page - Windows Internet Explorer

Select an action:

Stacking Plan: **View** **Save**

Stacking Plan Comparison: **View** **Save**

Main Menu

Local intranet 100%

Figure 8.8: Stacking: specification of parameters, generation of stacking plan, selection of results for viewing.

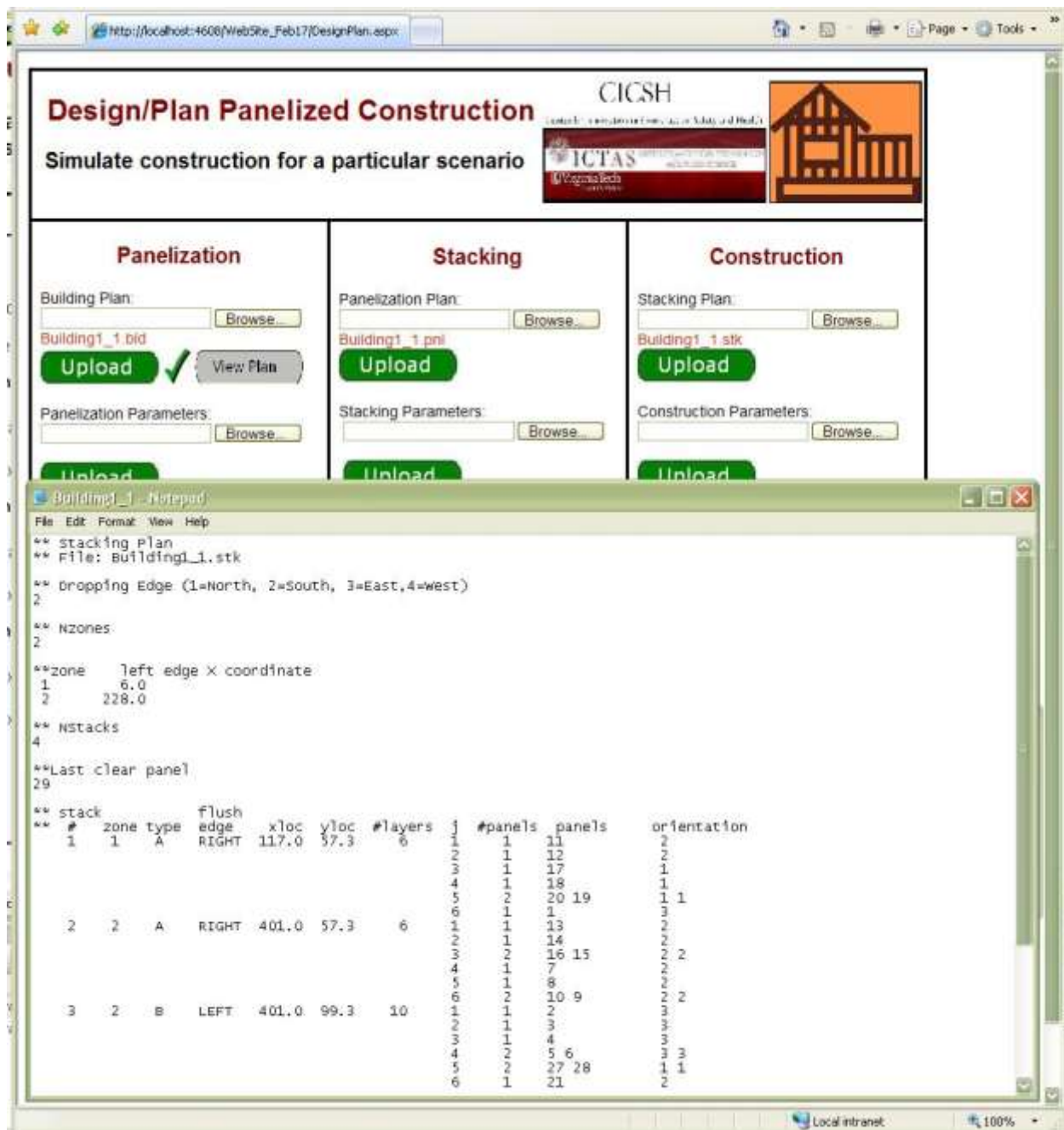


Figure 8.9: Stacking plan, provided as a text file.

http://localhost:4608/WebSite_Feb17/DesignPlan.aspx

Design/Plan Panelized Construction

Simulate construction for a particular scenario

CICSH
Center for Information in Construction Safety and Health

ICTAS
INTEGRATED TECHNOLOGICAL TRAINING AND SIMULATION
Virginia Tech



Panelization	Stacking	Construction
Building Plan: Browse... Building1_1.bld Upload ☒ View Plan	Panelization Plan: Browse... Building1_1.pnl Upload	Stacking Plan: Browse... Building1_1.stk Upload
Panelization Parameters: Browse... Upload	Stacking Parameters: Browse... Upload	Construction Parameters: Browse... Upload
1. On-Center Stud Spacing ☒ 12 inches ☐ 16 inches 2. Preferred Panel Length ☒ 8 ft. ☐ 10 ft. ☐ 12 ft. (9-4 ft.) 3. Maximum Panel Length ☐ 10 ft. (9-4 ft.) ☒ 12 ft. ☐ 14 ft. (13-4 ft.)	1. Accessible drop-off edges (one or more) ☐ N ☒ S ☐ E ☐ W 2. Maximum stack length (in.) 150 3. Maximum stack height (in.) 50	1. Quantity of workers: 4 2. Panel selection ☒ Rule 1 ☐ Rule 2 3. New panel worker quantity ☒ Rule 1 ☐ Rule 2 4. New panel workers ☐ Rule 1 ☒ Rule 2 5. Continuing panel workers ☒ Rule 1 ☐ Rule 2
Save parameters	Save parameters	Save parameters
Panelize	Stack	Simulate
View/Save Results	View/Save Results	

[Main Menu](#)

Local intranet 100%

Figure 8.10: Construction planning: specification of construction parameters, ready for simulation.

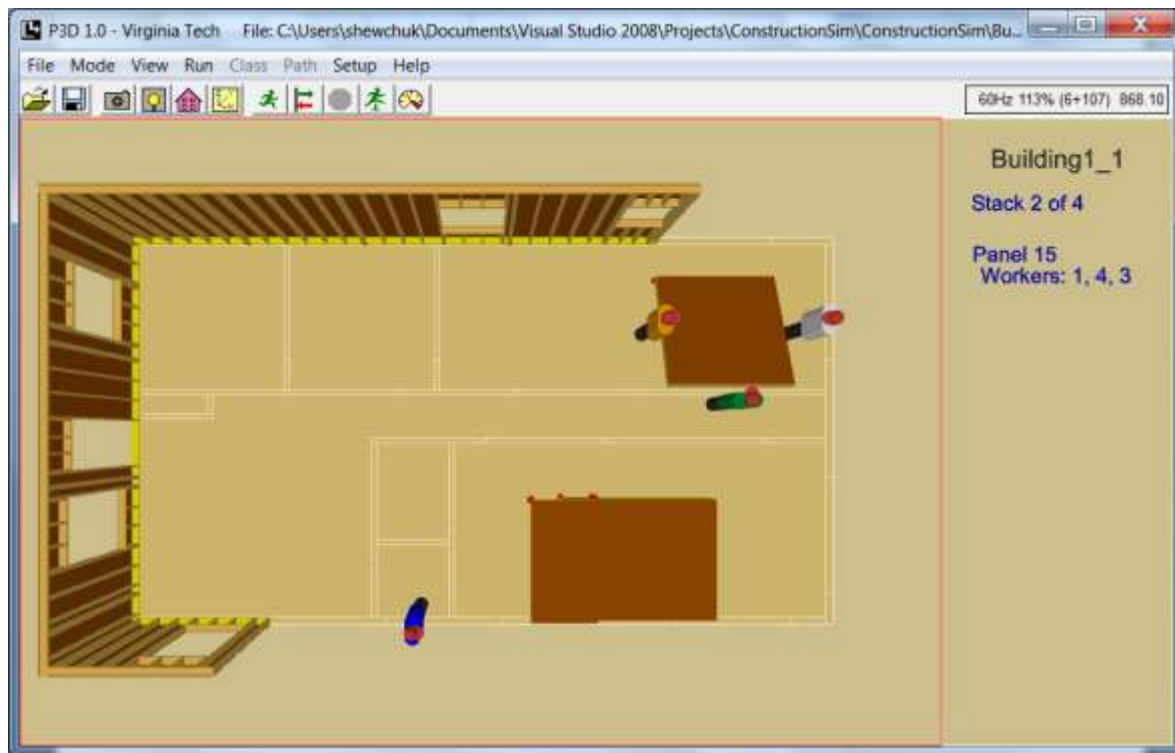


Figure 8.11: Simulation animation: three workers ready to erect a sheathed panel.

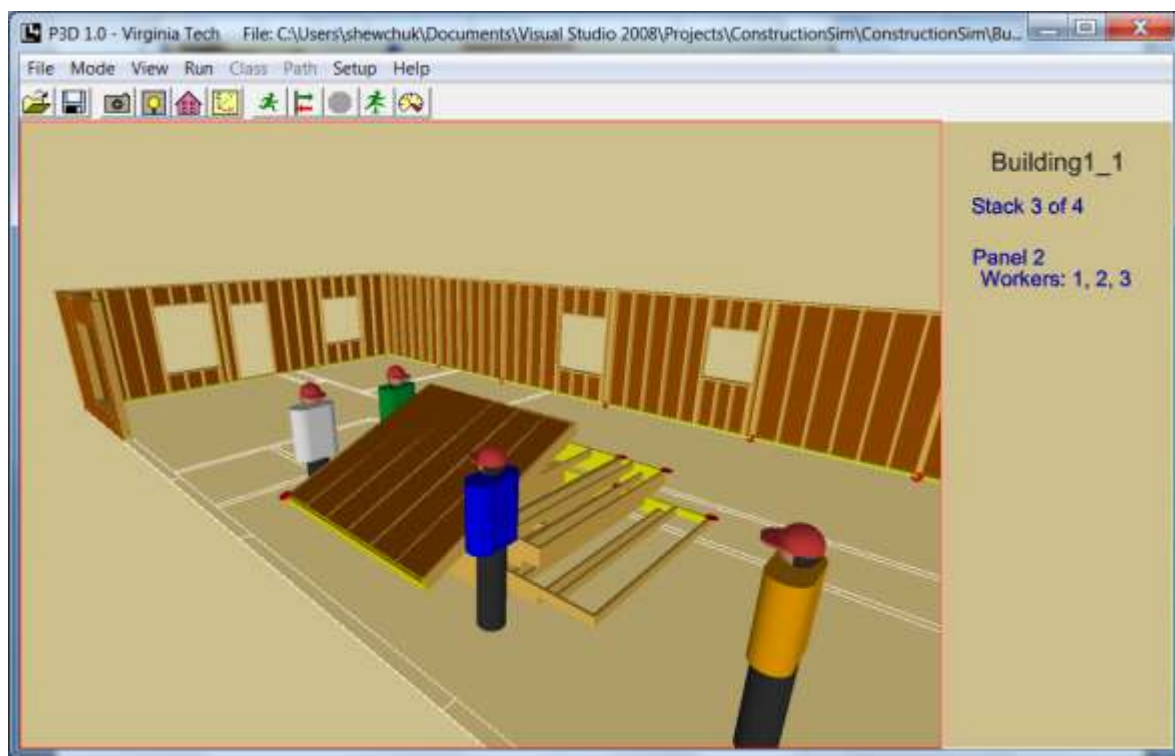


Figure 8.12: Simulation animation: tipping a sheathed dropping-edge panel off its stack.

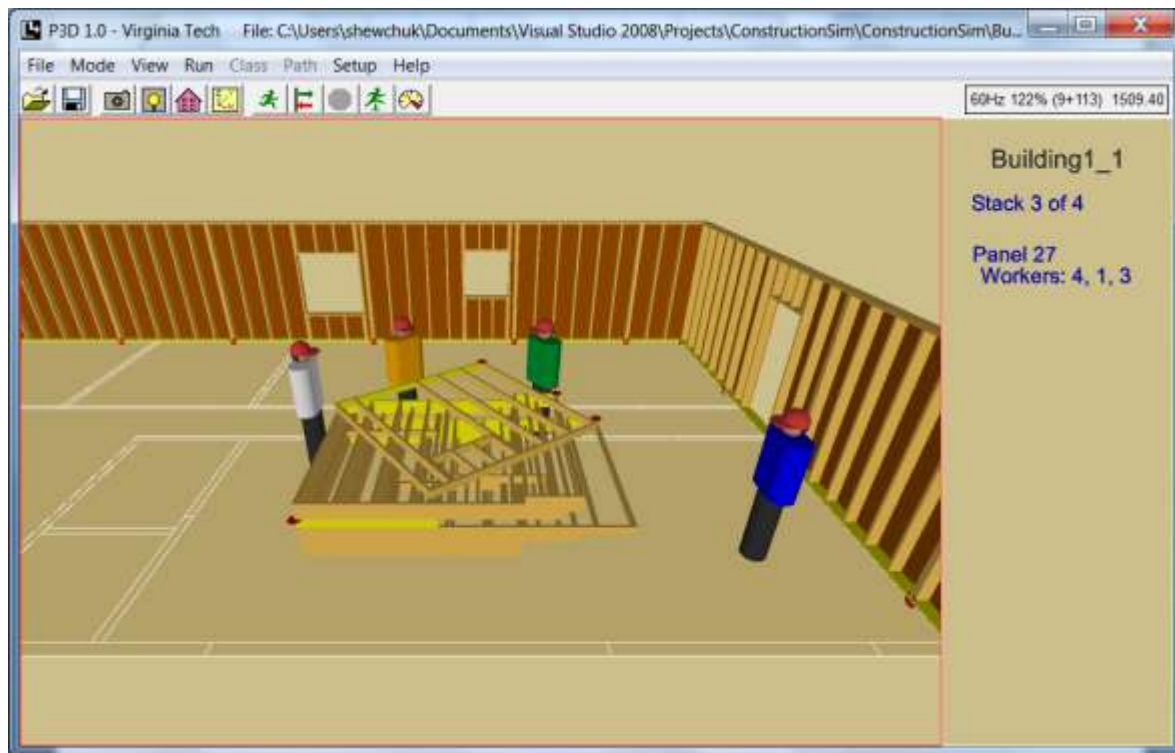


Figure 8.13: Simulation animation: rotating an unsheathed panel on its stack before tip.

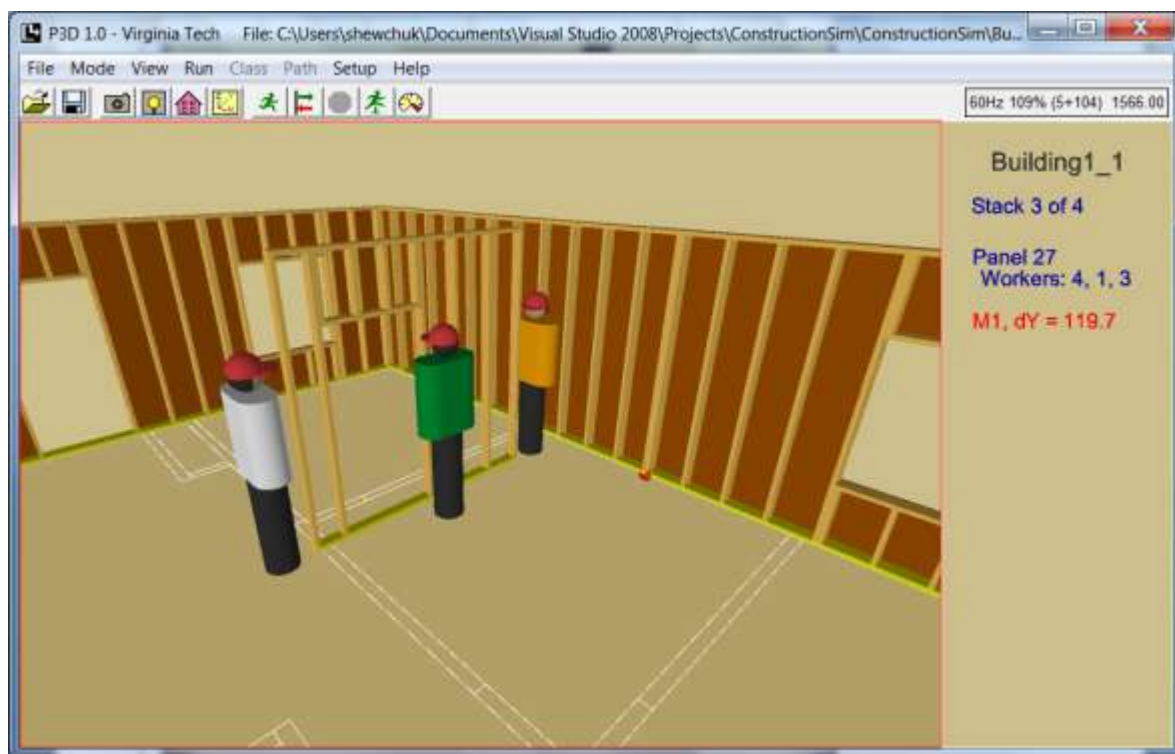


Figure 8.14: Simulation animation: moving an erected panel into final position.

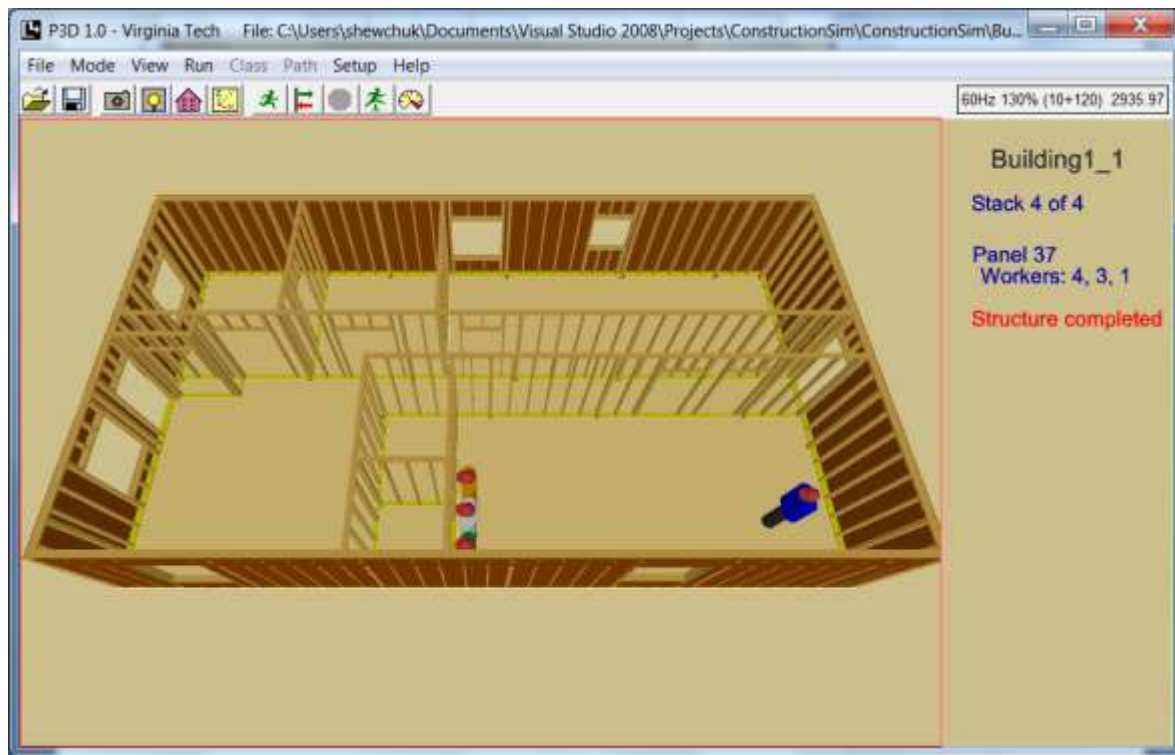


Figure 8.15: Simulation animation: completed panelized structure,

SimOutput - Notepad

File Edit Format View Help

```

*****
*   ConstructionSIM   *
*****

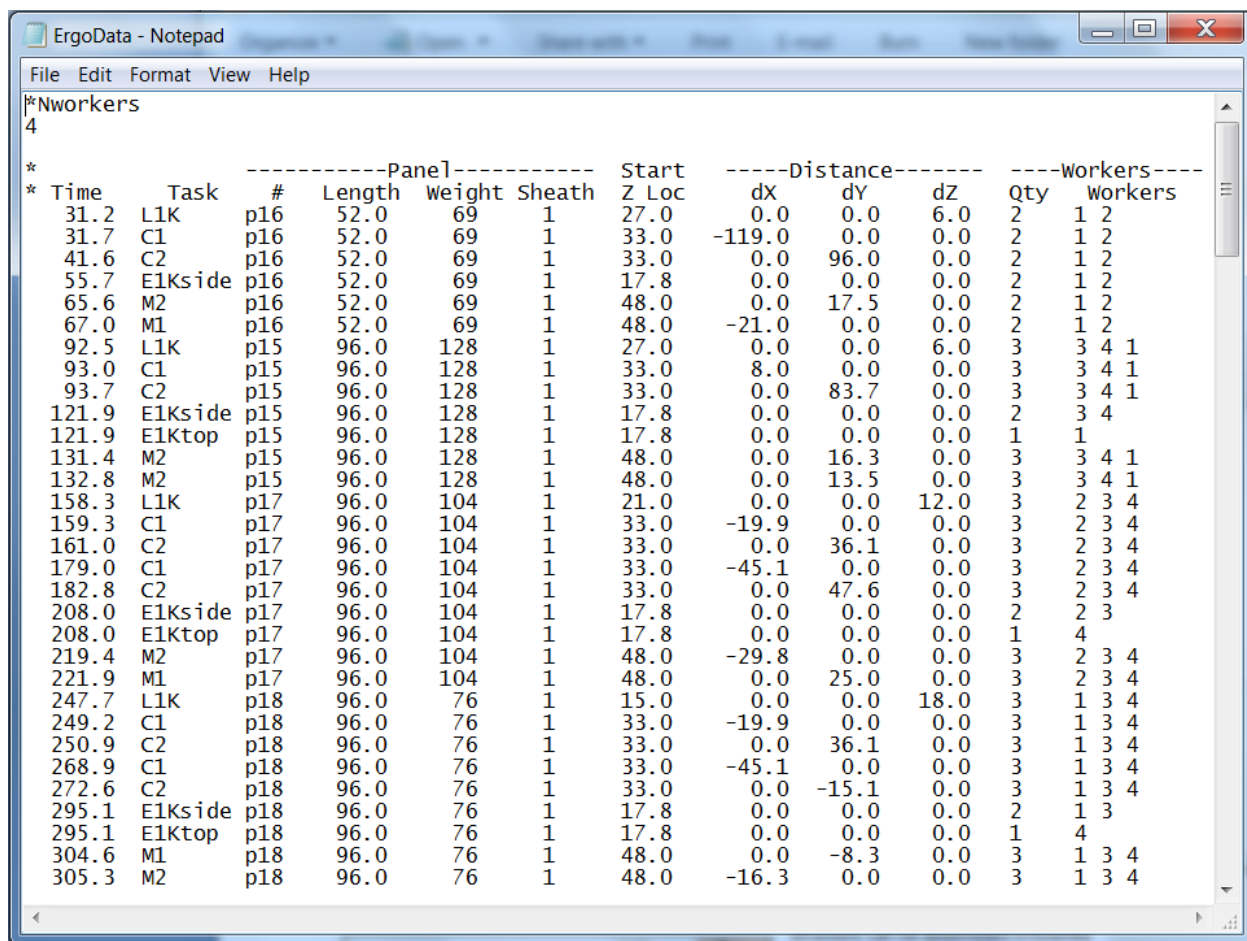
SIMULATION RESULTS

Project:                                     Date:
Total construction time:
Worker statistics:

Worker 1      IDLE    BUSY    WAITING    WALKING TO    WALKING TO    WALKING
              18.5    46.3    5.7        PANEL        WAIT AREA    AROUND
Worker 2      20.8    45.6    7.5        17.0         9.8         2.8
Worker 3      19.5    45.9    9.2        14.1         9.7         2.2
Worker 4      19.1    46.2    6.3        15.4         8.6         1.4
              17.9         9.1         1.4
TOTAL
100.0
100.0
100.0
100.0

```

Figure 8.16: Simulation output: general simulation results (under development).



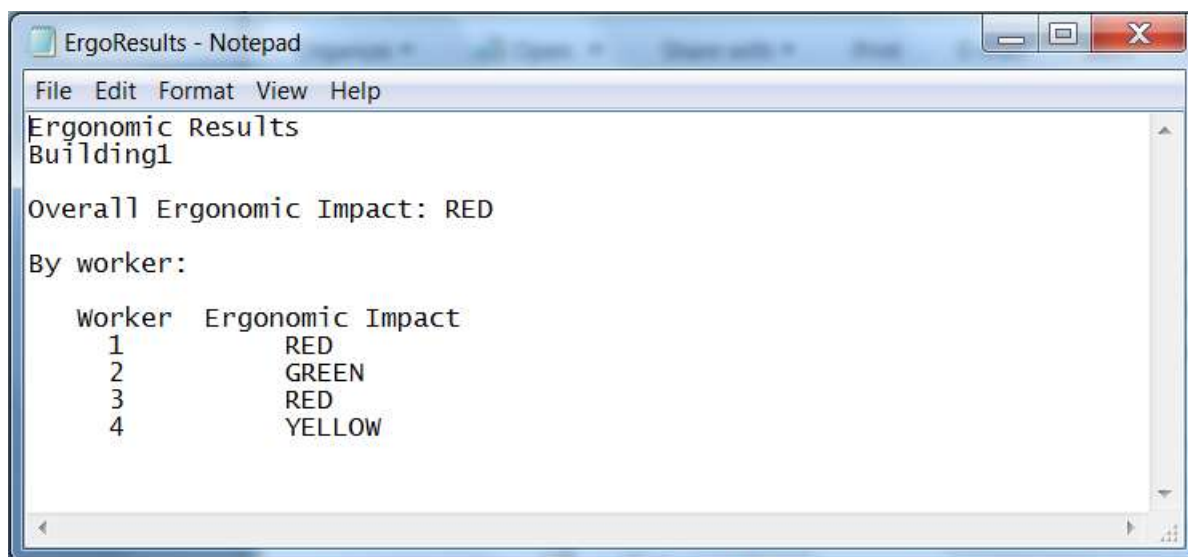
The screenshot shows a Notepad window titled "ErgoData - Notepad". The text content is a simulation output file. It starts with a header section followed by a table of task data. The header section includes labels for Time, Task, Panel, Start Z Loc, Distance (dX, dY, dZ), Qty, and Workers. The table contains 30 rows of data, each representing a task performed by a specific worker (p16, p15, p17, p18) with associated time, task name, panel number, length, weight, sheath, start location, distance, quantity, and worker assignment.

```

*
*-----Panel-----
* Time      Task      #      Length  Weight  Sheath  Start  -----Distance-----  Qty  Workers
*   31.2    L1K      p16     52.0     69      1      27.0    dX    dY    dZ    2    1 2
*   31.7    C1       p16     52.0     69      1      33.0   -119.0 0.0  0.0  2    1 2
*   41.6    C2       p16     52.0     69      1      33.0    0.0 96.0  0.0  2    1 2
*   55.7    E1Kside  p16     52.0     69      1      17.8    0.0  0.0  0.0  2    1 2
*   65.6    M2       p16     52.0     69      1      48.0    0.0 17.5  0.0  2    1 2
*   67.0    M1       p16     52.0     69      1      48.0   -21.0  0.0  0.0  2    1 2
*   92.5    L1K      p15     96.0    128      1      27.0    0.0  0.0  6.0  3    3 4 1
*   93.0    C1       p15     96.0    128      1      33.0    8.0  0.0  0.0  3    3 4 1
*   93.7    C2       p15     96.0    128      1      33.0    0.0 83.7  0.0  3    3 4 1
*  121.9    E1Kside  p15     96.0    128      1      17.8    0.0  0.0  0.0  2    3 4
*  121.9    E1Ktop   p15     96.0    128      1      17.8    0.0  0.0  0.0  1    1
*  131.4    M2       p15     96.0    128      1      48.0    0.0 16.3  0.0  3    3 4 1
*  132.8    M2       p15     96.0    128      1      48.0    0.0 13.5  0.0  3    3 4 1
*  158.3    L1K      p17     96.0    104      1      21.0    0.0  0.0 12.0  3    2 3 4
*  159.3    C1       p17     96.0    104      1      33.0   -19.9  0.0  0.0  3    2 3 4
*  161.0    C2       p17     96.0    104      1      33.0    0.0 36.1  0.0  3    2 3 4
*  179.0    C1       p17     96.0    104      1      33.0   -45.1  0.0  0.0  3    2 3 4
*  182.8    C2       p17     96.0    104      1      33.0    0.0 47.6  0.0  3    2 3 4
*  208.0    E1Kside  p17     96.0    104      1      17.8    0.0  0.0  0.0  2    2 3
*  208.0    E1Ktop   p17     96.0    104      1      17.8    0.0  0.0  0.0  1    4
*  219.4    M2       p17     96.0    104      1      48.0   -29.8  0.0  0.0  3    2 3 4
*  221.9    M1       p17     96.0    104      1      48.0    0.0 25.0  0.0  3    2 3 4
*  247.7    L1K      p18     96.0     76      1      15.0    0.0  0.0 18.0  3    1 3 4
*  249.2    C1       p18     96.0     76      1      33.0   -19.9  0.0  0.0  3    1 3 4
*  250.9    C2       p18     96.0     76      1      33.0    0.0 36.1  0.0  3    1 3 4
*  268.9    C1       p18     96.0     76      1      33.0   -45.1  0.0  0.0  3    1 3 4
*  272.6    C2       p18     96.0     76      1      33.0    0.0 -15.1  0.0  3    1 3 4
*  295.1    E1Kside  p18     96.0     76      1      17.8    0.0  0.0  0.0  2    1 3
*  295.1    E1Ktop   p18     96.0     76      1      17.8    0.0  0.0  0.0  1    4
*  304.6    M1       p18     96.0     76      1      48.0    0.0 -8.3  0.0  3    1 3 4
*  305.3    M2       p18     96.0     76      1      48.0   -16.3  0.0  0.0  3    1 3 4

```

Figure 8.17: Simulation output: partial task data text file.



The screenshot shows a Notepad window titled "ErgoResults - Notepad". The text content displays ergonomic results for "Building1". It includes an overall impact assessment and a breakdown by worker, showing the ergonomic impact for each of the four workers (1, 2, 3, 4).

```

Ergonomic Results
Building1

Overall Ergonomic Impact: RED

By worker:

Worker  Ergonomic Impact
1       RED
2       GREEN
3       RED
4       YELLOW

```

Figure 8.18: Simulation output: ergonomic results (under development).

Feedback from Potential Users

Using methods similar to those described earlier, we involved construction designers in assessing and evaluating our prototype DSS. We sought to take advantage of the knowledge and expertise of actual construction designers to improve the prototype version. At the time of this application, we have met with two (of a planned five) panel design/manufacturing firms (both of whom have committed to helping on the proposed work; see letters in Appendix). We interacted with them through open-ended discussions following a demonstration of the capabilities of our system and several representative examples showing how it can be used. Highlights of this are as follows. First, they both indicated a high level of interest in the DSS and saw it as a feasible approach to improve both ergonomics and productivity. Second, our DSS was seen as a method to help in marketing and expanding their customer bases, both of which were seen as particularly critical during the current economic downturn. Third, several specific and relevant items of information were identified, and we will address these during the remainder of our current project (e.g., include an option to allow panels to be dropped near, rather than on, the subfloor of a structure). Finally, it should be mentioned that aspects of our lean approach that are not currently utilized in practice (e.g., allowing different panel starting orientations in stacks, moving the stack drop-off location from one stack to another) were viewed positively and perceived as feasible.

Summary

The goal of our work is a software-based DSS that enables residential construction designers (and other potential users, such as contractors) to consider and control worker ergonomic risks when developing the panelization designs, stacking plans, and construction plans needed for panelized construction. While potential gains in efficiency are achieved using panels, increased exposures to MSD risk factors are an unfortunate consequence. Use of panels in construction involves a centralized designer (at the panel manufacturer), and we seek to take advantage of this by facilitating prevention through design. Our DSS yields plans that considerably reduce the likelihood of worker injury, and these plans are generated rapidly and in a consistent, documented manner. Along with ergonomics, the DSS allows users to assess the impact of their designs on productivity and worker needs. As such, the likelihood that ergonomic issues are actually addressed in this construction domain is assumed to be substantially higher than if the focus were solely on ergonomic issues. In addition, the system aids, through simulation animation, in visualizing the proposed construction process and providing increased assurance that a structure can be assembled efficiently and an ability to assess cost and time involved. Upon completing our initial project, we will have developed the basic software system in prototype form as originally proposed. To develop this system to be both useable and actually used, several additional steps are needed as described in the subsequent section. We intend to improve and expand several aspects of the DSS, facilitate its implementation, and demonstrate the benefits of its use.

9. Additional Work

In addition to the studies summarized above, several other studies and analyses were completed by the current investigators on related topics. Those that were supported by grant funding, either directly or indirectly, and for which the research is completed, are summarized in abstract form below.

9.1 Risk Assessment of Panelized Wall Construction

Kim HN, Nussbaum MA, Seol H, Kim S, Smith-Jackson TL: [2006] Risk assessment of panelized wall systems in residential construction using a critical incident technique. Proceedings of the 50th Annual Human Factors and Ergonomics Conference. San Francisco, CA. October 16-20, pp. 2222-2226.

Panelized wall systems are now extensively utilized in residential construction, which is recognized as a high-risk industry. A considerable number of construction injuries are reported every year. According to Occupational Safety & Health Administration (2005), 38,000 construction injuries occur each year. Safety on construction sites may not have the highest priority, as emphases of the construction industry are more on speed, efficiency, and economy. Furthermore, panelized wall systems have not been investigated in terms of hazard analysis. The primary purpose of the study was to identify the hazards related to panelized wall systems and to provide recommendations to improve the construction work environment. A critical incident technique was used to identify hazards through video-based observation, and the identified hazards were classified into five categories with twelve subcategories. Recommendations were provided for the hazards in each category. Based on the outcomes of the critical incident technique, risks associated with panelized wall systems were assessed using the MIL-STD-882B Risk Assessment Matrix.

9.2 Hand Forces and Trunk Motion

Kim S, Jia B, Nussbaum MA: [2009] Hand forces and trunk motion during panelized wall construction. Proceedings of the Industrial Engineering Research Conference (IERC). Miami, FL. May 30 – June 2. pp. 943-948.

There is a trend in residential building construction toward more industrialized construction methods (e.g. panelized walls). This study assessed physical demands during panel installation in relation to panel design factors. Twenty-four participants completed wall erection tasks. For each trial, resultant hand forces and trunk motion relative to the pelvis were obtained. Resultant hand forces were higher with larger panels, sheathed panels and some tasks. Trunk motion was affected by panel size and mass, but generally not by use of an additional worker. Understanding of physical exposures can be used to identify demanding tasks, and proactively for panel design.

9.3 Perceived Physical Demands

Kim S, Jia B, Nussbaum MA: [2009] Perceived physical demands during residential construction using panelized walls. Proceedings of the Industrial Engineering Research Conference (IERC). Miami, FL. May 30 – June 2. pp. 931-936.

Panelized walls are used with increasing frequency for residential construction. However, no formal ergonomic analysis has been performed to assess the different wall erection tasks involved. Twenty-four participants completed tasks in a laboratory environment, while four independent variables were manipulated. Ratings of perceived exertion (RPE) were obtained

from multiple body regions, and analyzed as preliminary evaluations. Main effects of panel mass, additional worker, and task type were generally found on RPE scores. Principal component analysis on RPE scores (excluding whole body) revealed two dominant components, which described task characteristics. Understanding physical demands can facilitate proactive control of exposures.

9.4 Muscle Activity and Trunk Kinematics

Jia B, Kim S, Nussbaum MA: [2009] Influence of panelized wall mass and wall erection tasks on physical demands in residential construction: muscle activity and trunk kinematics. Proceedings of the International Ergonomics Association (IEA) Conference. Beijing, China. August 9 – 14. pp. 103-108.

One trend in the residential construction industry is a move towards more industrialized methods, such as panelized (prefabricated) walls. As a consequence, construction workers may have higher levels of physical exposures due to the large mass of panelized walls and incidental changes in the process of wall erection. The purpose of this study was to investigate trunk kinematics and muscle activities associated with different wall masses and wall erecting tasks. Seventeen healthy participants performed eight different wall erection tasks (2 lifting (L), 4 erecting (E), 1 carrying (C), and 1 moving (M)) simulating observations from the field. Two 243.8 x 304.8 cm panelized walls were used, with masses of 53.6 kg (unsheathed) and 107.8 kg (sheathed). Trunk kinematics were measured using a passive marker system. Surface electromyographic (EMG) responses of eight trunk muscles were recorded bilaterally. All EMG responses were pre-processed (root mean square (RMS) converted and filtered) then normalized (nEMG) to peak values recorded during maximum voluntary contractions (MVCs). Peak trunk angles (relative to the pelvis) as well as mean and 90th percentile nEMG responses during each task were calculated, and subject to multivariate and univariate analyses of variance (MANOVAs and ANOVAs) to detect the overall effects of wall mass and erection task. Multivariate effects of wall mass, wall erection task and their interaction were significant. Univariate effects of task and task • mass were significant on most of the 90th percentile nEMG and peak trunk angles. In contrast, the effect of wall mass was significant only for peak trunk angles. Overall, the tasks of carrying and lifting from the ground required higher muscle activities. The largest 90th percentile nEMG (61% MVC) was found in the left longissimus thoracis pars lumborum during the carrying task. Of note, higher levels of activities in 10 muscles were observed with the unsheathed wall during erecting from the ground. Handling the sheathed wall significantly increased peak trunk angles during erecting tasks from knuckle height, and the largest peak trunk angle (88°) was found in the sagittal plane during lifting from the ground. These results suggest that sheathed walls and certain tasks involved in wall erection process may expose construction workers to both high levels of muscle activities (and likely high spinal loads) as well as highly non-neutral trunk postures. Understanding trunk kinematics and muscle activities during different wall erection tasks is expected to be beneficial for quantifying the risks associated with these tasks under a variety of panel design alternatives.

Inclusion of Gender and Minority Study Subjects

Study Title: Decision support tool for ergonomic construction design

Total Enrollment: 26

Grant Number: U19-OH008308

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race				
Ethnic Category	Sex/Gender			
	Females	Males	Unknown or Not Reported	Total
Hispanic or Latino	0	0	0	0 **
Not Hispanic or Latino	6	20	0	26
Unknown (individuals not reporting ethnicity)	0	0	0	0
Ethnic Category: Total of All Subjects*	6	20	0	26 *
Racial Categories				
American Indian/Alaska Native	0	0	0	0
Asian	0	5	0	5
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	1	1	0	2
White	5	14	0	19
More Than One Race	0	0	0	0
Unknown or Not Reported	0	0	0	0
Racial Categories: Total of All Subjects*	6	20	0	26 *
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	Females	Males	Unknown or Not Reported	Total
American Indian or Alaska Native	0	0	0	0
Asian	0	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	0	0	0	0
White	0	0	0	0
More Than One Race	0	0	0	0
Unknown or Not Reported	0	0	0	0
Racial Categories: Total of Hispanics or Latinos**	0	0	0	0 **

Inclusion of Children

The studies conducted under this grant involved children (i.e., those 18-21 years of age). Many workers are children by this standard, and are exposed to conditions of interest here. Specifically where there is a risk of falls and where muscular fatigue may influence this risk. Hence, the results of the research described here have relevance for conditions affecting children.

Materials Available for Other Investigators

All experimental data are available. Software (MatLab code) is available for the biomechanical models. These may be accessed by contacting the PI, whose information is provided below. Note that the investigators wish to limit such access to individuals requesting data or software for research purposes only.

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5. ADMINISTRATIVE CORE

Abstract

The Center for Innovation in Construction Safety and Health Research was formed in 2004 as a result of funding from the National Institute for Occupational Safety and Health (NIOSH)/Centers for Disease Control and Prevention (CDC). It was decided to house the unit within Virginia Tech's emerging Institute for Critical Technology and Applied Science (ICTAS). The Center's initial subprojects included a two-year project entitled, "Training Needs Analysis of Single Entity and Family-Owned Small Construction Businesses" (Smith-Jackson and Kleiner); a three-year project focused on "Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry" (Casali); a five-year project, "Noise and Vibration Control of Hammer Drills" (Burdisso, Johnson, and Nieto), and a five-year project, "Decision Support Tool for Ergonomic Construction Design" (Nussbaum, Madigan, and Shewchuk). An administrative core included some support for external industry advisory guidance, thesis and dissertation research, seminars and pilot projects.

Through ICTAS, an organization at the forefront of emerging issues across a variety of industries, the Center was able to generate additional activities, outputs, and outcomes including additional pilot projects, leadership team initiatives, and funding additional graduate students. Upon inception, the Center developed a pilot program (initially called "feasibility projects") with either NIOSH (construction only) or ICTAS funds to augment the four core subprojects. A Center Co-PI and friend, Kevin P. Granata, was killed on April 16, 2007. To honor Dr. Granata for his many accomplishments in innovative occupational safety and health (OSH) research, the Center, with Granata family support, renamed its pilot research program, the "Kevin P. Granata Occupational Safety and Health Pilot Research Program" (GPP). This program provided seed funds to investigators and was instrumental in creating a "Corps" of construction OSH researchers, enabling Virginia Tech to develop multidisciplinary and eventually interdisciplinary capacity to perform construction OSH research and r2p "under one virtual roof", serving a Country and American workers in need of support.

The Center conducted its research both in the field and in laboratories for the prevention of risk, guided by the hierarchy of safety & health controls and by integrating multiple technical disciplines leading to interdisciplinary research. Acknowledging that much of what is learned in construction can be extended to other sectors and vice-versa, the focus was to proactively remove workplace hazards in order to create and maintain safe and healthy environments. In doing so, the Center designed, developed, and provided training and continuing education to decrease the number of injuries, accidents, and fatalities, impacting workers, their families and friends. It was recognized that training is not the first line of defense in the hierarchical approach, but it is an important preventative and reinforcing tool. The Center's innovative training methods were designed to reach workers of different ages, genders, and ethnicities, paralleling the demographics of the actual workforce.

Section 1: Administrative Core

Highlights/Significant Findings

Fourteen faculty members across eight academic departments in the College of Engineering and the College of Architecture and Urban Studies were involved in this activity. This interdisciplinary team of researchers brought about a collaborative approach to the practice-to-research-to-practice (p2r2p) life cycle that has been cultivated over the past five years. The four major sub-projects encompassed an array of critical areas affecting safety and health in construction supportive of NORA strategic goals. As previously described, the initial subprojects included a two-year project entitled, “Training Needs Analysis of Single Entity and Family-Owned Small Construction Businesses” (Smith-Jackson and Kleiner-NORA 7,10,12); a three-year project focused on “Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry” (Casali-NORA 4); a five-year project, “Noise and Vibration Control of Hammer Drills” (Burdisso, Johnson, and Nieto-NORA 4,13), and a five-year project, “Decision Support Tool for Ergonomic Construction Design” (Nussbaum, Madigan, and Shewchuk-NORA 7,13).

Through the GPP research program, 16 project PIs received “seed” funding to jump start a construction safety or health research idea. Funds were allocated with the expectation that the research would lead to a NIOSH R21, R01, or other appropriate proposal within twelve months of the award. Three PIs were successful in receiving additional NIOSH funding to continue their research. Daniel Hindman, Assistant Professor in Wood Sciences, received a R21 followed by a R01 for his work entitled “Preventing Falls from Elevation Caused by Joist Buckling”. Thurmon Lockhart, Associate Professor in Industrial and Systems Engineering, transformed his pilot findings to develop a new proposal entitled “Effects of Localized Muscle Fatigue on Risk of Occupational Slips and Falls” and was awarded with an R01. Deborah Young-Corbett, Assistant Professor in the Myers-Lawson School of Construction, used her pilot findings as a foundation for her recent work entitled “Dust-Control Usage: Strategic Technology Intervention” and was awarded an R01 – a rare achievement for new assistant professors. Several other GPP PIs are in the process of submitting R01, R21, and R03 proposals. Benchmarking and outreach efforts such as seminars and scholarly presentations cultivated relationships and laid the foundation for collaborative work to be recognized with the Royal Melbourne Institute of Technology (RMIT) Australia, Duke University, and Wake Forest School of Medicine.

Translation of Findings

Research conducted through this cooperative agreement was a collective effort to improve the residential construction sector and redesign the workplace to increase safety and health levels by analyzing multiple factors that impact safety at the job site and providing interventions. The findings associated with the four sub-projects and projects funded through the administrative core have been translated into a variety of outcomes and media for improved occupational safety and health in the industry.

Ten thesis and dissertation studies (lab and field based) contributed to the literature, confirming and exploring knowledge about residential construction. Recommendations and specific findings were offered to companies/construction firms participating in the studies,

presented at various conferences, and included in journal publications. Nearly 30 conference presentations were delivered, based on findings from the research both from sub-projects and those stemming from the administrative core. Similarly, about 25 articles were accepted for publication in journals such as Industrial Health, International Journal of Industrial Ergonomics, and Journal of Construction Engineering and Management.

The Repository for Occupational Construction Knowledge (ROCK) Database (<http://www.csc.eng.vt.edu/rock/index.php>), a first generation, comprehensive English/Spanish web tool developed by the Center contains construction regulatory and non-regulatory information, best practices, and other resources for researchers and companies. Through benchmarking, organizations can improve their performance on a number of dimensions. Further site development is underway which includes populating it with statistics, best practices and guidelines from current and past studies.

Outcomes/Relevance/Impact

The overarching purpose of the awarded projects is to integrate an interdisciplinary focus in research that will produce systems capable of enhancing productivity, quality, and efficiency for the construction industry. The Center's Advisory Board contacts played an intricate role in evaluating the merit and quality of pilot projects. Each year, an update was given from pilot and major project investigators and an assessment of each project was conducted by the Board. Quantitative evaluations and comments were provided to investigators to further guide their research efforts. Board members also advised sub-project investigators by providing value-added input from an Industry perspective. This feedback was used to direct research and dissemination efforts and also aided in the development of additional research topics and proposals.

All GPP pilot projects funded with NIOSH and/or ICTAS funds supported NORA goals. Several of these projects received additional R01/R21 funding. Center leaders also served on NORA Goal Working Groups. Its unique position within ICTAS, as well as its affiliation with the Myers-Lawson School of Construction, provided a research environment driven by emerging issues in addition to industry knowledge and core values that promoted professional practice. As examples of highly relevant (gratis) non-NIOSH activities, especially related to emerging issues, the Center was involved in nationally publicized fast-track construction and was involved with the Department of Energy's Solar Decathlon construction project. In both cases, the Center designed and managed an innovative safety system. This led to several trade publications and press, as well as a tier 1 research publication (Construction Engineering and Management). Along with the Center's standing as a neutral, objective entity, these successful partnerships and activities created an organizational culture characterized by multidisciplinary teamwork, research rigor, integration, diversity, and pragmatic r2p.

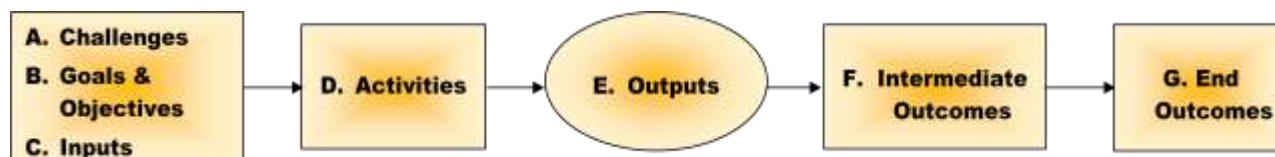
By providing national service on NORA committees, Institute of Medicine evaluation committees, and as symposia organizers, the Center strategically created intermediate outcomes. With a desire to directly impact end outcomes as well, and at a minimum, to demonstrate (a core mission of NIOSH) how research can lead to impacts on practice. the Center has leveraged many positive opportunities to directly impact the residential construction industry. For example, to augment its NIOSH supported objectives, the Center led a National Science Foundation funded Discoveries and Breakthroughs inside Science (DBIS) professional

media production of a construction safety and health awareness video that was distributed to public television stations across the Country.

Through these works and others, Center researchers have tested, developed, applied, and demonstrated worker-centered innovative technologies and other preventive solutions that improved the overall OSH of construction workers and maintained safe and healthy environments in the United States. Moreover, these technologies and recommendable solutions have implications in various other sectors where similar problems are realized.

Section 2: Administrative Core

(Logic Model-based) Scientific Report



A. Major Occupational Health and Safety Challenges

The construction industry is one of the largest industries in the United States, employing around 7,277 workers (Bureau of Labor Statistics [BLS], 2006). The BLS (2006) showed that in the private construction industry in 2005 there were 1186 fatal injuries that were work related. The BLS (2006) also concluded that the private construction industry had the highest rate of fatalities among other private industries (e.g. transportation and warehousing, agriculture, manufacturing, mining). The NIOSH focus for the reported period was the residential sector, where most accidents, injuries, and fatalities are evidenced. Reported herein, NIOSH funded four core subprojects and an administrative core. The subprojects included: a two-year project entitled “Training Needs Analysis of Single Entity and Family- Owned Small Construction Businesses” (Smith-Jackson and Kleiner); a three-year project focused on “Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry” (Casali); a five-year project, “Noise and Vibration Control of Hammer Drills” (Burdisso, Johnson, and Nieto), and a five-year project, “Decision Support Tool for Ergonomic Construction Design” (Nussbaum, Madigan, and Shewchuk). In addition to his core administrative and leadership functions, the director led a work organization research effort. A pilot program, renamed the “Kevin P. Granata Occupational Safety and Health Pilot Program” after the April 16th workplace tragedy, was also part of the administrative core of the Center.

B. Driving Goals and Objectives

The long term objective of the Center was to lead large-scale work-related accident, injury and fatality reduction in small enterprises in the United States. Specific aims were:

1. To be an energetic, productive, accessible, collaborative, cohesive team of researchers who would develop strategic partnerships with a diverse array of construction industry stakeholders;
2. To conduct exploratory, prevention/intervention and translation projects that will be innovative, integrated and multidisciplinary, characterized by a valid and unifying underlying theoretical framework;
3. To actively partner with NIOSH/CDC and its intramural and extramural research programs to achieve injury and fatality reduction in the United States; and
4. To be benchmarked for best practices associated with exploratory, prevention/intervention and translation projects.

In doing so, we hoped to increase understanding of construction sector attributes and contributing factors for improving occupational safety and health outcomes.

As the five-year period unfolded, the Center became more involved in NORA and NORA goals became more solidified, providing additional strategic direction for research and r2p activities.

External Advisory Board Members. The Center is advised by an external advisory board. This board meets physically at least once per year for an intensive formative evaluation process related to Center and project performance.

Susan Asmus

Vice President Advocacy
National Association of Home Builders

Tom Bailey

President
AMI Safety Inc.

Dr. P. Gunnar Brolinson, D.O.

Medical Director – Hokies Football
Virginia College of Osteopathic Medicine – Virginia Tech

Paul Carter

President
Kiewit Southern Co.

Grover Edwards

President
Lake Gaston Construction

Dr. Paul Fleming, Ph.D.

Director of Facilities and New Construction
Corporate Research Center – Virginia Tech

Pedro Herrera

Owner
P&S Enterprise

Charles W. Johnson

Director of Safety
BE& K Building Group

Kenneth Lanford

President
Lanford Brothers Co.

Mark Smith

Vice President Safety and Claims
American Infrastructure

Mike Walker

Vice President of Product Development in Northeast & Southeast Regions
Pulte Homes

Internal Stakeholder Committee Members. Per University policy, a stakeholders' committee provides internal oversight of the center. Membership is determined by the reporting relationships of Center leaders. For the period of this reported activity and through the present, the Chair of the Committee was Dr. G. Donald Taylor.

Department Head, Grado Department of Industrial and Systems Engineering

Additional seats on the committee included unit heads, or their designees, of the following units:

- The Institute for Critical Technology and Applied Science (ICTAS)
- School of Construction
- College of Engineering
- College of Architecture and Urban Studies
- Department of Industrial and Systems Engineering
- Department of Mechanical Engineering
- Department of Civil and Environmental Engineering
- Department of Building Construction
- Department of Mining and Minerals Engineering
- Department of Engineering Science and Mechanics

C. Inputs (funded activities)

The following represents the funded inputs for the activities reported herein.

Type	Title	Inputs	NORA Goal(s)
R, R21	Training Needs Analysis for Small Construction Work Systems	• Small construction firms • Attributes of informal work systems that increase the risk of accidents and reduce the likelihood of training or knowledge transfer	10,11,12
R01	Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry	• Hearing protection devices • Construction work-site access	3,4
R01	Noise and Vibration Control of Hammer Drills	• Pneumatic percussive power tools • Noise characterizations of pneumatic hand-held tools	4
R01	Decision Support Tool for Ergonomic Construction Design	• Designers, panel manufacturers and construction workers • Ergonomic analysis of construction tasks using prefabricated panels	7,13

D	Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers	• Partial NIOSH support with funds from Training Needs Analysis Project • Social exchange theory framework	10,11,12
D	A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction	• Partial support from Center Pilot Project Funds • Sociotechnical system framework	10,12
T	Design of a Construction Safety Training System Using Contextual Design Methodology	• Partial NIOSH support with funds from Training Needs Analysis Project • Information stemmed from the Training Needs Analysis Project • Small firm construction workers and managers	10,11
T	Influence of Acculturation and Individual Differences on Risk Judgments of Construction Laborers	• Partial support from Center Admin Funds and NIOSH Teaching Fellowship • People-Based Safety™	10,11,12
T	Vibration Characterization and Numerical Modeling of a Pneumatic Impact Hammer	• Partial support from Noise Vibration Project • Pneumatic impact hammer tools	7
T	Acoustic Characterization and Preliminary Noise Control of Pneumatic Percussion Tools	• Partial support from Noise Vibration Project • Pneumatic percussive power tools	4
T	Determination of a Backup Alarm Masked Threshold in Construction Noise	• Partial support from Speech Communication and Signal Detection Project • Hearing protection devices	3,4

D. Activities (research studies, technology transfer activities)

The following table represents the activities covered by this final report.

Type	Title	Author	PI/Advisor	Activity	Location	Nora Goals
R, R21	Training Needs Analysis for Small Construction Work Systems	Smith-Jackson, T.L	Smith-Jackson, T.L	- Analytical assessment of the small construction industry - MEAD analysis	NIOSH Closeout Report for Tonya L. Smith-Jackson <i>Also included in Appendix C</i>	10,11,12
R, R01	Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry	Casali, J.G.	Casali, J.G.	- Task analysis of auditory safety signals - Comprehensive noise sampling of noise emissions - Field investigation of backup alarm localization - Laboratory-based acoustical manikin tests	NIOSH Closeout Report for John G. Casali <i>Also included in Appendix C</i>	3,4
R, R01	Noise and Vibration Control of Hammer Drills	Burdisso, R.A.	Burdisso, R.A.	- Preliminary study of potential vibration control approaches - An in-depth tool characterization from the structural, acoustic, and fluid point of views	NIOSH Closeout Report for Ricardo A. Burdisso <i>Also included in Appendix C</i>	4
R, R01	Decision Support Tool for Ergonomic Construction Design	Nussbaum, M.A.	Nussbaum, M.A.	- Task analysis through field observations of home building sites - Laboratory-based task Simulation - Exposure and ergonomic risk	NIOSH Closeout Report for Maury A. Nussbaum	7,13

				assessment • Computer simulation and animation of panelized construction process	<i>Also included in Appendix C</i>	
D	Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers	Artis, S.	Kleiner, B. M., Smith-Jackson, T.L.	• Study of the Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers • Needs Analysis and Content Analysis	ETD	10,11,12
D	A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction	Thongsamak, S.	Kleiner, B.M.	• Risk-taking behavior analysis • Motivation theory analysis for the use of “rewards” and “penalties”	ETD	10,12
T	Design of a Construction Safety Training System Using Contextual Design Methodology	Baldev, D.	Smith-Jackson, T.L., Winchester, W.W.	• MEAD Analysis	ETD	10,11
T	Vibration Characterization and Numerical Modeling of a Pneumatic Impact Hammer	Kadam, R.	Johnson, M.E., Burdisso, R.A.	• Hand transmitted vibration characterization of impact hammers • Validity experiments on hand-arm test rig	ETD	4
T	Determination of a Backup Alarm Masked Threshold in Construction Noise	Muchenje, L.	Casali, .J.G.	• Analysis and evaluation of hearing protection devices	ETD	3,4
T	Acoustic Characterization and Preliminary Noise Control of Pneumatic Percussion Tools	Schwartz, K.	Burdisso, R.A.	• Mechanical analysis of tool • Fluid measurements of the tool • Noise measurements of tool (loaded and unloaded)	ETD	7

T	Influence of Acculturation and Individual Differences on Risk Judgments of Construction Laborers	Thomas, C.	Smith-Jackson, T.L	• Risk factor assessment • Focus groups – video safety training	ETD	10,11,12
UGR	Safety Training Officers for “Lumenhaus” Solar Decathlon Project	Vonder-Reith, K. and John, I.	Brian Kleiner	• In conjunction with the Environmental, Health and Safety Services (EHSS) Office at Virginia Tech students worked to provide safety support and training to solar decathlon team. • Receive OSHA 30hr training • Maintained and monitored safety during construction/demolition of the solar home	--	--
M	Advisory Board Meetings	--	--	• Held once a year for strategic planning purposes • Formal presentations by pilot project investigators on project progress/results • Assessment of projects conducted by the Board for innovation within the field, relevance of topic/area, and potential impact on industry	--	--
M	1 st International Symposium in Construction Safety and Health at the 21 st Annual International Society of Occupational Ergonomics and Safety (ISOES) Conference	--	--	• 10 presentations on construction OSH research topics	--	1,9,11, 12

E. Outputs (recommendations, reports, workshops, databases, training and education materials, demonstration programs, trained professionals, tools and methods, best practices, licenses, patents). The outputs include the production of OSH professionals (*italicized*) as well as informational outputs. Publications are listed separately.

Type	Title	Author	PI/Advisor	Outputs	Location	NORA Goals
R, R21	Training Needs Analysis for Small Construction Work Systems	Smith-Jackson, T.L	Smith-Jackson, T.L	Recommendations and design requirements to support the adoption and use of safety training within small construction firms	NIOSH Closeout Report for Tonya L. Smith-Jackson <i>Also included in Appendix C</i>	10,11,12
R, R01	Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry	Casali, J.G.	Casali, J.G.	- Guidelines for establishing safe working envelopes to help accommodate the hearing needs of construction workers - Recommendations and guidelines for backup alarm standards	NIOSH Closeout Report for John G. Casali <i>Also included in Appendix C</i>	3,4
R, R01	Noise and Vibration Control of Hammer Drills	Burdisso, R.A.	Burdisso, R.A.	- Development of a numerical model of the chipping tool - Developed a model to measure the impact vibration absorbed	NIOSH Closeout Report for Ricardo A. Burdisso <i>Also included in Appendix C</i>	4
R, R01	Decision Support Tool for Ergonomic Construction Design	Nussbaum, M.A.	Nussbaum, M.A.	- Identified several gaps in the area of ergonomic risk assessment - Identified hazards related to panelized wall systems	NIOSH Closeout Report for Maury A. Nussbaum	7,13

				• Provided recommendations to improve the construction work environment	<i>Also included in Appendix C</i>	
D	Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers	Artis, S.	Kleiner, B. M., Smith-Jackson, T.L.	• <i>OSH professional</i> • Guidelines to improve workers' perceptions of organizational support and safety climate • Guidelines to involve Latino workers in construction research • Development of a safety training program	ETD	10,11,12
D	A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction	Thongsamak, S.	Kleiner, B.M.	• <i>OSH professional</i> • Risk – taking behavior assessment between different cultures (American, Asian, Latin-American)	ETD	10,12
T	Design of a Construction Safety Training System Using Contextual Design Methodology	Baldev, D.	Smith-Jackson, T.L., Winchester, W.W.	• <i>OSH professional</i> • Recommendations for safety in small construction companies • Recommendations on future use of Contextual Design for developing training systems • Design of a Construction Safety Training System using Contextual Design Methodology	ETD	10,11

T	Vibration Characterization and Numerical Modeling of a Pneumatic Impact Hammer	Kadam, R.	Johnson M.E. / Burdiso, R.A.	• <i>OSH professional</i> • Developed a mechanical experimental rig to simulate the average dynamics of the hand-arm system while operating the hammer drill	ETD	7
T	Acoustic Characterization and Preliminary Noise Control of Pneumatic Percussion Tools	Schwartz, K	Burdisso, R.A.	• <i>OSH professional</i> • Proposed methodology for determining the acoustic noise sources of pneumatic tools	ETD	4
T	Influence of Acculturation and Individual Differences on Risk Judgments of Construction Laborers	Thomas, C.	Smith-Jackson, T.L	• <i>OSH professional</i> • Recommendations for the identification & assessment phase of total safety management implementation • Recommendations to assist in developing training programs that address risk factors	ETD:	10,11,12

Sample Outputs from Graduate Research Studies affiliated with the Administrative Core

The Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers (in support of NORA Training (11.0) and Disparities (12.0) Goals) <http://scholar.lib.vt.edu/theses/available/etd-08172007-142231/>

Workplace safety, if not managed appropriately, can result in human and economic tolls. The need to establish and maintain a safe working environment has probably never been more important. Despite a mounting emphasis on safe work practices, the Bureau of Labor Statistics (BLS) reported a total of 5,702 fatalities in the United States in 2005. Among these fatalities, Latino workers, defined as both foreign-born and native-born (U.S.-born) workers of Latino ethnicity (BLS, 2006; Dong and Platner, 2004), accounted for 16% of those fatalities (BLS, 2006).

Researchers are increasingly acknowledging that organizational factors are important in workplace safety (Hofmann, Jacobs, and Landy, 1995; Hurst, Bellamy, Geyer, and Ashley, 1991). However, there is a lack of cross-cultural comparison in this area. With the continuing increase in Latino construction workers and the level of injuries and fatalities, little attention has focused on the comparison of employment relationships between Latino and non-Latino construction workers and their supervisors and work environment. Therefore, this research endeavor used social exchange theory to examine the role of organizational factors in small construction firms to help explain why Latino workers have a disproportionate number of construction casualties compared to their non-Latino counterparts and to design a safety training program to help reduce the number of injuries, accidents, and fatalities in the workplace.

The results of this research endeavor demonstrated that both Latino and non-Latino and Latino groups had relatively equal perceptions of organizational support and distributive justice implying that Latinos and Latinos have identical support needs or that the construction firms' practices meet the support the workers need regardless of ethnicity. In addition, the study found ethnic group differences for safety climate, safety behavior, and cultural dimensions, which may contribute to the disproportionate number of fatalities for Latino workers.

After uncovering group differences, this study tested the affect of training on perceived organizational support, distributive justice, safety climate, and safety behavior. This research demonstrated that providing training, of any type, as a source of perceived organizational support increases workers' perception of organizational support. Additionally, the study concluded that embedded sources of perceived organizational support in the training program increase workers' perceptions of distributive justice and safety climate. As a result, guidelines to improve workers' perception of organizational support and safety climate were created. Since high perceptions of safety climate are linked to less risky safety behaviors, embedding perceived organizational support into training programs can have an indirect affect on the workers' safety behavior. For that reason, improving the safety behavior of workers and the workers' perception of a safe work environment can lead to reduced accidents, injuries, and fatalities in the construction industry.

A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction (in support of NORA Work Organization (10.0) and Disparities (12.0) Goals) <http://scholar.lib.vt.edu/theses/available/etd-10312007-234714/>

The overall research objective was to identify the effects of reward systems (rewards and a penalty) on risk-taking behavior and performance (quality and time) of construction workers from different cultures (American, Asian, and Latin American cultures). This research used the sociotechnical system as the underlying, guiding scientific framework. The research found that Americans and Latin Americans had higher risk-taking behavior than Asians ($p < 0.01$). No difference in risk-taking behavior was found between Americans and Latin Americans ($p < 0.05$). Although culture may influence individuals' risk-taking behavior, the results from this study showed that risk-taking behavior could be altered and suppressed by providing individuals with the proper safety training, education, and safety equipment. Customized safety training for people from different cultures would be useful because the culture elements that contribute to high risk-taking behavior could be addressed. The results also showed that the effects of reward systems on risk-taking behavior were not statistically significant ($p > 0.1$). One possibility that no difference was found may be because the tasks used in this study did not contain enough possibility for participants to take more risk. The effects of reward systems on risk-taking behavior may have been reduced by the low possibility of risky behavior. It is suspected that if the tasks contained more opportunities for participants to take risk, differences in risk-taking behavior would have been significant.

The researcher concluded that risk perception is situation-specific and has an influence on the individual's risk-taking behavior on that particular situation but cannot be used to predict risk-taking behavior. Also, general locus of control and general self-efficacy cannot be used to predict risk-taking behaviors. These findings are consistent with many studies that explore locus of control (Iversen & Rundmo, 2002; Rolison & Scherman 2002; Crisp & Barber, 1995), and many researchers that suggested self-efficacy is situation specific (Murdock et al., 2005; Martin et al., 1995; Perraud, 2000; Slanger & Rudestam, 1997). This study also found no relationship between risk-taking behavior and productivity, for both time and quality.

F. Intermediate Outcomes (policy impact, training/education, implemented guidelines, technology, standards, trade/media releases, websites). The following table highlights intermediate outcomes derived from the activities reported herein.

Type	Title	Author	PI/Advisor	Intermediate Outcomes	Location	NORA Goals
R, R21	Training Needs Analysis for Small Construction Work Systems	Smith-Jackson, T.L	Smith-Jackson, T.L	- Guidelines to encourage the use of informal training practices. - Recommendations for best practices and outreach efforts.	NIOSH Closeout Report for Tonya L. Smith-Jackson	10,11,12
R, R01	Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry	Casali, J.G.	Casali, J.G.	Formula that predicts at what distance normal-hearing workers, wearing a hearing protection device, should be to allow time to remove themselves from the vehicle's path.	NIOSH Closeout Report for John G. Casali	3,4
R, R01	Noise and Vibration Control of Hammer Drills	Burdisso, R.A.	Burdisso, R.A.	- Development of hand-arm test rig - Prototype of impact vibration absorber device	NIOSH Closeout Report for Ricardo A. Burdisso	4
R, R01	Decision Support Tool for Ergonomic Construction Design	Nussbaum, M.A.	Nussbaum, M.A.	- Identified several gaps in the area of ergonomic risk assessment - Developed a decision Support System prototype for residential construction.	NIOSH Closeout Report for Maury A. Nussbaum	7,13
D	Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers	Artis, S.	Kleiner, B.M., Smith-Jackson, T.L.	Spanish and English training modules adapted from BuildIQ®	ETD:	10,11,12

D	A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction	Thongsamak, S.	Kleiner, B.M.	Concluded that risk perception is situation-specific and has an influence on the individual's risk-taking behavior for that particular situation. However, it cannot be used to predict risk-taking behaviors	ETD	10,12
T	Design of a Construction Safety Training System Using Contextual Design Methodology	Baldev, D.	Smith-Jackson, T.L., Winchester, W.W.	Low fidelity paper training system prototype	ETD	10,11
T	Vibration Characterization and Numerical Modeling of a Pneumatic Impact Hammer	Kadam, R.	Johnson M.E. / Burdiso, R.A.	Discovered that the consistency of the hand-arm rig was comparable to that of human experiences. Thus a simple heavy beam with an appropriately high amount of damping can be used to get the dynamic characteristics of hand-arm system experimentally	ETD	7
T	Determination of a Backup Alarm Masked Threshold in Construction Noise	Muchenje, L.	Casali	Determined that from the research, it could not be determined whether one type of hearing protection device was more comfortable and safer than the other.	ETD	3,4
T	Acoustic Characterization and Preliminary Noise Control of Pneumatic Percussion Tools	Schwartz, K	Burdisso, R.A.	Developed a preliminary noise control method employing commercial-off-the-shelf pneumatic silencers	ETD	4

A	Researchers Look Upstream to Mitigate Ergonomic Risk Factors for Residential Carpenters	Jennifer Anderson – <i>Ergonomics Report</i>	Nussbaum, M.A.	• Researchers Look Upstream to Mitigate Ergonomic Risk Factors for Residential Carpenters	Ergoweb	7,13

Sample Intermediate Outcomes from Graduate Research Studies affiliated with the Administrative Core

The Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers (in support of NORA Training (11.0) and Disparities (12.0) Goals) <http://scholar.lib.vt.edu/theses/available/etd-08172007-142231/>

Guidelines to Improve Foreign-Born Workers' Perception of Organizational Support and Safety Climate

1. Describe the importance of safety in the work environment.

Provide migrantforeign workers safety statistics that personally relate to them as an individual. These statistics can relate to the workers occupation, age, ethnic group, etc. Demonstrating the relevance of safety to the individual will potentially help increase the foreign-born workers' self esteem and value. For example, foreign-born Latino immigrants typically have a sense of economic deficiency, and they migrate to the United States to make money. When foreign-born Latino workers, especially undocumented workers, arrive in the United States, they have feelings of low self-esteem (value for oneself), desperation, and a need to survive (Escarcega, 2004). The feelings of low self-esteem develop from the feeling of not having the freedom to live their lives and do what they would like to do and not having a high level of education and being able to read and write. Because migrant foreign workers typically need to make money (Kras, 1995), they are willing to take on more dangerous jobs and take short cuts to finish the job faster so they can get paid sooner. To help reduce the high risks migrantforeign workers take in the workplace, supervisors should explain the importance of safety and address concerns relevant to migrant foreign Latino workers.

2. Be clear and precise about the importance of completing safety training programs.

Explicitly discuss the purpose of the safety training and the desired outcome of the training program as it relates to the individual workers, the group of workers, and the work environment. Often migrant foreign workers have a lower level of education than their non-migrant foreign counterparts. For example, a majority of foreign-born Latino workers likely have an average education no higher than a sixth-grade level (Brunette, 2005). Therefore, many of these workers fundamental reading, writing, and communication skills are limited, and they are probably not accustomed to formal training in their native countries. When foreign-born Latino workers do receive formal training or education, it may take time for them to adjust to this new experience (Escarcega, 2004). As they adjust, questions of trust may develop. Since many foreign-born Latino workers are not used to receiving training, they may question the supervisor, "What is the catch?" or "What do you want from me?" To alleviate this concern of trust, supervisors should ensure that migrantforeign workers understand why safety training is taking place, the importance of safety training, and the results of completing safety training in the workplace.

3. Describe the worker's role to ensure safety in the work environment.

Hold migrantforeign workers accountable for ensuring a safe work environment (individual safety, group safety, task safety). Communicate with the worker his or her responsibility to ensure workplace safety. Safety is not always strictly regulated and monitored in some countries

outside of the United States. For example, many Latin countries do not have a governing body, like OSHA, to regulate safety. Therefore, it may be difficult for foreign-born Latino workers to understand the importance of individual safety. These workers typically work to live (Kras, 1995) and are used to working in unsafe conditions in extreme weather conditions without personal protective equipment or proper training. Many foreign-born workers likely associate accidents as being part of the job. In addition to communicate with the workers their responsibility to ensure workplace safety, supervisors should be aware that foreign-born Latino workers come from a collectivist culture, in which, identity is usually based on family and extended family, where as non-Latino workers typically come from a individualist culture, in which, identity is based on the individual (Hofstede, 1997). Understanding this cultural difference will allow supervisors to emphasize the importance of being safe and how being safe can protect the migrantforeign workers, and co-workers from accidents, injuries, and fatalities in the workplace.

4. Be clear and precise about the desired results of safe behaviors in the work environment.

Explicitly discuss the desired safety behaviors in the workplace. MigrantForeign workers from a collectivist and high power distant country are likely accustomed to being assigned tasks, not authority (Kras, 1995). For example, Latino workers usually show exceptional respect for authority figures and will rarely disagree with individuals in position of authority. As a result, many workers do not know how to communicate their needs and feelings of frustration. Additionally, showing emotions, crying, or sharing personal problems or feelings to anyone can possibly take away self-respect Latino workers have as men (Escarcega, 2004). If problems exist, Latino workers typically will only speak up when approached by the supervisor, whereas non-Latino workers generally will not hesitate to approach supervisors with concerns (Hofstede, 1986). When migrantforeign workers demonstrate desired behaviors in the workplace, supervisors should provide verbal praise and appreciation. However, for undesired behaviors, supervisors should provide positive feedback to correct the unwanted behavior.



Screen shot of Training Program developed and tested. Available from Build IQ.

Instrucciones: Por favor responda a las declaraciones siguientes poniendo una “X” en el cuadro que represente, lo más exactamente posible, la probabilidad de su comportamiento una vez que usted vuelta a su lugar de trabajo. No hay ninguna respuesta “correcta”; sus propias opiniones son las más importantes.

	1 = Fuertemente desacuerdo	2 = Desacuerdo	3 = Ni de acuerdo o desacuerdo	4 = De acuerdo	5 = Fuertemente de acuerdo
1. El proporcionar entrenamiento demuestra que mi supervisor valora mi contribución a la compañía para la cual trabajo.					
2. El entrenamiento considera fuertemente mis metas y valores.					
3. El entrenamiento me dará ayuda cuando tenga una pregunta sobre seguridad en el trabajo.					

New Organizational Support Instruments developed and tested (available in Spanish and English)

Guidelines for conducting field research with Latinos based on this study

1. Have a champion on the research team
2. Build trust and relationships with potential participants
3. Maintain short-term and long-term contact with Latino participants.
4. Know the Spanish language
5. Gain support from authority figures
6. Explain relevance to Latino community
7. Understand the nature of the work environment
8. Research type of compensation
9. Visit construction sites to recruit construction workers
10. Conduct study during lunch or after work
11. Take referrals from current participants
12. Expect the unexpected

Recommendation 1: Have a Champion on the Research Team

If the primary researcher is not bilingual, it is imperative to have a bilingual (Spanish and English) researcher or research champion on the research team. Research champions are in the best position to encourage Latino construction workers to participate in the study. The purpose of the research champion is to build trust in the Latino community and to serve as the voice of the primary researcher. Additionally, the research champion should know all the details of the research study. These details include, but not are limited to, demographics of the participants (e.g., education level, socioeconomic status), the purpose of the study, study benefits to the researcher and participant, who is funding the study, criteria for participants, procedures of the study, what is required of the participants during the study, when the study will take place, instruments used in the study, estimated time for the study, and compensation for the study. For this study, the research champion was a bilingual undergraduate student with previous research experience and exposure to the construction industry.

Recommendation 2: Build Trust and Relationships with Potential Participants

To gain access to the Latino community—or to any ethnic community that is to be the subject of a research study—it is necessary for the researcher to build trust within that community by building relationships with potential participants. Building trust and building relationships are essential to the successful execution of any research project. For the Latino community, building trust in people is an especially important core value (Vásquez and Stalnaker, 2004) that can facilitate greater access to a viable participant cohort. For researchers, this process of building trust should begin at least six months prior to the onset of the study. To help build trust and subsequent relationships in the Latino community, the researcher and research champion should try to immerse themselves in the Latino community. Although physical immersion into the Latino culture and exposure to daily lifestyle is preferred, there are other opportunities for immersion that require less time and financial resources. These activities include attending Latino interest group meetings, dining at Latino restaurants, shopping at Latino stores, and taking part in Latino cultural events. These strategies will allow the Latino community to become familiar with the researcher and his or her research interests, thereby enabling the researcher to

build a network of Latino individuals and meet key Latino advocates in the community. Becoming known in the Latino community and networking with Latino individuals prior to conducting research helps provide easier access to potential participants.

Recommendation 3: Maintain Short-term and Long-term Contacts with Latino Participants

When building relationships with the Latino community, it is important to maintain short-term (e.g., 1-3 months) and long-term (6-12 months) contact with participants. Short-term contact is necessary once participants have agreed to participate in the study. For example, a month or more before the study is to be conducted, it is important to call or visit the participants occasionally (every two weeks) to say, *hola* (hello), remind them about their commitment to the study, and ask them if they know other participants that may be interested in participating in the study. Furthermore, contact with the participants one to two days prior to the study is required to remind them about the study and to clarify the logistics of the study. In the case of construction work, unpredictable weather and deadlines can alter daily activities. Therefore, calling five to eight hours prior to conducting the study is essential to ensure participants will be available at the appointed time and place. Long-term contact is also essential when a study requires the manipulation of data longitudinally. For example, some research studies require multiple data collection sessions at various intervals; therefore, maintaining long-term contact is critical for retaining participants for the existing or future studies. Besides, continued contact with participants over a period of time will assist with future studies in which other Latino participants are needed. Keeping in touch with participants demonstrates a genuine interest in the participants, making them more willing to assist the researcher in finding potential participants for future studies. Ways to maintain long-term contact with Latino participants include calling the participants occasionally after completing the study, visiting the participants' worksite, sending cards on appropriate holidays, and remaining active in the Latino community.

Recommendation 4: Know the Spanish Language

Although the research team may consist of a Spanish speaking individual, it is critical for all team members to have some familiarity with the Spanish language. It is not necessary to be fluent in Spanish, but it is essential to know key phrases (e.g., hello, good-bye, my name is, I am from, how are you, thank you, you are welcome, I speak very little Spanish), and be willing to try to converse in at least a minimal way in Spanish with Latino participants. Latino individuals are generally pleased to know that non-Spanish speaking individuals want to communicate in Spanish, even if the non-Spanish speaking researchers may not say phrases in Spanish properly. Trying to communicate in Spanish or knowing common phrases in Spanish demonstrates the researcher's willingness to learn Spanish and communicate in Spanish. In turn, the Latino individuals are likely to be more receptive to working with the researchers. For this study, the researcher took Spanish courses for five years so she was able to initiate some type of communication with the participants. However, if the researcher does not have any experience with the Spanish language, the researcher should consider taking a Spanish course or using a self-help book or audio tape to learn Spanish.

Recommendation 5: Gain Support from Authority Figures

When dealing with the construction industry, whether it is residential or commercial, it is important to gain the support of the person in charge of the construction project (superintendent, project manager, and/or general contractor). To gain support, the researcher should come prepared to share the important details of the study with the appropriate authority figure. These details include the purpose of the study, estimated length of time, number of participants needed, when the study will take place (including time of day), what is required of the participants, and the type of compensation the participants will receive. Time is essential in this industry so the researcher should try to explain everything succinctly in just 5-10 minutes. After gaining support from an authority figure, the researcher should use this figure of authority to inform the sub-contractors and workers on his or her site about the research study. If potential participants are encouraged by their supervisor or an authority figure to participate in the study, it is easier to recruit dependable participants. To gain support and to recruit participants for this study, the researcher and the research champion should visit different construction sites and make contact with the general contractors of construction projects and supervisors of crews.

Recommendation 6: Explain Relevance to Latino Community

A key factor in recruiting Latino participants is to inform the potential participants about the importance of the research and how the research could benefit him or her as a Latino construction worker, and thus the larger Latino community. As long as Latino construction workers are valued, treated with respect, and can understand how they are contributing to the research topic, they are likely to be a loyal resource to assist with the research study. Most of the time, they enjoy taking part in research studies because they feel they are being accepted in the U.S. and that non-Latino individuals care about their well-being. This type of treatment is, unfortunately, atypical for Latino construction workers because of the discrimination and disrespect they often face in the U.S. (Vásquez and Stalnaker, 2004). To explain why the research is relevant to the Latino community, the researcher and research champion always presented the statistics of fatalities in construction to demonstrate the importance of this research before discussing participation in the study. After discussing the statistics and why the research is focused on Latino construction workers, it was not difficult to convey the importance of this study to the Latino community.

Recommendation 7: Understand the Nature of the Work Environment

When it comes to conducting research in the construction environment, it can be very frustrating because of the relative lack of formality in construction. For example, start/finish and break times can be highly variable from job site-to-job site. To be successful in conducting research in the construction field, the researcher should be flexible and understand that a variety of unanticipated circumstances can postpone or even derail data collection. These circumstances include schedule changes, weather, fatigue, and high employee turnover. It is not unusual for a construction project to fall behind schedule, making it difficult for a worker to find time to contribute to the study. Conversely, if a project finishes ahead of schedule, the worker may leave early and be unavailable at the appointed time. Under certain weather conditions, construction workers may not come to work at all or may leave work early. Moreover, since construction is a manual labor-intensive field, at the end of the workday a participant may be

physically exhausted to contribute to the study, requiring the researcher to postpone and reschedule. To understand the nature of the work environment, prior to the study, researchers should interview and/or shadow construction workers and supervisors to learn more about the demands and structure of the area of construction he or she is researching.

Recommendation 8: Research Type of Compensation

It is usual for participants to receive some type of compensation for taking part in a research study (Marín and Marín, 1991). In human factors engineering research, participants are normally compensated at a rate of \$7-10 per hour. In this study, Latino construction workers are very hesitant about receiving monetary compensation for participating in a study. A possible explanation for being reluctant to accept payment could be their high level of power distance, in which the Latino workers may have viewed the researcher as an authority figure. If this is the case, the researcher should discuss with the potential participants what they would like in exchange for participating in the study. Suggestions for other forms of compensation include giving English lessons (for free or at a discount), providing them with protective equipment (e.g., safety glasses, hard hat, ear plug or muff), tools (e.g., hammer, nail gun), or clothing items (e.g., t-shirts, hats) that they can use for their job. The researcher could also consider giving the participants gift certificates to a hardware store (e.g., Home Depot, Lowe's, etc.) where they can purchase personal protective equipment or tools of their choosing.

Recommendation 9: Visit Construction Sites to Recruit Construction Workers

There are many avenues to pursue when recruiting construction workers. For example, a researcher can compile a list of construction companies from the phone book, newspaper, Internet, home builders associations, or current construction sites to call or email to solicit participation in the research study. The researcher can also make unannounced visits to local construction sites, which is often the most successful way of soliciting support. When walking on-site, remember to be safe, obey the signs, and wear personal protective equipment (PPE). Once at the site, find a figure of authority to whom to explain the study. Sometimes the figure of authority may be busy or not on site. If this is the case, the researcher has three options: (1) the researcher can return at a later time to talk to the authoritative figure, (2) the researcher can discuss the study with the construction workers present, or (3) the researcher can do both. If time permits, discussing the study with the workers present and returning to the construction site at a later time to meet with the authority figure is often the best option. Also, if the researcher is already collecting data when he or she visits a new construction site, he or she should be prepared to conduct the study then and there, since the workers may be willing and available to participate in the study on the spot.

Recommendation 10: Conduct the Study during Lunch or After Work

If the study involves more than visual observation, the best time to conduct the study is during the lunch hour. If possible, the researcher should provide lunch for the participants. Prior to providing lunch, the researcher would want to know what is the most common type of food Latino workers consume. Providing lunch is a nice gesture to show appreciation, and a free lunch can also be used as an incentive to get more participants for the study. Alternatively, if a study cannot be conducted during the lunch hour, the next best time to conduct the study is

immediately after work. If conducting the study after work, it is important to note that most Latino construction workers carpool to their jobsite. Therefore, a group of Latino construction workers will likely be taking part in an “after-hours” study. Estimate double time for the data collection—it typically takes the Latino participants longer to complete the study.

Recommendation 11: Take Referrals from Current Participants.

Referrals are an excellent recruitment tool. After successfully finding participants for the research, always ask the participants if they know other construction workers who may be interested in participating in the study. Most construction workers know other construction workers on other job sites. If they had a good experience during the study, they are more likely to be willing to tell other construction workers about the study. However, if the protocol calls for random selection, referrals cannot be made. As an alternative to taking referrals, the researcher can ask the participant to post flyers advertising the study in common areas Latino construction workers convene.

Recommendation 12: Expect the Unexpected

Always expect the unexpected. When conducting studies with Latino construction workers, a researcher is likely to experience no-shows, or perhaps even more people than originally scheduled for the study. Moreover, a researcher will experience rejection. No matter how persuasive the researcher and/or research champion is, or how important the study is likely to be to the Latino community, there will be individuals who will want no part of the study. The researcher should not become discouraged, but accept the fact that research in the field of construction is likely to be unpredictable.

A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction (in support of NORA Work Organization (10.0) and Disparities (12.0) Goals) <http://scholar.lib.vt.edu/theses/available/etd-10312007-234714/>

There were two major challenges conducting cross-cultural risk research. First, inducing risk in the research was limited by many factors. The researcher wanted to conduct an experiment that contained similar risks to the real world, but it was unethical to knowingly put participants in harms way. It was also the duty of the research, as a human being, to warn the participants of any danger that they may cause to themselves. Therefore, recreating risks similar to those found in the real world was difficult. The study in this field may have to be mainly carried out by (a) using video recorders to record actual behaviors at construction sites (b) using surveys to retrieve information, and (c) investigating/interviewing construction workers to identify the phenomena of safe and unsafe behaviors. Another major challenge was the difficulty of recruiting participants from the targeted countries. This type of research is mostly limited by the budget. Researchers would opt out of conducting a cross-cultural study and turn more into domestic study. This research showed that the cross-cultural research could be done, however more effort is needed from the researcher to identify and recruit qualified participants. For future studies, a great option would be to collaborate with studies between different research centers around the world so that data could be collected from each country. With these lessons learned and limitations in mind, the following outcomes were achieved:

Limited statistics retrieved from dILO (2006) indicate that the fatality rates in the construction industry in countries in Asia and Latin America are mostly higher than in the U.S. The cILO (2006) also reported that injury rates in developing countries are increasing, while the rates are decreasing in developed countries. In the U.S., the Bureau of Labor Statistics (Richardson, 2005) also raises concerns that the fatality rate of foreign-born Latin American workers in 2004 was higher than the fatality rate of all workers combined. With these statistics and reports, this study was initiated to investigate whether workers from the U.S., Asia, and Latin America have the same level of risk-taking behavior. It was suspected that Latin Americans would have the highest risk-taking behavior, followed by Asians, and Americans. Reward systems were identified as triggers that could make the differences in risk-taking behavior even more pronounced. The research found that Americans and Latin Americans had higher risk-taking behavior than Asians. No difference in risk-taking behavior was found between Americans and Latin Americans.

There are several explanations that could contribute to the differences between the results of this study and what had been reported. First, eILO (2005) reported that injury rates in industrialized countries are decreasing while the rates are increasing in developing countries. Most of Asian and Latin American countries are developing countries. Laws, rules, and regulations on safety are likely not as advanced and well-developed as in the U.S. Governments must put safety in the workplace as one of their top priorities. Tougher laws, rules, regulations and enforcement from governments will help reduce injuries and fatalities (Teo et al., 2005). Second, safety training and personal protective equipment (safety glasses/goggles, gloves, and earplugs) were provided to participants during the experiment. The researcher believes that the safety training and personal protective equipment provided during the experiment reduced and suppressed the risk-taking behavior of all participants who otherwise would have shown higher risk-taking behavior. Safety training and the equipment were the means for changes in the participant's behavior. Many participants indicated that the reasons for not wearing safety glasses were because they were not comfortable, or they got foggy and wet during experiment. Many also did not wear gloves because they thought the gloves were too bulky and were not as comfortable as working with their bare hands. Better safety equipment would increase the likelihood that workers would wear personal protective equipment when performing the tasks. Equipment manufacturers should incorporate these elements when designing and developing better personal protective equipment, to provide people with better equipment that eliminates all of these flaws.

Lastly, cultures may contribute to these differences. Higher PDI was observed for Asian participants compared to their counterparts. Also note that the researcher was an Asian, and therefore PDI might even be more pronounced with Asian participants. The researcher concluded that individuals from high PDI culture tended to have less risktaking behavior in construction. On the other hand, low MAS was observed in Asian participants when compared to Americans and Latin Americans. The researcher concluded that individuals from low MAS culture tend to have lower risk-taking behavior in construction. Even though culture may influence individuals' risk-taking behavior, the results from this study showed that an individual's risk-taking behavior could be altered and suppressed by providing them with the proper safety training and safety equipment.

Many researchers also have suggested that effective safety training would help reduce injuries and fatalities (Teo et al, 2005). Customized safety training for people from different cultures would be useful because the culture elements that contribute to high risk-taking behavior could be addressed. The U.S. Bureau of Labor Statistics (Richardson, 2005) reported that the fatality rate of foreign-born Latin American workers (in the U.S.) was much higher than the rate of all U.S. workers. The results of this study suggested that it was not because of the culture. Americans' and Latin Americans' risk-taking behaviors were not different. It is suspected that other sources may contribute to this difference. Some of the possible sources are (1) safety training may not be provided to a day job worker, (2) safety training may not be provided in Spanish, making it difficult for Latin American workers who do not speak English to understand and follow, (3) difficulty of communication at construction sites may increase the risk level for Latin American workers (ex. Warning signs may only available in English), and (4) Latin American workers may mostly work in the jobs that contain riskier activities in nature than Americans (Greenhouse, 2001; Ortega-Wells, 2006; Tucker, 2007).

The results showed that the effects of reward systems on risk-taking behavior were not statistically significant. When participants were asked to rate how careful they were in terms of their own safety during the experiment, no difference was found between all three reward systems ($p > 0.1$). These results contradicted with reports from a study conducted by Sawacha *et al.* (1999), which indicated that reward systems lead to higher risk-taking behavior. Sawacha *et al.* (1999) reported a strong relationship between productivity bonus pay and unsafe behavior at construction sites. They suggested that bonus pay is an incentive for workers to work faster and therefore engage in unsafe behavior. Their suggestions that people would work faster when an incentive is offered was consistent with the findings in this study that reward systems made participants' feel pressure to rush and work faster. One possible explanation that no difference in risk-taking behavior was found among reward systems is because the tasks used in this study did not contain enough possibility for participants to take more risk. The effects of reward systems on risk-taking behavior may have been reduced by the low possibility of risky behavior. Therefore, differentiation between reward systems was minimized. It is suspected that if the tasks contained more opportunities for participants to take risk, differences in risk-taking behavior would have been significant.

The researcher concluded that risk perception is situation-specific and has some influence on the individual's risk-taking behavior on that particular situation but cannot be used to predict risk-taking behavior. General locus of control and general self-efficacy cannot be used to predict risk-taking behaviors of the individuals. These findings are consistent with many studies that explore locus of control (Iversen & Rundmo, 2002; Rolison & Scherman 2002; Crisp & Barber, 1995), and many researchers that suggested self-efficacy is situation specific (Murdock et al., 2005; Martin et al., 1995; Perraud, 2000; Slanger & Rudestam, 1997). This study also found no relationship between risk-taking behavior and productivity, in terms of both time and quality. Participants with higher risk-taking behavior did not perform any faster than those who had lower risk-taking behavior. No difference was found in the quality of the finished products produced by individuals with different levels of risk-taking behavior.

G. End Outcomes (observed and potential improvements in safety and health in workplaces).

Demonstrating end outcomes was a challenging task for researchers. While not all projects, theses and dissertations had outcomes that exhibited a direct improvement to the overall safety and health in the workplace, they all have contributed to the review of literature available pertaining to construction OSH. At a minimum, recommendations provided can be observed and demonstrated in controlled settings such as laboratories to show such an effect. Their findings, if adopted, and in some cases if furthered explored by future students and/or investigators could potentially have viable outcomes that impact workplace risks and safety. The impact of guidelines and other innovations developed in the field can be tracked longitudinally for adoption of use. Potential outcomes are italicized in the table.

Type	Title	Author	PI/Advisor	End Outcome / Potential Outcome	Location	Nora Goal(s)
R, R21	Training Needs Analysis for Small Construction Work Systems	Smith-Jackson, T.L	Smith-Jackson, T.L	Adoption and use of informal training practices within a small construction company	NIOSH Closeout Report for Tonya L. Smith-Jackson	10,11,12
R, R01	Noise and Vibration Control of Hammer Drills	Burdisso, R.A.	Burdisso, R.A.	<i>Noise and vibration reduction of pneumatic tools with minimal impact to the tool performance. Lab tests showed a 63% percent reduction of the amplitude of impulses produced by the tool.</i>	NIOSH Closeout Report for Ricardo A. Burdisso	4
R, R01	Decision Support Tool for Ergonomic Construction Design	Nussbaum, M.A.	Nussbaum, M.A.	<i>The Decision Support Tool will enable designers to quantitatively establish and evaluate the ergonomic consequences associated with various design alternatives during the design process. As such, long-term success towards reducing the high prevalence of</i>	NIOSH Closeout Report for Maury A. Nussbaum	7,13

				<i>musculoskeletal injuries in residential construction will be realized</i>		
R, R01	Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry	Casali, J.G.	Casali, J.G.	<i>The results yielded statistically-significant, but relatively small in magnitude, improvements in several metrics of localization performance for listeners when using the modified backup alarm (400 to 4000 Hz) as compared to the standard backup alarm (1000 to 4000 Hz).</i> <i>The data outlining the localization performance improvement could also lead to a revised backup alarm Standard for industry, requiring a broader spectrum of tonal content, which could reduce the incidence of construction vehicle runovers of on-ground workers</i>	NIOSH Closeout Report for John G. Casali	3,4
D	Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers	Artis, S.	Kleiner, B.M.; Smith-Jackson, T.L.	Demonstrated improvements from organizational factors in laboratory conditions	ETD	10,11,12
T	Acoustic Characterization and Preliminary Noise Control of Pneumatic Percussion Tools	Schwartz, K	Burdisso, R.A.	<i>Through further research, the reduction of high frequency resonances will greatly reduce the contribution of the high frequency noise to the overall sound power.</i>	ETD	4

Major Subproject Brief Summaries (detailed earlier in this report):

1. Training Needs Analysis for Small Construction Work Systems, PI: Tonya Smith-Jackson

This project focused on conducting a needs analysis and organizational scan of small construction work systems, defined as 20 or fewer employees. This subgroup of the construction industry accounts for almost 80% of the injuries and fatalities occurring in construction. Little is known about the needs and barriers to training experienced by these small informal works systems. Two methods were used to assess needs – the Macroergonomic Analysis and Design method (MEAD) and traditional interviews and questionnaires. Needs and barriers were identified across a number of construction contractors (a total of 72). For many work systems, training was not perceived to be important, was considered to be time consuming and resource demanding, and was influenced by friend and family dynamics that are common to small contractors (yet remain undocumented). Informal training emerged as the most preferred and compatible method and was one of the most frequently used methods.



This study had two aims. The first aim was to conduct an overall needs analysis using the MEAD method, interviews, and focus groups to identify attributes of small construction firms that employ family members and close acquaintances. The second aim was to translate the results into requirements for training in informal construction work systems.

Translation of Findings

Findings were translated into design requirements to support the adoption and use of safety training within small construction firms whose employees consist mainly of family members and close friends. The recommendations provided can be used to develop either informal or formal training systems that are compatible with the limitations and preferences of these workplace environments. For training systems to be effective, they must consider and/or incorporate certain requirements into their designs. These include understanding the following:

1. Family dynamics will impact safety training effectiveness, so 'train the trainer' programs should consider including conflict as a potential contributor to workplace hazards.
2. Training programs must be integrated into the day-to-day work practices so they are situated and informal.
3. Since there are few lines of formal authority in small construction companies, training formats should focus on peer training and informal training.
4. Safety training activities should be short and concrete.
5. Formal training opportunities such as classes or meetings should only be done if they can be incorporated into scheduled breaks such as lunch breaks.
6. Individual training, as opposed to group training, is more compatible with these workplace environments.

7. The use of labels such as 'training' and 'trainer' should be avoided so the power dynamics inherent among family members and close friends does not interfere with implementation or effectiveness of the training.

Since most workers believe family and social ties are important in the workplace, these beliefs should be integrated in training programs as well.

Outcomes/Relevance/Impact

The outcomes of this research described the specific characteristics of small construction firms that consist of family members and close social acquaintances. The outcomes revealed a number of attributes that impacted safety climate and that must be considered when exploring ways to affect the delivery of effective safety training. In addition, the specific barriers and needs relevant to small construction work systems were helpful in understanding how to design safety training and organizational interventions to enhance productivity and safety. This work is relevant to NIOSH initiatives of surveillance, social and economic consequences of work, and work organization.

2. Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry, PI: John G. Casali

The overall project goal was to improve the safety of construction workers.

This goal was supported through the following specific aims

related to the acoustic environments of construction: 1)

determinations of what impediments exist to the hearing of auditory signals (e.g., backup alarms on construction vehicles)

in the construction industry (including a general assessment of

workers' noise exposures, 2) quantification of the magnitude of the problems, 3)

determination/development of appropriate interventions aimed at mitigating or removing the impediments, and 4) evaluation of the interventions to empirically determine their effectiveness.

This project report provided a comprehensive discussion of the research activities conducted toward each specific aim, and recommendations with respect to: 1) warning signal design

(specifically, backup alarms), 2) hearing protection device (HPD) selection, 3) the use of

'augmented hearing protectors' advertised for improving hearing, and 4) guidance for establishing 'safe working envelopes to help accommodate the hearing needs of construction

workers. A systematic human factors methodology was implemented that characterized and

quantified representative construction environments in which the ability to hear auditory signals was important. This was accomplished through the use of task and job-analysis techniques to

characterize all aspects of the communications and listening tasks.

This project assessed the noise exposures of construction workers, and has identified and tested a large number of hearing protection devices that provide adequate protection against NIHL, some of which may provide some enhanced hearing capability in construction noise over conventional passive protectors.



Translation of Findings

Governing Standards bodies should consider the adoption of a revised backup alarm standard that includes additional frequencies, such as 400 Hz and 4000 Hz or thereabouts, to the current backup alarm's primary frequencies of 1250 Hz and 2500 Hz, in that the research herein indicated that significant improvements in right-left and front-rear localization of the backup alarm could be realized with the additional frequencies. Along with these design changes, new Standards are needed to govern the design, manufacture, and placement of alarms on vehicles.

Due to the intense noise exposures measured at various construction sites in this research, coupled with the dirty environment, it was suggested that construction workers be issued premolded earplugs which, while providing moderate-to-high levels of attenuation (depending upon the device and the prevailing hazard risk), afford the listener with backup alarm localization ability on a par, or at least near to that afforded by the unoccluded (open) ear, as evidenced in this research for normal hearers.

Outcomes/Relevance/Impact

In addition to the impacts stated above, this research report provided valuable data with respect to not only the noise endemic to various construction operations, but moreover its impact on the construction workers themselves from both a hearing hazard risk as well as a signal detection/localization standpoint. The noise levels, spectra, and dose for road construction operations add to the existing knowledge base of equipment sound levels and their effect on construction workers. Both the field- and laboratory-based experimentation outlined below provide data that indicate that certain types of HPDs are more appropriate to the construction environment than others, in that some products are better suited to help construction workers to not only protect their hearing, but also avoid potential incidents with respect to reversing vehicle accidents. The data outlining the localization performance improvement that was realized through the use of a modified backup alarm could also lead to a revised backup alarm Standard for industry, requiring a broader spectrum of tonal content, which could reduce the incidence of construction vehicle runovers of on-ground workers.

3. Noise and Vibration Control of Hammer Drills, PI: Ricardo Burdisso

Pneumatic percussive power tools are extensively used in the construction industry. They are one of the noisiest pieces of machinery, generating noise levels well above 110 dBA which are beyond the Permissible Exposure Limit (PEL) of 85 dBA set by National Institute for Occupational Safety and Health (NIOSH). In addition, the vibrations from these hand held power tools lead to hand-arm vibration (HAV) disorders such as pain, numbing, and blanching of the fingers commonly known as white finger. The main objective of this project was, thus, the development of noise and vibration control technologies for pneumatic tools.

A chipping hammer was selected as the tool to demonstrate these technologies. However, the technologies can be translated to other tools. The approach taken was to first perform an in-depth vibration, acoustic, and fluid characterization of the tool. This effort provided



valuable physical insight that was then used to develop noise and vibration control approaches. From the acoustic characterization, it was determined that the dominant noise source was the high pressure exhaust, which was expected. More importantly, the fluid measurements indicated that the exhaust velocity was sonic over a small fraction of the operating cycle of the tool. This suggested that slowing the exhaust velocity and dissipating the energy at the peak exhaust velocities should lead to significant noise reductions. Experiments were performed using a commercially available small silencer that demonstrated a 10 dB overall noise reduction without any noticeable reduction in the tool performance.

The acoustic characterization under simulated operating conditions revealed that significant noise is radiated by the parts being broken by the chipping hammer. In the experiments performed, it was found that only half of the total acoustic energy was from the tool. Thus, noise reduction of the tool will not be sufficient to reduce the exposure to the operator.

The final significant finding was the demonstration of an effective vibration control approach using impact vibration absorbers (IVA). This device is a simple mass sliding inside a cavity. The vibration data clearly indicated that the acceleration spectrum was dominated by strong tones at the fundamental operating frequency (~27Hz) and the harmonics within the 0-500 Hz band. These tones were the results of the impact produced by the tool piston on the chisel and the rest of the tool's body. To reduce the hazard to the operator, it is critical that all of these tones be reduced. The implementation of IVAs for the vibration control of the chipping hammer was undertaken experimentally. A very extensive test matrix to assess the effect of materials, number of IVAs, and designs was investigated. The most important finding was that an array of six IVAs was capable of reducing the amplitude of the impacts by 63% which implies a reduction of the same factor for all the tones in the spectrum. The IVAs are small, inexpensive, and could be easily integrated into the tool design.

Translation of Findings

The research efforts undertaken revealed that relevant noise and vibration reduction of these types of tools can be achieved with practical devices. It is also very likely that a combination of control approaches will need to be implemented. However, reduction of the hazards to the tool operator lies on the implementation of these devices as an integral part of the tool by the manufactures. For successful translation of the technologies, there must be mechanisms to bring together researchers, manufactures, and government agencies together. This effort must be spear headed by the government agencies responsible for the health of the construction workers. It is very unlikely that the industry will implement new control concepts, in particular in the current economical down turn.

Outcomes/Relevance/Impact

Noise measurements were carried out on the chipping hammer to determine the spectral characteristics, overall sound power level, and spatial source strength maps of the tool. To this end, an advanced 63 microphone phased array was used to successfully locate and identify the major sources of noise from this tool, e.g. acoustic pictures. Fluid measurements using hot wire were also performed on the exhaust and Kulite pressure sensors to measure the pressure in the upper and lower tool chambers. The fluid tests found that the velocity of the exhaust was approximately Mach 1.0 or greater. In addition to the laboratory measurements, noise data was

also collected in the field under simulated operation conditions. The main conclusion was that the exhaust was the most dominant noise source at low frequency (≤ 1500 Hz) while tool vibration contributed to the mid to high frequency range. Noise control of the exhaust low frequency was targeted since earmuffs are less effective at low frequency. The approach for attenuation of this source was undertaken employing six commercial-off-the-shelf pneumatic silencers. Noise reduction ranged from 5.1 to 10.1 dB in the 0-1500 Hz frequency range. To assess the effect on the tool performance, the operating frequency of the tool was also monitored and found to be unaffected. Further noise reduction technologies were investigated by using particle impact noise absorbers and porous materials integrated into the conventional mufflers used in these tools. The noise reduction measured were again promising with attenuations ranging from 5 to 10 dB below 1250 Hz. Insignificant reductions were observed above 3150 Hz.

4. Decision Support Tool for Ergonomic Construction Design, PI: Maury Nussbaum

Work-related musculoskeletal disorders (WMSDs) are prevalent among residential construction workers; the team's long-term goal was to reduce these disorders, particularly those related to the handling of panelized walls. Such walls are used increasingly in residential construction, but are large and difficult to handle and result in high exposures to WMSD risk factors. This study addressed the need for improved prevention-through-design (PtD), specifically by providing a software system that can be used by the panel designer or others (e.g., contractor). As such, changes at the design stage in the construction life cycle can positively affect a large number of construction sites and workers. The multidisciplinary approach used included both ergonomics and production issues as fundamental components, and both were improved through use of the system. It thereby addressed the need to support the economic/business case for PtD and increases the likelihood that the system will actually be used. The system also supports the development and assessment of interventions to reduce ergonomic exposures and risks.



The overall design and planning process for panelized residential construction was divided into three closely related problems: panelization, stacking, and construction planning. Panelization consisted of breaking up walls into discrete panels, and incorporated several user-set parameters. Stacking referred to groups of panels that were bundled and delivered to the work site. Construction planning involved determining which panels were being worked on, how, and by which workers. The approach used towards the last problem was to develop one or more construction rules that could be employed in the field to achieve specified goals (e.g., minimize ergonomic risks). Software, including several novel algorithms, was developed to address these three problems; the approach stems from several fundamental principles, many of which were based on concepts derived from lean manufacturing.

A variety of software applications and programs were developed and implemented. Ergonomic risks for a given design were obtained from a combination of task simulations and use of the aforementioned database. A 3D simulation animation of the construction process

was provided to the user. Several construction designers and builders reviewed the prototype system. All indicated a high level of interest and the approach was seen as feasible and as a method to gain both greater efficiency and safety.

Translation of Findings

The results supported several specific recommendations and general guidance to prevent workplace injury in residential construction (and beyond). Similar to the case for “design for safety”, there are inherent barriers to the use of PtD to reduce ergonomic exposure in residential construction. PtD tools (software) must accommodate or address current design practices. The effects of major panel design parameters on physical exposures and risks are quite complex, often with opposing influences on ergonomic and productivity aspects. This emphasized the need, in such complex work situations, for a system that could collectively consider physical demands and productivity and that allowed users to assess the tradeoffs involved. The use of task-based analyses, as conducted in the project, was an efficient and likely effective approach to achieving PtD in complex work situations such as residential construction. Integration of traditional engineering concepts (simulation, lean, dispatching rules, etc.) can be effective in achieving PtD in residential construction. PtD approaches that jointly consider ergonomic and productivity aspects of a design, and can reasonably quantify each, are likely to be well received in the construction industry.

Outcomes/Relevance/Impact

Findings from this work offer several areas of guidance for future investigations and research, both to continue a process to improve panelized wall construction and more generally to achieve PtD in this sector and others. The core of approach – a simulation of complex tasks comprising a job together with task-based ergonomics assessments and heuristics to facilitate decision making – should be considered as an approach for other jobs and/or sectors. Such an approach should be applicable wherever there is (or could be) a central design effort, and has the potential for substantial “downstream” positive effects. This study identified several gaps in the area of ergonomic risk assessment. Specifically, future work is needed to facilitate both interpolation and extrapolation of risks associated with discrete, measured tasks, in order to allow for estimations to be generated for a wider range of tasks (i.e., to obviate the need for extensive data collection). Future work is also needed to provide both conceptual and concrete approaches to: 1) compiling ergonomic assessments either across different types of exposures and body regions, or across multiple workers, and 2) including time-dependent effects of exposures (e.g., related to task sequencing or fatigue). Subsequent investigations should assess the use of such decision support tools: 1) for training and education; 2) to identify safety (in addition to ergonomic) concerns; 3) as a method to specify worker accommodations. Use of simple construction rules, provided to workers and similar to dispatching rules in manufacturing, may be a useful adjunct to traditional intervention approaches.

Pilot Project Summaries

Several pilot projects have been funded with NIOSH and/or ICTAS support. These projects were intended to prove a concept, and/or lead to additional NIOSH R21, R01 or equivalent grant proposals, or determine that further pursuit of an idea would be inappropriate. Calls for pilot

project proposals were issued twice a year. A secure, web-based feasibility proposal submission process was established and implemented. The Center leadership team served as the proposal review committee. In support of professionalism and ethics, members did not review proposals with which they were personally involved. An application was designed initially around key socio-technical factors to support the NIOSH/Center mission and to meet NIOSH programmatic goals. Once NORA goals were solidified, these were RFA drivers. Pilot research was presented annually to the Advisory Board, and the Advisory Board provided written formative evaluations. Sample pilot projects supported by the Center over the past five years are listed in the following table. One to two page summaries are on file at NIOSH (contact Inserra, Steve (CDC/NIOSH/OD) [sai0@cdc.gov]). In addition to the pilot projects, which were funded through the GPP, additional projects received support from the Center core and/or matching funds.

Kevin P. Granata Occupational Safety and Health Pilot Program Projects.

NORA Goal	Title	Principal Investigator(s)	Outputs and Outcomes
1. Falls 11. Training	Training Effects of Slip Perturbation: Towards Development of an Occupational Fall Prevention Program	Lockhart & Bowman	- Training program - VR scenes - Articles
1. Falls	Preventing Falls From Elevation Caused by Joist Buckling	Hindman	- Test rigs - R21 proposal - Articles
12. Disparities	Reducing Jobsite Accidents Involving Hispanic Construction Workers through Participatory Design of Visual Communication Tools	Evia	- Comics, <i>fotonovelas</i> - R21 proposal - Articles
12. Disparities 11. Training	Localizing Online Training for Hispanic Construction Workers	Evia	- Training materials - Computer-based modules
1. Falls 11. Training	Innovative, Interactive Fall Protection	Songer & Fiori	- Training materials - Articles
13. ChPtD	Intersections between Pervasive Computing and Construction Safety	O'Brien, et al.	- PPE Prototypes - Articles
11. Training	Application of Context-Based Design in the Identification and Design of Technology Based Safety Intervention for the Small Builder	Winchester	- Handheld prototype - Articles
11. Training	A Multi-Media Rich Digital Safety Manual	Thabet	- Training materials - Articles

5. Silica	Dust Control Effectiveness	Young-Corbett	- Articles - Design guidelines
7. Musculoskeletal	Modeling Total Body Fatigue Experienced by Construction Workers	Babski-Reeves	Articles
12. Disparities	An Investigation of the Impact of Fatigue in Aging on the Performance Spatially Combined Assembly Tasks Commonly Found in the Construction Industry	Agnew	- Prototype - Baseline data
1. Falls	Recovery Envelopes: A New Tool in the Evaluation of Fall Risk	Ross	Robust numerical toolkit
Emerging Issues	Wearable Computing Innovations for Carbon Monoxide Monitoring	Young-Corbett	- Prototype - R21 proposal - Articles
12. Disparities 11. Training	Developing Effective Safety Training Documentation for Hispanic/Latino Workers	Evia, Brunette	- Safety comics - R21 proposal
1. Falls 11. Training	Promoting Fall Protection in Small Construction Companies	Cline, Davis	- Training course and materials - Articles
14. Surveillance	Analysis of NIOSH Face Reports	Maloney	Climate/culture factors of fatalities

Sample Results from Pilot Studies

Pilot Project / PI	Results/ Progress
- Application of Context-Based Design in the Identification and Design of Technology Based Safety Interventions for the Small Builder: A Pilot Study Woodrow W. Winchester, III, PhD	<u>Aims:</u> To investigate the viability of a context-based design model in the identification and design of technology based safety interventions for the small builder by: - Gaining knowledge of what builders do, what is important, and the structure of the work domain, with an emphasis on understanding the “fit” of safety. - Obtaining a shared and consolidated perspective of garnered insight from the contextual inquiries to identify and inform the design of a technology based safety intervention. - Developing a paper prototype of the identified technology based safety intervention. - Performing a field-based evaluation of the prototype. - Evaluating interventions to provide evidence to support the inference to efficacy of the context-based design model in the subject domain. <u>Outputs:</u> - Prototypes of the technology based safety intervention

	instantiated utilizing the iPOD design. - Baldev, D. (2006). Design of a construction safety training system using contextual design methodology, Virginia Tech. Unpublished M.S. Thesis. - Baldev, D., Winchester, W., Smith-Jackson, T., Kleiner, B. & Hughes, C. (2008) Safety training recommendations for small construction companies using contextual design methodology. In Proceedings of the 2008 Industrial Engineering Research Conference (IERC 2008), Vancouver, BC. - Hung, Y.H. & Winchester, III, W.W. (2008). Using contextual design techniques to identify work tasks problems in dynamic work environments: A field study of isolating safety challenges for small builders. In Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting (HFES 2008), New York, NY. - Mead, P., Winchester, W. & Hung, Y. (2009). Application of contextual design methodology within dynamic work environments. In Proceedings of the 2009 IIE Annual Conference (IREC 2009), Miami, FL. – <u>Outcomes:</u> - A NIOSH R21 proposal (unfunded) - Application of Context-Based Design in the Identification and Design of Technology Based Safety Interventions for the Small Builder
– Lateral-Torsional Buckling of I-Joists Caused by Walking Loads – Daniel P. Hindman, PhD	– <u>Aims:</u> To measure the load that will cause lateral buckling of unsupported I-joists over different lengths and I-joist sizes – <u>Outputs:</u> - Hindman, D.P. 2007. Lateral Buckling. Recent Research on the Testing and Installation of Unbraced I-joists During Construction. Frame Building News, November, pp. 32-37. - Hindman, D. P., P. D. Timko, and C. R. Bamberg. Dynamic Loading of Unbraced and Partially Braced Wood I-joists. Forest Products Society 63rd International Convention. Doubletree Hotel Boise-Riverside, Boise, ID. June 21-23, 2009. – <u>Outcomes:</u> - A NIOSH R21 proposal: Preventing Falls from Elevation Caused By Joist Buckling - Hindman, D.P. R&T: Safety trends affecting the industry. Construction Magnet Magazine Network. November 13, 2008. (http://www.ruralbuilder.com/article/RT_Safety_trends_affecting_the_industry/)
– Reducing Jobsite Accidents Involving	– <u>Aims:</u> Analyze workplace communications in construction and mining sites with the intention of developing visual and textual

Hispanic Construction Workers through Participatory Design of Visual Communication Tools – Carlos Evia, PhD	materials that will help Hispanic workers better communicate with their supervisors. – <u>Outputs:</u> 1. Presentation at the annual conference of the Society for Technical Communication on May 2007. 2. Presentation at the annual conference of the Association of Teachers of Technical Writing on April 2008. – <u>Outcomes:</u> 1. A NIOSH R21 proposal (unfunded). Received a Grant from the Virginia Tech Center for the Study of Rhetoric in Society to fund additional work. 2. Preliminary findings supported the use of comic books (<i>fotonovelas</i>) as forms of technical documentation for Hispanic construction workers. 3. Development and testing of stop-motion videos aimed at Hispanic construction workers. Videos used Little People Construction Worker figures with the permission of Fisher-Price and were found to be more effective than comic books. Videos: • Included a plot with characters to keep the audience interested • Had little or no text • Depicted consequences of bad safety practices • Used elements of humor to break the workplace routine • Portrayed positive images of camaraderie and family relationships
– Localizing Online Training for Hispanic Construction Workers – Carlos Evia, PhD	– <u>Aims:</u> Localize and test the usability of an online course designed for construction workers. The course is adapted for an audience of Hispanic-speaking, low-literacy users. – <u>Outputs:</u> 1. Target documentation and report with recommendations were sent to the client • Preliminary findings supported the development of technical documents for professional audiences defined by language and discourse similarities • The study also supported the use of oral instructions when developing materials for Hispanic construction workers 2. Presentation at the 2008 Conference on College Composition and Communication. – <u>Outcomes:</u> 1. Received a Grant from the Virginia Tech Center for the Study of Rhetoric in Society to fund additional work.
– Training Effects of	– <u>Goal:</u> to assess the effectiveness of slip perturbation training

Slip Perturbation: Towards Development of an Occupational Fall Prevention Program – Thurmon E. Lockhart, PhD	on balance maintenance (i.e., in reducing future slips and falls). – <u>Outputs:</u> 1. Lockhart T.E, Spaulding J., and Park, S. H., (2007), Age-related slip avoidance strategy while walking over a known slippery floor surface. <i>Gait & Posture</i>, 26:1, 142-149. 2. Kim, S., Lockhart, T.E., (2008), The Effects of 10% Front Load Carriage on the Likelihood of Slips and Falls. <i>Industrial Health</i>, 46, 32-39. 3. Kim, S. and Lockhart, T.E., (2008), Effects of 8-Week Exercise Training on the Likelihood of Slips and Falls. <i>Proceedings of the XX Annual ISOES Conference</i>, 80-83, Chicago, IL, USA, June 12-13. – <u>Outcomes:</u> 1. Virtual Reality rig scene 2. Training programs 3. NIOSH R01 Proposal: Effects of Localized Muscle Fatigue on Risk of Occupational Slips & Falls
– A Multi-Media Rich Digital Safety Manual for Conveyor Belts in Mining Applications – Walid Thabet, PhD	– <u>Aims:</u> To develop a interactive multimedia device to used for conveyor safety and maintenance in mining applications – <u>Outputs:</u> 1. Lucas, J., Thabet, W., Worlikar, P. A VR-based training program for conveyor belt safety, (2008). <i>ITcon</i> Vol. 13, pg. 381-407, http://www.itcon.org/cgi-bin/works/Show?2008_25. – <u>Outcomes:</u> 1. Training materials 2. Developed a prototype multimedia device 3. A digital prototype training manual intended to give users a sound knowledge of safety issues and hazard factors related to conveyor belts and its components. The manual was developed for three components (selected based on their criticality): • Return idlers • Bend pulley/take-up pulley • Belt/Belt assembly/platform

External Pilot Study Examples (Full reports are available upon request)

Granata pilot awards were also made to external researchers. These included awards at the University of Kentucky, Boise State University and the University of Massachusetts.

Evaluating Safety Climate Deficiencies that led to Construction Fatalities: An Analysis of NIOSH FACE Reports. B. Mason and Maloney, W. (in support of NORA Safety Culture (8.0) and Surveillance (14.0) Goals) University of Kentucky

The National Institute for Occupational Safety and Health (NIOSH) maintains a database of fatality investigation reports through its Fatality Assessment and Control Evaluation (FACE) program. These reports provide in-depth investigations of targeted fatalities across all industries. This study focuses on the Construction Industry FACE Reports produced by NIOSH In-House as well as each of the NIOSH Cooperative State partners. In all, this encompasses 690 reports each representing one or more fatalities in the construction industry occurring between the years 1982 and 2008. For this study, nine different aspects of safety climate have been identified: management commitment; supervisor competence; time/productivity pressure; hazard control/housekeeping; safety training; safety equipment unavailable; safety equipment not used; organizational communication; and inspection/maintenance. Using these nine categories, each FACE Report has been analyzed to determine the deficient area(s) of safety climate that were present when the investigated fatality occurred.

Results

Once the above categories were selected, the actual analysis process began. This consisted of reading each of the 690 FACE reports while recording the previously specified General Information and then analyzing each of the selected aspects of safety climate to determine whether or not one or more of the aspects were considered deficient for the investigated fatality. As described above, this was an extensive process and required fairly subjective decisions for a few of the aspects. However, the majority of the aspects were included at least somewhat explicitly or objectively in the standard format of the FACE reports. Since the classification system allowed for multiple deficiencies to be present for each investigated fatality, the actual number of reports with a deficiency was normalized by dividing by the total number of reports in the sample size. For instance, when all of the FACE reports were analyzed together, the total number of reports was 690, and this is clearly indicated on each of Figures 1 – 5.

First, the data was plotted in Figure 1, which represents the distribution of safety climate deficiencies in all 690 NIOSH FACE Reports. This actually represents ten different types of accidents as described earlier and shown in the “Type of Accident” column in the General Information pages of Appendix A. It became clear from this analysis that both Management Commitment and Safety Training are the most commonly cited safety climate deficiencies. Since these are probably the most recognizable aspects of safety climate, it makes sense that these would be the areas that need the most work. Since much of the organizational culture research emphasizes a trickle-down effect from management to workers, it is probably also true that improving the management commitment and safety training aspects of a safety climate can have the biggest effect on reducing the number of accidents and fatalities that occur.

Furthermore, it is hypothesized that the Time/Productivity Pressure category does not necessarily represent all of the investigated fatalities that actually experienced some kind of pressure of this sort. This is mainly due to the difficulty of obtaining the appropriate information from the FACE reports. This concept is discussed further in the Recommendations for Future Work section of this report. However, the FACE reports that did actually identify some sort of time pressure do represent actual data and should not be ignored if further analysis into this category is deemed important.

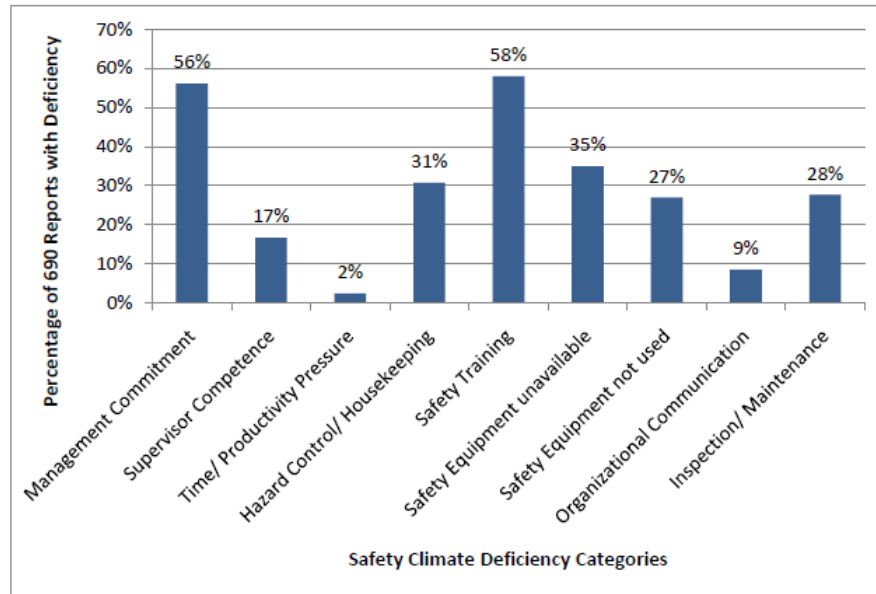


Figure 1 - Distribution of Safety Climate Deficiencies in NIOSH FACE Reports

By normalizing the data based on the number of reports in the particular type of accident, this allowed the data to be compared across different types of accidents. Although there were ten different types of accidents identified in the FACE reports, the Focus Four Hazards, namely, caught-in-between, electrocution, fall from heights, and struck-by, represented 653 of the 690 reports. Thus, only the Focus Four Hazards were used to show the distribution of safety climate deficiencies.

Figure 2 shows the distribution of safety climate deficiencies that occurred in the 108 FACE reports that described caught-in-between accidents. Caught-in-between accidents are fairly self-explanatory in that they involve accidents where a worker gets trapped, crushed, 20 entangled, or somehow caught between a piece of equipment, wall, or other structure. Safety Training is by far the most commonly cited safety climate deficiency that is shown among the caught-in-between accidents described in the FACE reports. Since Safety Training and Management Commitment are the two most common safety climate deficiencies for each of the types of accidents (in Figures 1-5), this study will then focus on the various other aspects that are the third most commonly cited for each of the types of accidents. For instance, in the case of caught-in-between fatalities, inspection and maintenance shows up as the third most commonly cited safety climate deficiency. It makes sense that this would be true because most caught-in-between fatalities involve some sort of equipment. Thus, if construction equipment is not maintained and inspected on a regular basis, the likelihood of an equipment malfunction is greatly increased, and this is an area of safety climate that should be continuously monitored and improved upon.

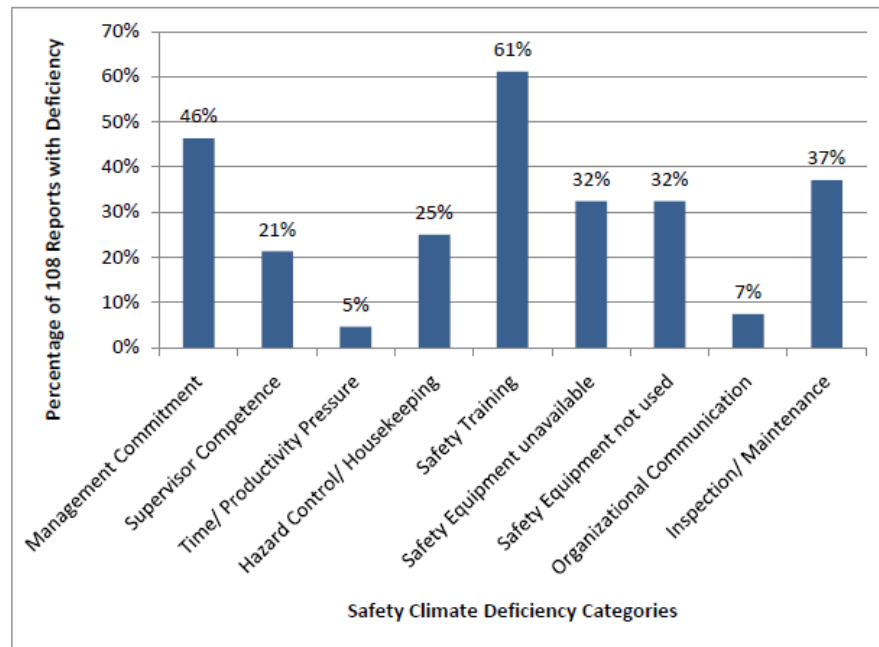


Figure 2 - Distribution of Safety Climate Deficiencies in Caught-in-between Fatalities

Next, the distribution of safety climate deficiencies was plotted for electrocution fatalities, and it can be seen in Figure 3 below. Again, the Management Commitment and Safety Training aspects are the most commonly cited, but in this case Hazard Control and Housekeeping is the third most commonly cited safety climate deficiency. Again, this seems logical, since electrical hazards very often involve situations where intense planning needs to occur prior to the work to ensure that the electrical hazards are appropriately controlled. Specifically in the case of electrical hazards, these are not usually hazards that workers should be required to “just work around.” Instead, they should be eliminated prior to a worker even stepping foot on the site. In addition, housekeeping is very important when working around electrical hazards. If any item is allowed to come into contact with an energized conductor and create a path to ground, a severe electrical hazard is then created. Thus, when working around electrical hazards, it is very important to maintain a neat and orderly workspace and to eliminate all necessary hazards that a worker should not be required to work around.

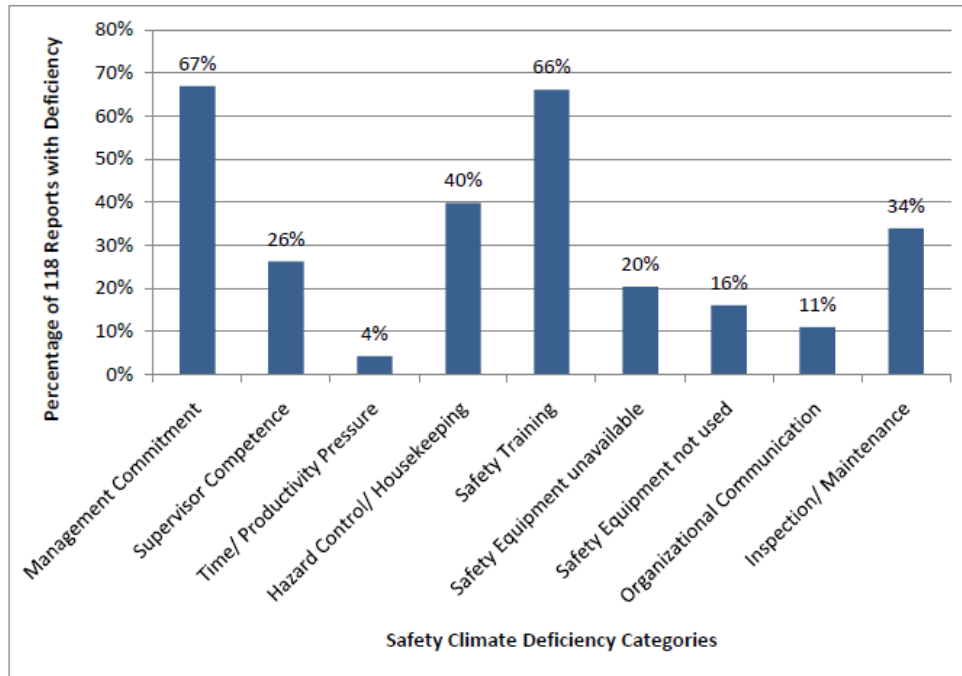


Figure 3 - Distribution of Safety Climate Deficiencies in Electrocution Fatalities

Next, the distribution of safety climate deficiencies was plotted for fall from heights fatalities, and it can be seen in Figure 4 below. Again, the Management Commitment and Safety Training aspects are the most commonly cited, but in this case Safety Equipment Unavailable is the third most commonly cited safety climate deficiency. This demonstrates that in addition to safety training and management commitment issues, many fall from heights fatalities are likely caused by the unavailability of safety equipment. It is important to note that this aspect is much more of a factor than Safety Equipment Not Used, which seems to make it clear that safety equipment is not provided to employees more often than employees just simply don't wear it. This makes it seem like it is extra important for a company to ensure that they provide their employees with fall protection since it is so often a safety climate deficiency when a fatality occurs.

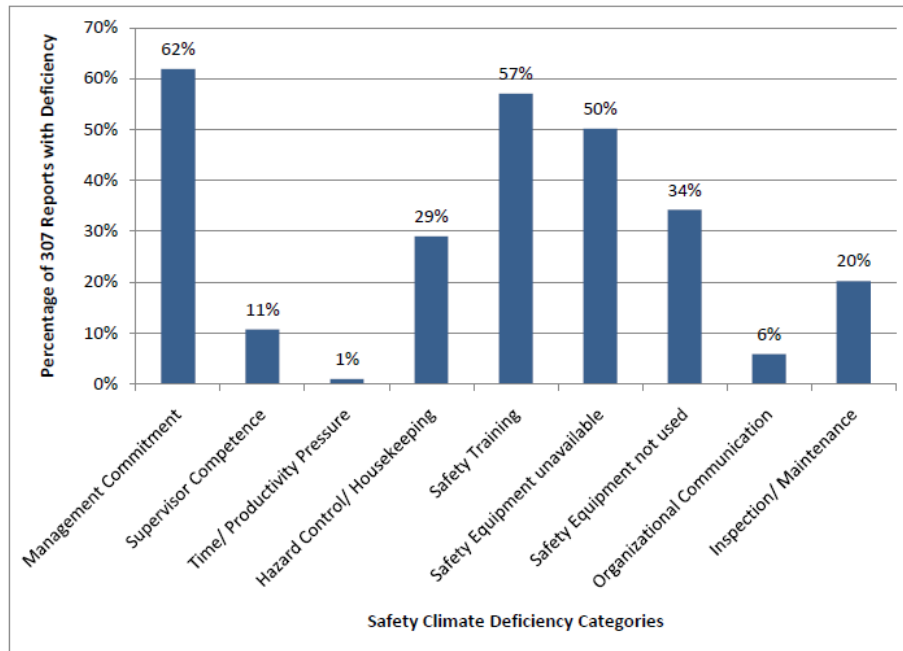


Figure 4 - Distribution of Safety Climate Deficiencies in Fall from Heights Fatalities

Finally, the distribution of safety climate deficiencies was plotted for struck-by fatalities, and it can be seen in Figure 5 below. Again, the Management Commitment and Safety Training aspects are the most commonly cited, but in this case Hazard Control and Housekeeping and Inspection and Maintenance are tied for the third most commonly cited safety climate deficiency when struck-by fatalities occur. Much like caught-in-between fatalities, many struck-by fatalities involve heavy equipment that can be neglected in terms of inspection and maintenance. Thus, this seems like a reasonable aspect to focus on to reduce the amount of struck-by fatalities. In addition to struck-by fatalities involving contact with equipment, struck-by fatalities also involve falling objects and that could explain the higher amount of safety climate deficiencies noted in the area of Hazard Control and Housekeeping.

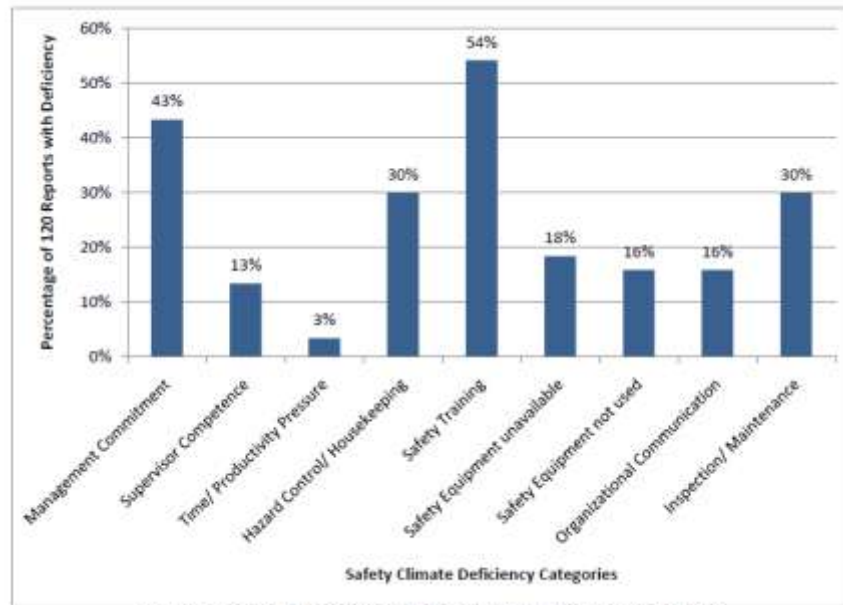


Figure 5 - Distribution of Safety Climate Deficiencies in Struck-by Fatalities

Conclusions and Recommendations for Future Work

Through an analysis of NIOSH FACE reports, this study has investigated the relationship between safety climate deficiencies and the causation of construction fatalities. After analyzing the results, it has become evident that Management Commitment and Safety Training need to see the most improvement in order to ensure that fewer fatalities occur. Once these two aspects of the safety climate improve, there will be a greater chance that several of the other aspects will follow suit. Through the analysis of the distribution of safety climate deficiencies across each of the Focus Four Hazards, it has also become evident that each type of accident has specific aspects of safety climate that are more likely to be present when a fatality occurs. Although the actual correlation between safety climate deficiencies and the underlying causes of construction fatalities has not been investigated by this study, it is evident that there is a relationship that exists and by analyzing this relationship, the actual correlation could be determined, which could provide a supported and proven connection between the leading indicator known as safety climate and lagging indicator of actual fatality statistics.

Furthermore, depending on the particular area of research that is of interest, this data could be used to take this study multiple steps forward to better understand the complexities of safety climate in the construction industry and the relationship between safety climate and the causation of fatalities. The following recommendations have been organized to promote future analysis using the data that was obtained through this study:

1. NIOSH could investigate the aspect of time and productivity pressure more closely when performing the fatality investigations prior to writing the FACE reports. If this aspect was incorporated into the standard procedure for these investigations, then an objective statement could be included in the FACE reports so that this information would be available for future analysis. Simply by reviewing the status of the project schedule, work hours, and other issues of time and productivity, a FACE

investigator would be able to gain an adequate sense of the possible deficiency that could be present in this area.

2. In addition to the results that were presented here, this data could be used to analyze a wide variety of combinations of fatality investigations. For instance, this data could be used to evaluate individual aspects of the safety climate for their relationship with several of the other items in the General Information section. This study was limited to the relationship among different types of accidents, but future analyses could involve sorting the safety climate data by the age of the employer, the size of the employer (number of employees), or even the age or occupation of the employee. Especially since United States construction fatality data shows that certain occupations, like laborers, are more prone to fatalities than others, these specific occupations could be analyzed based on the safety climate data that was accumulated for this study (BLS 2008).

Finally, this work is in the process of being incorporated into an R01 proposal to support NORA Goal area 8, Safety Culture.

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Introduction

Not all construction companies are required to comply with OSHA regulations regarding fall protection. Examples include:

- Non-incorporated construction companies (i.e., sole proprietorships and partnerships) in which the owners perform the actual work are not required to comply with OSHA standards.
- Governmental agencies are not required to comply with OSHA standards.
- In work designated as residential construction, the OSHA standards have lesser requirements than those for commercial construction, even though the fall dangers may be just as great.

Nearly 92 percent of construction companies have 19 employees or less and could be considered “small construction companies.” These small companies employ over 2.8 million people – about 40% of the entire construction workforce. Yet, because of exclusions and exceptions such as those above, many small construction companies do not have to follow all of the OSHA fall protection standards. This leaves a large portion of the construction workforce potentially unprotected and possibly even unaware of fall protection standards.

Objectives

The primary goal of this pilot study was to create a training course designed to instruct small construction company owners about the business implications of fall related accidents and fatalities. The intent of the training course is to encourage small construction companies to provide employee training in fall protection practices that meet or exceed federally mandated OSHA regulations. A secondary goal of this pilot study was to supplement and build on the current pilot study by Songer and Fiori entitled “Innovative, Interactive Fall Protection.”

Objectives to accomplish these goals included:

- 1) Perform a needs assessment of fall protection training, including:
 - a) Document existing training practices regarding fall protection in the construction industry, focusing on small construction companies.
 - b) Assess effectiveness of existing training practices (or lack thereof) through OSHA fall protection violation records, injury and fatality rates, and interviews and/or surveys with both employers and employees regarding the existing training practices.
- 2) Document and assess the process by which employees learn safety techniques (correctly or incorrectly) from their peers through peer opinion leaders and social networking.
- 3) Compare and contrast fall protection equipment used in construction vs. other industries (including types of equipment and relevant injury rates). These industries include:
 - a) Rock climbing/mountaineering
 - b) Electrical linemen
 - c) Window washing

- d) Tree trimming
- 4) Create a training course designed to instruct small construction company owners about the business implications of fall related accidents and fatalities and assess its effectiveness.

This report discusses the findings of each of the above objectives.

Needs Assessment

The pilot study by Songer and Fiori focused on fall protection training and equipment similar to that of a worker performing steel erection. Many fall related incidents occur in circumstances that do not require harnesses, lanyards, or other personal fall arrest equipment, such as falls from ladders, scaffolding, roofs, and through floor or roof openings. Consequently, these other types of fall related dangers should also be included in any fall protection training provided to an employee. Per NIOSH, construction trades with high rates of fatal falls include roofers, painters, ironworkers, carpenters, and general laborers. More than 40% of the fatal falls from 1982-1997 discussed in a 2000 NIOSH report were in companies with 24 or less employees.

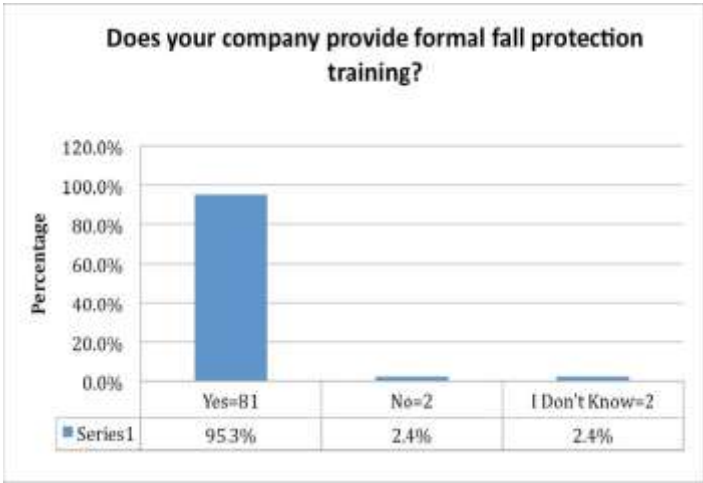
Existing Fall Protection Training Practices

This work first documented and evaluated the existing fall protection training practices of small construction companies. It is important to understand what training practices currently exist, as well as their effectiveness, in order to successfully design a training course that aims to improve the rate of fall protection training.

In accordance with the quantitative approach, a dependent variable, defined response, Likertscale survey instrument (see Appendix) was developed to assess what training processes exist and which methods are preferred when learning fall protection safety techniques. To meet university requirements, the researchers submitted the research plan and the survey instrument to the Boise State University Institutional Review Board for approval. The study followed ethical requirements set forth by that committee.

The participants were a representative convenience sample of construction personnel employed by construction entities located within the Pacific Northwest region of the United States. All of the companies participating in the survey agreed to assist in the survey process by ensuring that the employees at their companies completed and returned the survey in a timely manner. No minimum sample size was required because no specific statistical testing was to be performed. However, to advance the validity of the findings, an attempt was made to obtain as large a number of responses as possible, thus the survey was distributed to approximately 170 participants. All resulting data gathered from the completed surveys was organized and converted into an electronic format for data analysis. Descriptive statistic analysis was conducted on the resulting data to assess the process by which employees learn safety techniques. Calculations performed on the survey data consisted of summing the responses of the participants and determining answers with the highest mean score. The data analysis was then interpreted and the findings were reported. Completed surveys were analyzed to ensure all of the responses were completed and that the responses were within the range of responses allowed in the survey instrument. An initial survey response rate of 58% (98 of 170) was received and 50% (85 of 170) met the pilot study criteria for data analysis. The following are the survey questions and the responses for each question.

Question 1. - Does your company provide formal fall protection training?



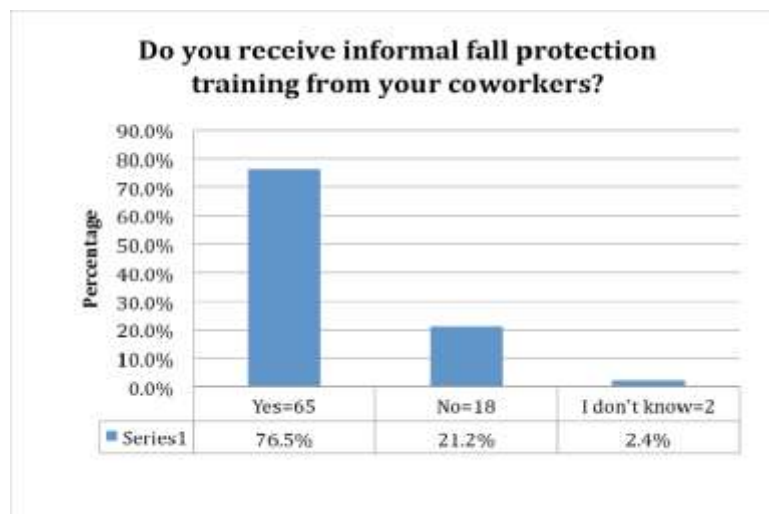
Question 2. How often does your company provide formal fall protection training?



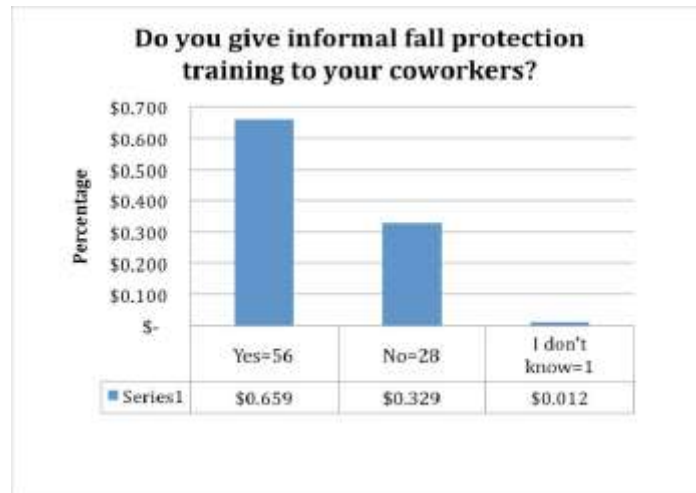
Question 3. How many formal fall protection training sessions have you received in the past year?



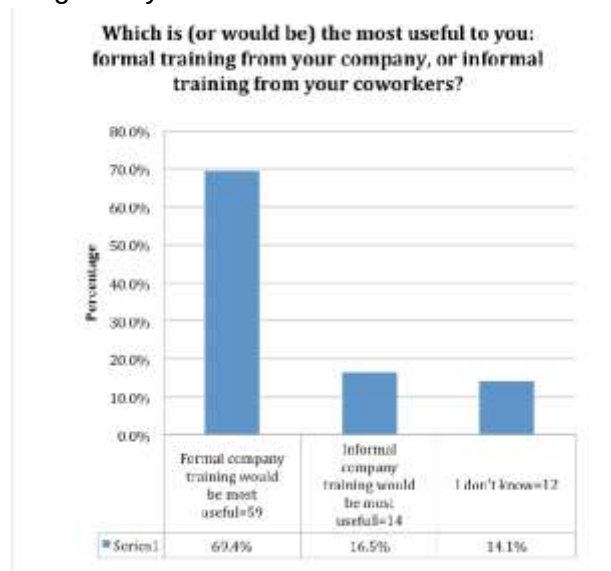
Question 4. Do you receive informal fall protection training from your coworkers?



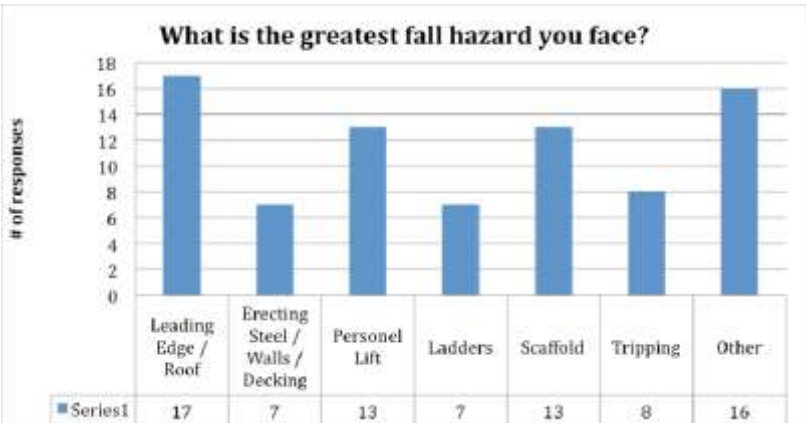
Question 5. Do you give informal fall protection training to your coworkers?



Question 6. Which is (or would be) the most useful to you: formal training from your company, or informal training from your coworkers?



Question 7. What is the greatest fall protection hazard you face?



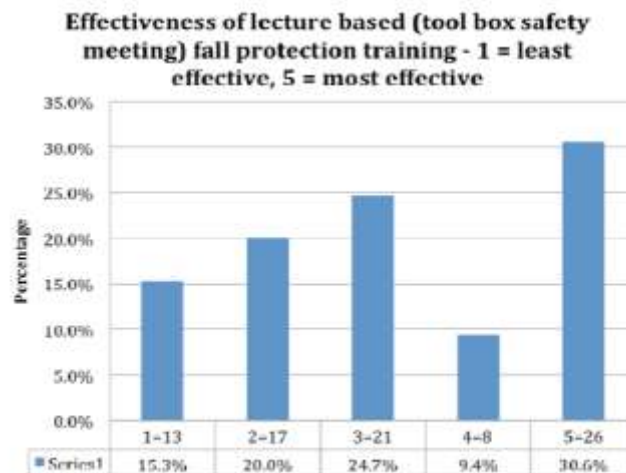
Question 8. Is the hazard you wrote above addressed in either your formal or informal fall protection training?



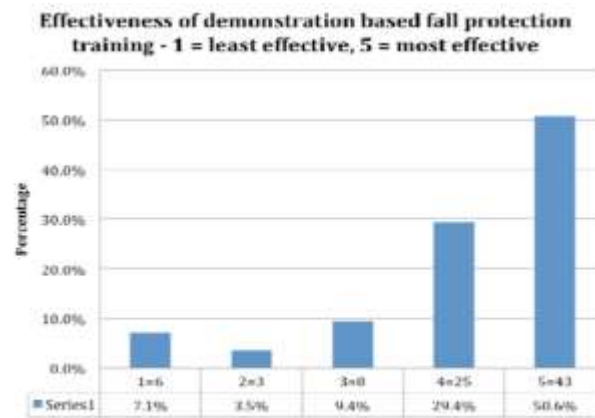
Question 9. In your opinion, what makes fall protection training most effective for you?



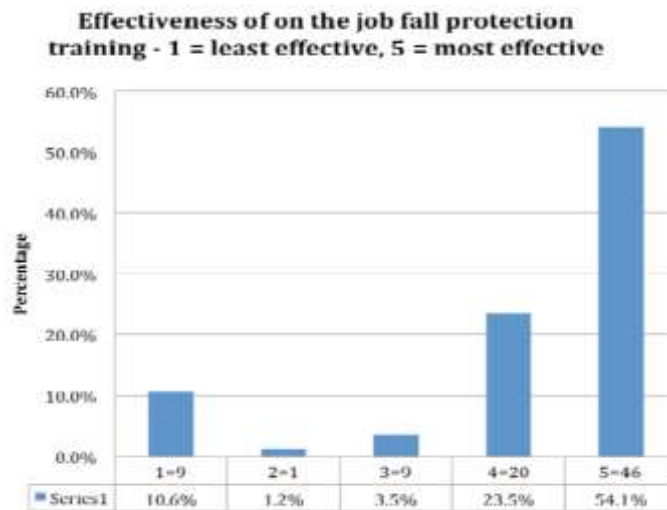
Question 10a. Effectiveness of lecture based (tool box safety meeting) fall protection training - 1 = least effective, 5 = most effective



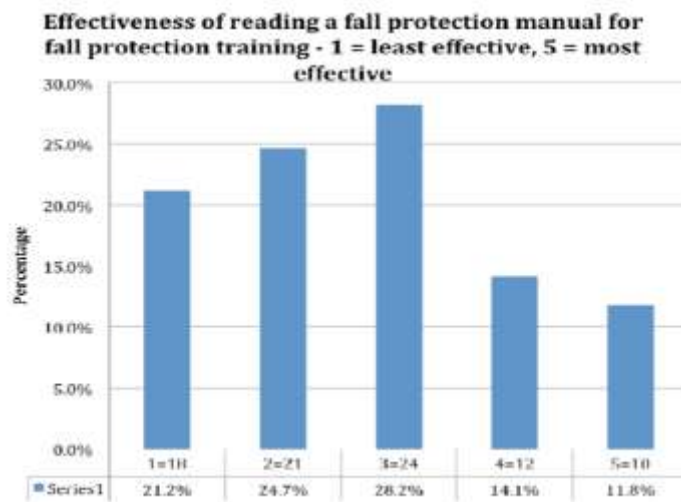
Question 10b. Effectiveness of demonstration based fall protection training - 1 = least effective, 5 = most effective



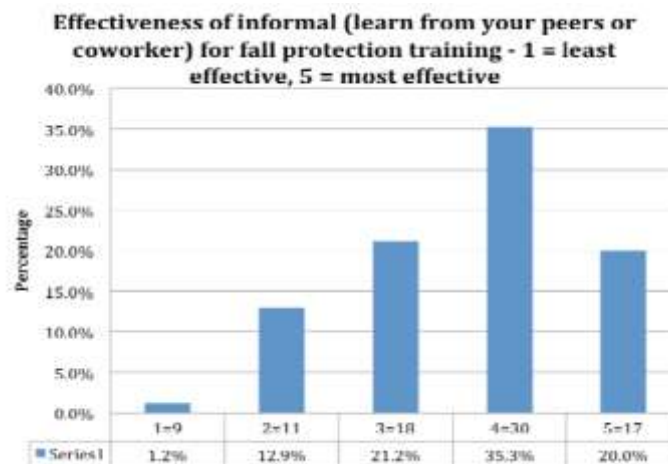
Question 10c. Effectiveness of on the job fall protection training - 1 = least effective, 5 = most effective



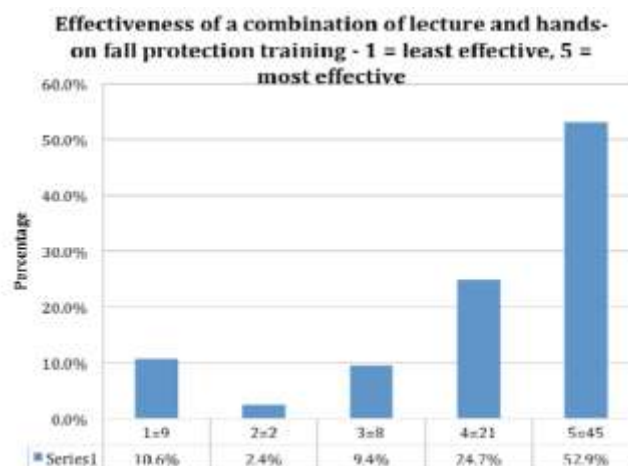
Question 10d. Effectiveness of reading a fall protection manual for fall protection training - 1 = least effective, 5 = most effective



Question 10e. Effectiveness of informal (learn from your peers or coworker) for fall protection training - 1 = least effective, 5 = most effective



Question 10f. Effectiveness of a combination of lecture and hands-on fall protection training - 1 = least effective, 5 = most effective



It appears that nearly everyone surveyed receives some sort of formal fall protection training through their company, though the amount and type of training varies. Three-quarters of those surveyed also receive informal training from their peers and two-thirds give informal training. Most think that the formal training is the most useful, however.

The type of fall hazards reported varied greatly, but most felt that between the formal and the informal training, their greatest hazards were addressed. Of the instructional methods given, demonstrations, on-the-job training, and the combination of lecture and hands-on were the preferred methods, chosen as most effective by over 50% of those surveyed. Informal training by peers was overall ranked next highest, but not as effective as the previous methods listed. Lecture based training was favored by some, but considered

less effective by others. Reading a manual for training was considered the least effective method of the instructional methods given.

While the data collected is not statistically significant due to the convenience sampling method used, there is useful information to be gained. Though nearly everyone receives formal training, the amount of informal training occurring is surprising and should be studied further. Also, the instructional methods most preferred by those surveyed are not necessarily the methods being used to instruct. This is also an area that could use further study. Is safety training being provided to employees in their preferred method or in the method that is most convenient for the supervisors/trainers?

OSHA Fall Protection Records. The effectiveness of existing training practices were examined through OSHA fall protection violation records, injury and fatality totals. OSHA fall protection violation records were examined to learn what typical issues with fall protection occur and in what type of environment. Injury and fatality totals in residential construction trades were compared between states with only federal OSHA requirements (such as ID and MT) and those with state OSHA requirements (such as WY, OR, NV, UT). Those injury and fatality totals were also compared with commercial construction trades in those same states, as they often follow different OSHA requirements.

There are discrepancies in the reporting of fatalities regarding what is reported and to which agency (see Table 1 and Table 2 for examples of discrepancies pertaining to fatalities between the Bureau of Labor Statistics and OSHA Accident Summaries). There are also states that appear not to report injuries from falls (MT, WY, UT) (see Table 3) and states that have no OSHA citations for fall violations (WY, OR, UT) (see Table 4). While it is possible that these states had no injuries or OSHA violations over the five-year period investigated (2003-2007), it is very unlikely. Additionally, it is unlikely that the residential trades in WY, NV, and UT combined have had zero fatalities, one injury, and zero citations from falls in the five-year period investigated. It appears that residential trades (defined by SIC codes 1521 and 1522) are largely omitted from the OSHA records for these states.

Table 1. Fatalities in Construction from falls (data from Bureau of Labor Statistics)

	Idaho	Montana*	Wyoming**	Oregon	Nevada	Utah	Totals
2003	3						3
2004		4	3		6		13
2005		3			6		9
2006		4			4	5	13
2007		5		5	8		18
Totals	3	16	3	5	24	5	56

* Montana data is for all occupations with an attempt to reconcile with fatalities in all aspects of construction

**Wyoming data includes extraction occupations - 3 fatalities removed from 2003 to reconcile with fatalities in all aspects of construction

Table 2. Fatalities in Construction from falls (data from OSHA Accident Summaries)

	Idaho	Montana	Wyoming	Oregon	Nevada	Utah	Totals
2003	3 (1 res)			2 (2 res)	2	2	9 (3 res)
2004		3		1	7	4	15
2005				2	5	1	8
2006							0
2007							0
Totals	3 (1 res)	3	0	5 (2 res)	14	7	32 (3 res)

Table 3. Injuries in Construction from falls (data from OSHA Accident Summaries)

	Idaho	Montana	Wyoming	Oregon	Nevada	Utah	Totals
2003	3			13 (3 res)	11		27 (3 res)
2004				8	11 (1 res)		19 (1 res)
2005	1			9 (2 res)	6		16 (2 res)
2006							0
2007							0
Totals	4	0	0	30 (5 res)	28 (1 res)	0	62 (6 res)

Table 4. OSHA Citations for fall related violations (data from OSHA Inspection Reports)

	Idaho	Montana	Wyoming	Oregon	Nevada	Utah	Totals
2003	2				3		5
2004	5 (2 res)	3 (2 res)			15		23 (4 res)
2005	3	1			2		6
2006	1				6		7
2007	1	2 (1 res)			4		7 (1 res)
Totals	12 (2 res)	6 (3 res)	0	0	30	0	48 (5 res)

Of the nine injuries and fatalities that were reported in residential trades in the six states investigated from 2003 to 2007:

- 3 were from roof related incidents
- 2 were from ladder related incidents
- 2 were from top of wall related incidents
- 1 was from an elevator shaft incident
- 1 was from a scaffold incident

Due to the small number of incidents within the six states over the five-year period studied, it is difficult to make any sound comparisons between states. Adding to this issue is the lack of consistency in reporting fatalities, injuries, and OSHA citations within each state. Additionally, any comparisons are essentially meaningless unless the numbers reported can be modified to reflect rates of incidence. For example, comparing 1 residential fall-related fatality in Idaho in 2003 with 2 residential fall-related fatalities in Oregon in the same year is meaningless. Although one can say that Oregon had 100% more residential fall-related fatalities than Idaho, the statement is relatively useless. Instead, knowing that there was 1 residential fall-related fatality in Idaho among X residential tradespeople in 2003, and comparing that with similar data for Oregon provides context and meaning.

The Bureau of Labor Statistics calculates incidence rates representing the number of injuries and illnesses per 100 full-time workers using the equation: $(N/EH) \times 200,000$, where:

N = number of injuries and illnesses

EH = total hours worked by all employees during the calendar year

200,000 = base for 100 equivalent full-time workers (working 40 hours per week, 50 weeks per year)

Unfortunately, obtaining accurate data for EH in a particular segment of the construction industry (and for a particular state) is extremely difficult, if not impossible. This information may be available at the State level, however. This was not investigated for this pilot study, but is important for future research.

Learning Safety Techniques

A second documentation and evaluation process was undertaken to examine the manner in which employees learn safety techniques (correctly or incorrectly) from their peers through peer opinion leaders and social networking. For information to be transferred effectively from one person to another, the provider of knowledge must be perceived as knowledgeable in the subject area and must be well respected by the receiver. The respect the receiver has for the provider of knowledge is often much more important than the provider's actual knowledge about the subject. From a safety perspective, this means that employees often disregard the official safety talks and listen to their respected peers instead. If the respected peer is knowledgeable about the safety aspect in question, all is well, but unfortunately, this is not always the case. Learning who the peer leaders are in an organization and ensuring that they have the correct safety knowledge can significantly improve the safety knowledge of all employees within the organization. A short survey administered to all employees in an organization is appropriate to determine which employee(s) are the peer leaders in communicating safety aspects within the

organization. This documentation and evaluation process occurred in tandem with the needs assessment of fall protection training from objective 1. Data collection and analysis was discussed previously in the section titled Existing Fall Protection Training Practices.

Fall Protection Equipment

Fall prevention and protection is a mandatory part of nearly every type of construction. Not only is it required by OSHA, it is also necessary for any non-ground level jobsite to be run safely. According to the Construction Industry Research and Policy Center, falls are the highest ranked cause of injury and account for roughly one third of all construction fatalities annually (Schrivier 2005). From this astounding figure, it is clear that fall protection is a large area of concern for the construction industry and should be taken very seriously. It is noteworthy, however, to mention that almost two thirds of the construction related fatalities were a result of workers either not using their equipment correctly or not using it at all (Schrivier 2005). This raises an issue of concern for the proper training and continued education of fall protection equipment. Even when employees know that they should wear personal fall arrest equipment, many choose not to for various reasons, including:

- It interferes with their productivity on the job
- It is uncomfortable to wear

There are other industries and activities that expose people to fall dangers, including high rise window washing, rock climbing, utility lineman, and tree trimming. To ensure that the construction industry is using the most appropriate personal fall arrest equipment, it is important to examine the equipment used in these and other industries. They may provide ideas for how to eliminate reasons not to wear the fall protection equipment. An examination of the equipment used is discussed below. High rise window washing- According to Chris Laprelle of Clearview Window Washing in La Grande, Oregon, “The harnesses used in multi-story window washing are quite a bit different than your typical yellow construction harness.” (Laprelle 2009). One of the big differences is that most of the harnesses used are a simple “diaper” configuration. A diaper harness is basically just a belt around your waist that is attached to the leg straps. Manufacturers also make a full body harness for this application but it is not as common. In either case, there is a D-ring style attachment in front on the waist where you attach your secondary rope. A secondary rope is required because unlike construction, where you are typically standing on something, window washers are already suspended in a Bosun’s seat. This secondary rope is your backup fall protection system in case the working rope fails or the Bosun’s chair breaks. The ropes used in this line of work are highly specialized. The key to this form of fall protection, much like every other industry, is making sure your equipment is in excellent condition before using it.

Below is an example of a typical setup for high rise window washing:

 A man wearing a light blue t-shirt, shorts, and a safety harness stands in front of the open back of a white van. The van's interior shows some equipment, including a red step ladder.	 A person in a blue jumpsuit and a white hard hat is suspended in a Bosun's Seat, cleaning a large glass window on a high-rise building. A bucket is hanging from the seat.
Figure 1. Chris Laprelle demonstrating his equipment (Photo courtesy of Chris Laprelle, Clearview Window Cleaning)	Figure 2. A typical Bosun's Seat (www.fallprevention.co.za)

Rock climbing/ mountaineering. A rock climbing harness looks very similar to many other industry harnesses. It too is a simple waist belt with leg straps. However, unlike the equipment used by other industries; a rock climbing harness must be designed for repeated use. Even though this feature is part of the design, the equipment must still be thoroughly inspected between uses. Climbing harnesses offer the most versatility relative to other industry equipment. There are specialized harnesses for indoor wall climbing, rock climbing, ice climbing, etc. Though there are small differences among these specialized harnesses, there are many features that are universal for all climbing harnesses. Some of the key features of a climbing harness include being smaller, lighter, and more flexible (comfortable) than those used in other industries. This is necessary because a climber is typically wearing their gear all day and must be able to maneuver constantly. Another big difference is that there are virtually no metal components. Even the typical steel D-ring attachment point is replaced with a synthetic fabric loop. Not only does the lack of metal keep the harness lighter, it doesn't allow the abrasive rock surface to create rough edges or burrs at the point of attachment which could eventually wear through the supporting rope. Similar to harnesses used in window washing, tree trimming and linemen work, the point of attachment is in front, at waist level. This is because the ideal post-fall position for people in these industries is to be in a suspended "sitting" position, facing the working surface. This allows for a better chance at self recovery according to Brandon Prince, a veteran rock climber (Prince, 2009).

	
Figure 3. Rock climbing protection in use (www.codinghorror.com)	Figure 4. A close-up view of a rock climbing harness (www.binet.lv/go.pl)

Tree Trimming and Utility Linemen. The fall protection equipment in both of these types of work is very similar. With the majority of fall protection used in the construction industry, the worker is attached to a fixed anchor point or line. In the tree trimming and lineman industries however, often there is no fixed anchor point until you reach the top and tie off. The exception would be if the work area can be reached with a boom truck, in which case a standard body harness or belt harness can be used and attached to the bucket. When a boom cannot be used however, a specialized harness is necessary. For these workers, there is a positioning belt that has D-rings on both sides allowing them to wrap a separate belt around the tree or power pole and attach it to the belt around their waist. Coupled with specialized climbing boots that dig in to the tree or pole, the worker is allowed to lean back and be fully supported. Once the worker reaches the top, they can fasten a secondary point of attachment should the belt break or slip. According to Gill Maiuro of the Northwestern Lineman College, linemen are only held to OSHA's general industry standards (Maiuro 2009). While he says that they have partnered with OSHA to create a set of six "best practices", there is currently no specific set of regulations regarding fall protection for electrical linemen.

One of the major downfalls of this type of fall protection is the high degree of risk attached to the structure itself, particularly in tree trimming. According to a case study performed by the Centers for Disease Control (CDC), many of the fall related fatalities in the tree trimming industry are a direct result of not having secondary fall protection. In one case, a worker accidentally cut his own support strap with a chainsaw while trimming a branch and in several other cases, a portion of the tree had unknowingly rotted and resulted in the tree breaking in half below the tie off point (Braddee 1992).

Construction. Unlike the previously discussed industries, the construction industry does not have the luxury of being specialized. The fall hazards that accompany the construction industry change on a daily basis. Every job is custom built and provides its own unique fall hazards. These could include anything from bridge work, roofing (commercial and residential),

steel erection, concrete and form work, scaffolding and more. The only thing that is common amongst them is that it requires the ability to be highly mobile in an unsafe environment. There are literally hundreds of different kinds of harnesses for these various applications but they are all generally the same. Most types of construction require a full body harness that includes a belt, leg straps and shoulder straps. However, unlike other industries that allow a forward point of attachment, OSHA standard **1926.502(d)(17)** requires that:

The attachment point of the body belt shall be located in the center of the wearer's back. The attachment point of the body harness shall be located in the center of the wearer's back near shoulder level, or above the wearer's head (OSHA 1995).



Figure 5. A worker demonstrating the proper fall protection (www.meico.cz)



Figure 6. An assortment of available harnesses (courtesy of Boise Rigging Supply)

This is unique to the construction industry. In many circumstances, this can result in a fall victim relying solely on a rescue from others. This can be very dangerous if a proper fall rescue plan is not implemented. According to Shelley Mihalic, Senior Product Manager for Miller brand fall protection, there have been many improvements to fall protection equipment in recent years. Some of these improvements include a higher level of comfort, stretch webbing, more padding, breathable materials and an easier level of adjustment. (Mihalic 2007) Although these improvements have been made in recent years, there is still a high risk for a fatal type of post fall suspension trauma called orthostatic incompetence. This occurrence is not uniquely dangerous to the construction industry, any fall victim that is suspended for a prolonged period of time can be affected by it. A basic description is provided by Bill Weems and Phil Bishop of the Occupational Health & Safety Magazine: "What happens in orthostatic incompetence is that the legs are immobile with a worker in an upright posture. Gravity pulls blood into the lower legs, which have a very large storage capacity. Enough blood eventually accumulates so that return blood flow to the right chamber of the heart is reduced. The heart can only pump the blood

available, so the heart's output begins to fall. The heart speeds up to maintain sufficient blood flow to the brain, but if the blood supply to the heart is restricted enough, beating faster is ineffective, and the body abruptly slows the heart. In most instances this solves the problem by causing the worker to faint, which typically results in slumping to the ground where the legs, the heart, and the brain are on the same level. Blood is now returned to the heart and the worker typically recovers quickly. In a harness, however, the worker can't fall into a horizontal posture, so the reduced heart rate causes the brain's blood supply to fall below the critical level. Orthostatic incompetence doesn't occur to us very often because it requires that the legs remain relaxed, straight, and below heart level. If the leg muscles are contracting in order to maintain balance and support the body, the muscles press against the leg veins. This compression, together with well-placed one-way valves, helps pump blood back to the heart. If the upper-legs are horizontal, as when we sit quietly, the vertical pumping distance is greatly reduced, so there are no problems. In suspension trauma, several unfortunate things occur that aggravate the problem. First, the worker is suspended in an upright posture with legs dangling. Second, the safety harness straps exert pressure on leg veins, compressing them and reducing blood flow back to the heart. Third, the harness keeps the worker in an upright position, regardless of loss of consciousness, which is what kills workers.” (Bishop and Weems 2003) There is actually a product on the market that is designed to prevent this phenomenon. The suspension trauma safety strap is a safety feature developed to allow a fall victim to exert downward pressure with their legs in order to keep blood flowing during suspension.



Figure 7: A worker demonstrating the use of a suspension trauma safety strap (www.tessco.com)

These straps are relatively inexpensive and can prove to be very valuable in a fall situation. During an interview Bob Duhaime of Boise Rigging Supply, it was discovered that as a result of these straps not being required by OSHA, very few construction companies use them (Duhaime 2009). As was mentioned, a large percentage of construction related fall injuries or fatalities are a direct result of the lack of knowledge about available fall protection equipment or the refusal to use it. Reasons for refusal to follow OSHA regulations can be caused by anything from a low comfort level to a perceived lack of productivity. The bottom line is that for every situation that a fall hazard is present, there is a piece of equipment designed to keep that worker safe and productive. The key to lowering the injury and fatality rates is to know what is available and to make the best use of it.

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Training Course

The results of the first two objectives assisted in the creation of a training course to instruct small construction company owners about the business implications of fall related accidents and fatalities. The educational materials the team produced from this research includes a training course designed to instruct small construction company owners about the business implications of fall related accidents and fatalities. The intent of the training course is to encourage small construction companies to provide employee training in fall protection practices that meet or exceed federally mandated OSHA regulations. The training course focuses on educating small business owners regarding the business implications of fall related accidents and fatalities, with the goal of convincing them that fall protection training is of value to their business, even though they may not be required to follow all government regulations. Specific educational focuses of the training include:

- Insurance modification rates;
- Workman's compensation rates; and
- Productivity losses due to injuries and fatalities.

An overhead presentation and handout material were developed, as were a pre-test and post-test (available upon request) to assess the effectiveness of the course. The training course participants were a representative convenience sample of owners and/or principals of construction entities located within the Pacific Northwest regions of the United States. A recruitment letter (available upon request) was sent to perspective course attendees on two separate occasions. The letters were followed by e-mails and personal phone calls attempting

to recruit individuals to attend the course. Despite the efforts of the researchers and the effort of local risk management professionals, no individuals responded to the course offering. Assessment of the effectiveness of the training course was examined for short term gains. In the short term, the goal is to convince small construction companies to provide employee training in fall protection practices that meet or exceed federally mandated OSHA regulations. This would have been measured using a pretest to learn the intention of construction business owners to use fall protection training in their company that meets or exceeds OSHA standards prior to attending the training course. A posttest was also intended after the completion of the training course to evaluate whether this had changed their intentions to provide fall protection training in their company. The pretest and posttest information can be used to determine strengths and weaknesses of the course and adjustments should be made based upon the results. In the long term, the goal is to assist companies in lowering their injury and fatality rates, as well as lower their insurance modification rate. These are goals that must be assessed over many years to determine whether this training course has been effective.

Despite the attempt of the researchers to provide a free, informative course that could benefit the owners of small construction companies, no individuals responded to the offering. The researchers assumed that if information was offered for free to individuals that have less experience and/or knowledge of safety and risk management that the course would be well received and attended. However, the researchers found that despite their efforts, the course was not attended. This finding leads to more questions than answers and certainly provides a stimulus to further study why individuals do not attend such offerings.

Funded Students

Over the past five years, there were 28 students who received partial financial support from the Center. Funding supported students as graduate research assistants aiding sub-project and GPP PIs or supported their own research efforts for completion of a thesis or dissertation.

Graduate Students Funded through the Center. Graduate research assistants are vital to the efficient production of outputs and outcomes.

Student	Department
Artis, Sharnnia	Industrial and Systems Engineering
Baldev, Darshan H.	Industrial and Systems Engineering
Bullinger, Jesse D.	Mechanical Engineering
Camargo, Hugo E.	Mechanical Engineering
De La Riva, Diego	Mechanical Engineering
Ellie Rigby	Civil and Environmental Engineering
Errasquin, Leonardo A.	Mechanical Engineering
Guo, Cheng	Industrial and Systems Engineering
Haro, Elizabet	Industrial and Systems Engineering
Hung, Yu-Hsiu	Industrial and Systems Engineering
Hurley, Michael J.	Building Construction

Jia, Bochen	Industrial and Systems Engineering
Kadam, Rahul S.	Mechanical Engineering
Kant, Ravi	Industrial and Systems Engineering
Kim, Hyung Nam	Industrial and Systems Engineering
Kim, Sun Wook	Industrial and Systems Engineering
Lin, Dingding	Industrial and Systems Engineering
Mehta, Ranjana K.	Industrial and Systems Engineering
Muchenje, Lovejoy	Industrial and Systems Engineering
Qu, Xingda	Industrial and Systems Engineering
Remillieux, Marcel	Mechanical Engineering
Sarkar, Sourish	Industrial and Systems Engineering
Schwartz, Kyle W.	Mechanical Engineering
Singh, Navrag B.	Industrial and Systems Engineering
Tallapragada, Phanindra	Engineering Science and Mechanics
Thomas, Chanel T.	Industrial and Systems Engineering
Thongsamak, Sasima	Industrial and Systems Engineering
Zhang, Hong B.	Industrial and Systems Engineering

The following table lists graduate students who were supported through administrative core and sub-project funds to complete a thesis or dissertation.

Demographics for these students are as follows: 4 female and 6 male; 1 Latino-American, 1 African, 2 African-American, 1 Asian, 1 Asian-American, 1 French, 1 Indian, and 1 European-American.

Graduate Students Funded for Completion of a Thesis or Dissertation.

Name: Elizabeth Haro	Status: In Progress Title of Project: An Evaluation of Perceived and Observed Safety and Productivity in Homebuilding Construction Faculty Advisor: Dr. Brian M. Kleiner
Name: Sharnnia Artis	Status: Complete Title of Project: The Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers Faculty Advisor: Drs. Brian M. Kleiner & Tonya Smith-Jackson

Name: Darshan Baldev	Status: Complete Title of Project: Design of a construction safety training system using contextual design methodology Faculty Advisor: Drs. Tonya L. Smith-Jackson and Woodrow W. Winchester
Name: Rahul Kadam	Status: Complete Title of Project: Vibration Characterization and Numerical Modeling of a Pneumatic Impact Hammer Faculty Advisor: Dr. Martin E. Johnson (Supported by Burdisso)
Name: Lovejoy Muchenje	Status: Complete Title of Project: Determination of Backup Alarm Masked Threshold in Construction Noise Faculty Advisor: Dr. John G. Casali
Name: Marcel Remillieux	Status: Complete Title of Project: Aeroacoustic Study of a Model-Scale Landing Gear in a Semi Anechoic Wind Tunnel Faculty Advisor: Drs. Ricardo A. Burdisso and Wing F. Ng (Supported by Burdisso)
Name: Sourish Sarkar	Status: Complete Title of Project: The Effect of Advance Demand Information on a Pull Production System with Two Customer Classes Faculty Advisor: Dr. John P. Shewchuk (Supported by Nussbaum)
Name: Kyle Schwartz	Status: Complete Title of Project: Acoustic Characterization and Preliminary Noise Control of Pneumatic Percussion Tools Faculty Advisor: Ricardo A. Burdisso
Name: Chanel Thomas	Status: Complete Title of Project: Influence of Acculturation and Individual Differences on Risk Judgments of Construction Laborers Faculty Advisor: Dr. Tonya Smith-Jackson

Name: Sasima Thongsamak	Status: Complete Title of Project: A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction Faculty Advisor: Dr. Brian M. Kleiner

Faculty Advisors' (Theses and Dissertations) Affiliations

Ricardo A. Burdisso, Ph.D.

Professor, Mechanical Engineering
Virginia Tech

John G. Casali, Ph.D.

John Grado Professor of Industrial and Systems Engineering
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Martin E. Johnson, Ph.D

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Adjunct Professor, Civil and Environmental Engineering
Adjunct Professor, Building Construction
Virginia Tech

Wing F. Ng, Ph.D.

Christopher C. Kraft Endowed Professor, Mechanical Engineering
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Virginia Tech

Woodrow W. Winchester, III, PhD

Assistant Professor, Industrial and Systems Engineering
Virginia Tech

Abstracts for Thesis and Dissertation Research Projects

Dissertations

Artis, S: “Effects of Perceived Organizational Support on Training and Safety in Latino and Non-Latino Construction Workers” (2007) *(Supported with funds from Training Needs Project)*

Workplace safety, if not managed appropriately, can result in human and economic tolls. The need to establish and maintain a safe working environment has probably never been more important. Despite a mounting emphasis on safe work practices, the Bureau of Labor Statistics (BLS) reported a total of 5,702 fatalities in the United States in 2005. Among these fatalities, Latino workers, defined as both foreign-born and native-born (U.S.-born) workers of Latino ethnicity (BLS, 2006; Dong and Platner, 2004), accounted for 16% of those fatalities (BLS, 2006). Researchers are increasingly acknowledging that organizational factors are important in workplace safety (Hofmann, Jacobs, and Landy, 1995; Hurst, Bellamy, Geyer, and Ashley, 1991). However, there is a lack of cross-cultural comparison in this area. With the continuing increase in Latino construction workers and the level of injuries and fatalities, little attention has focused on the comparison of employment relationships between Latino and non-Latino construction workers and their supervisors and work environment. Therefore, this research endeavor used social exchange theory to examine the role of organizational factors in small construction firms to help explain why Latino workers have a disproportionate number of construction casualties compared to their non-Latino counterparts and to design a safety training program to help reduce the number of injuries, accidents, and fatalities in the workplace. The results of this research endeavor demonstrated that both Latino and non-Latino and Latino groups had relatively equal perceptions of organizational support and distributive justice implying that Latinos and Latinos have identical support needs or that the construction firms’ practices meet the support the workers need regardless of ethnicity. In addition, the study found ethnic group differences for safety climate, safety behavior, and cultural dimensions, which may contribute to the disproportionate number of fatalities for Latino workers. After uncovering group differences, this study tested the affect of training on perceived organizational support, distributive justice, safety climate, and safety behavior. This research demonstrated that providing training, of any type, as a source of perceived organizational support increases workers’ perception of organizational support. Additionally, the study concluded that embedded sources of perceived organizational support in the training program increase workers’ perceptions of distributive justice and safety climate. As a result, guidelines to improve workers’ perception of organizational support and safety climate were created. Since high perceptions of safety climate are linked to less risky safety behaviors, embedding perceived organizational support into training programs can have an indirect affect on the workers’ safety behavior. For that reason, improving the safety behavior of workers and the workers’ perception of a safe work environment can lead to reduced accidents, injuries, and fatalities in the construction industry.

Participant Overview. Phase 1 of the study began with 60 participates: 30 Latino construction workers and 30 non-Latino construction workers. Phase 3 ended with 46 participates: 19 Latino construction workers and 27 non-Latino construction workers. From

Phase One to Phase Three, 14 participants dropped out of the study for various reasons. Methods used were questionnaires and interviews.

<http://scholar.lib.vt.edu/theses/available/etd-08172007-142231>

Haro, E. “An Evaluation of Perceived and Observed Safety and Productivity in Homebuilding Construction” (In Progress) *(Supported with funds from Admin Core Budget)*

Construction worker safety continues to be at the forefront of concerns for the industry. The challenge for any safety program occurs when apparent conflicting priorities exist which can include necessary productivity increases, expedited schedules, and schedule slips, among others. Workers may perceive a tradeoff is necessary between productivity and safety. It is critical to understand if a tradeoff exists because awareness of performance pressure can lead workers to perceive that engaging in short cut and unsafe behavior is anticipated or a required part of the job. The purpose of this research is to increase the understanding of the relationship between perceived and observed safety and productivity and to understand the variability in perception and behavior between crews working for the same general contractor in the homebuilding construction industry. This research includes two field studies in the Northern Virginia and Maryland area. Study one (n=150) includes a total of three survey instruments and a demographics questionnaire. The objective of phase one is to evaluate the relationship between perceived safety climate, perceived risk behavior and perceived productivity in residential homebuilding crews. Study two (n=70) includes a combination of questionnaires and videos of a framing task. The goal is to compare the worker's perceptions with their behavior. This will provide information that will help design interventions that address both perception and behavior of safety.

Participant Overview. A two-phase, field-based study consisting of 198 construction workers. Phase I used 157 participants and Phase II used 41. No participants were repeated in Phase II from Phase I. Additionally, the framing of a first floor single family home was videotaped for eight hours.

Thongsamak, S. “A Cross-Cultural Examination: Effects of Reward Systems and Cultures on Low Severity Risk-Taking Behavior in Construction” (2007) *(Supported with Pilot Projects funds from Admin Core Budget)*

The overall research objective was to identify the effects of reward systems (rewards and a penalty) on risk-taking behavior and performance (quality and time) of construction workers from different cultures (American, Asian, and Latin American cultures). This research used the sociotechnical system as the underlying, guiding scientific framework. The research found that Americans and Latin Americans had higher risk-taking behavior than Asians ($p < 0.01$). No difference in risk-taking behavior was found between Americans and Latin Americans ($p < 0.05$). Although culture may influence individuals' risk-taking behavior, the results from this study showed that risk-taking behavior could be altered and suppressed by providing individuals with the proper safety training, education, and safety equipment. Customized safety training for people from different cultures would be useful because the culture elements that contribute to high risk-taking behavior could be addressed. The results also showed that the effects of reward

systems on risk-taking behavior were not statistically significant ($p>0.1$). One possibility that no difference was found may be because the tasks used in this study did not contain enough possibility for participants to take more risk. The effects of reward systems on risk-taking behavior may have been reduced by the low possibility of risky behavior. It is suspected that if the tasks contained more opportunities for participants to take risk, differences in risk-taking behavior would have been significant. The researcher concluded that risk perception is situation-specific and has an influence on the individual's risk-taking behavior on that particular situation but cannot be used to predict risk-taking behavior. Also, general locus of control and general self-efficacy cannot be used to predict risk-taking behaviors. These findings are consistent with many studies that explore locus of control (Iversen & Rundmo, 2002; Rolison & Scherman 2002; Crisp & Barber, 1995), and many researchers that suggested self-efficacy is situation specific (Murdock et al., 2005; Martin et al., 1995; Perraud, 2000; Slanger & Rudestam, 1997). This study also found no relationship between risk-taking behavior and productivity, for both time and quality.

Participant Overview. Lab based project surveying 54 Americans, 76 Asians, and 23 Latin Americans

<http://scholar.lib.vt.edu/theses/available/etd-10312007-234714/>

Theses

Baldev, D. “Design of a Construction Safety Training System Using Contextual Design Methodology” (2006). *(Partially supported with funds from Training Needs Project)*

In the U.S., the majority of construction companies are small companies with 10 or fewer employees (BLS, 2004). The fatality rate in the construction industry is high, indicating a need for implementing safety training to a greater extent. This research addresses two main goals: to make recommendations and design a safety training system for small construction companies, and to use Contextual Design to design the training system. Contextual Design was developed by Holtzblatt (Beyer and Holtzblatt, 1998) in an effort to address the challenge of designing new systems. Ethnographic in nature, the Contextual Design methodology requires field data collection, requirements analysis, model building, visioning and story boarding, and prototyping. A sample of 12 participants consisting of 7 tradespersons, 3 forepersons, and 2 owners/ managers, was selected for data collection. The data was analyzed based on the Contextual Design approach and a training system prototype was designed. The results of this study are recommendations for safety in small construction companies, a low fidelity paper prototype of the training system, and recommendations on future use of Contextual Design for developing training systems.

Participant Overview. Field-based study using 12 construction workers from small construction companies, ranging from 3 to 20 employees in Virginia and North Carolina area. Method used was contextual inquiries.

<http://scholar.lib.vt.edu/theses/available/etd-09262006-160427/>

Kadam, R. “Vibration Characterization and Numerical Modeling of a Pneumatic Impact Hammer” (2006) *(Supported with funds from Noise Vibration Project)*

Hand transmitted vibration (HTV) is one of the most common hazards faced by workers in the construction industry. A major source of HTV is hand held percussion tools, such as pneumatically driven chipping hammers and rock drills. This thesis presents a new approach to measuring the vibration from these tools using an experimental hand arm model to which the tools are attached. The experimental hand-arm model has been designed to have similar dynamic characteristics to that of a human hand-arm system. This approach addresses the issue of repeatability as HTV measurements suffer from variability between cases. The measured acceleration of the hand-arm system is in range or close to range of the measured accelerations of the test subjects with superior repeatability. Further, the thesis presents a nonlinear numerical model of a pneumatic impact hammer. Fundamentally, the numerical model was made up of two different sub-models, 1) a fluid flow model and 2) a structural dynamic model. The fluid flow model was based on the equations for mass flow rate of air through a bleed orifice assuming an isentropic process. The second sub-model deals with modeling the structural components of the impact hammer consisting of the major hammer like the center body, handle, piston and chisel as well as the human hand and the ground. Time domain simulations of the hammer were carried out by using a state space formulation to get

displacements, velocities and accelerations of the each component as well as the exhaust jet velocities. Experiments were carried out to measure the handle response and exhaust jet velocities as well as pressure profiles. The results obtained from the numerical model were then validated using these experimental results. Finally, a parametric study using the numerical model was carried out to explore different vibration control techniques.

Participant Overview. Lab-based study using 3 participates, current graduate students in the Vibration and Acoustics Laboratoy.

<http://scholar.lib.vt.edu/theses/available/etd-08052006-111525/>

Muchenje, L. “Determination of Backup Alarm Masked Threshold in Construction Noise” (2008)
(Supported with funds from Speech Communication and Signal Detection Project)

Sound transmission devices have advanced filtering abilities that theoretically protect the ear from harmful masking noise while amplifying the sounds that need to be heard, such as backup alarms. Therefore, such devices should provide improved signal detection in noise when compared to their passive counterparts. The masked threshold of a vehicular backup alarm was determined for audiometrically normal and non-normal hearers using two types of sound transmission devices and their passive counterparts within pink noise and milling machine noise at intensities of 75, 85, 95 and 105 dBA. Results indicated that the sound transmission devices did not have any statistically significant advantages over the passive devices with respect to masked threshold of a backup alarm. Therefore, it cannot be concluded that these devices offer advantage over similar passive devices with respect to signal detection. Additionally, ratings of comfort and the ability to detect the alarm for each device were gathered. Both scales did not show any significant differences between the two device types.

Participant Overview. Lab-based study with 11 participants.

<http://scholar.lib.vt.edu/theses/available/etd-06042008-203917/>

Remillieux, M. “Aeroacoustic Study of a Model-Scale Landing Gear in a Semi Anechoic Wind Tunnel” (2007) (Supported with funds from Noise Vibration Project)

An aeroacoustic study was conducted on a 26%-scale Boeing 777 main landing gear in the Virginia Tech (VT) Anechoic Stability Wind Tunnel. The VT Anechoic Stability Wind Tunnel allowed noise measurements to be carried out using both a 63-elements microphone phased array and a linear array of 15 microphones. The noise sources were identified from the flyover view under various flow speeds and the phased array positioned in both the near and far-field. The directivity pattern of the landing gear was determined using the linear array of microphones. The effectiveness of 4 passive noise control devices was evaluated. The 26%-scale model tested was a faithful reproduction of the full-scale landing gear and included most of the full-scale details with accuracy down to 3 mm. The same landing gear model was previously tested in the original hard-walled configuration of the VT tunnel with the same phased array mounted on the wall of the test section, i.e. near-field position. Thus, the new anechoic configuration of the VT wind tunnel offered a unique opportunity to directly compare, using the same gear model

and phased array instrumentation, data collected in hard-walled and semi-anechoic test sections. The main objectives of the present work were (i) to evaluate the validity of conducting aeroacoustic studies in non-acoustically treated, hard-walled wind tunnels, (ii) to test the effectiveness of various streamlining devices (passive noise control) at different flyover locations, and (iii) to assess if phased array measurements can be used to estimate noise reduction. As expected, the results from this work show that a reduction of the background noise (e.g. anechoic configuration) leads to significantly cleaner beam forming maps and allows one to locate noise sources that would not be identified otherwise. By using the integrated spectra for the baseline landing gear, it was found that in the hard-walled test section the levels of the landing gear noise were overestimated. Phased array measurements in the near and far-field positions were also compared in the anechoic configuration. The results showed that straight under the gear, near-field measurements located only the lower-truck noise sources, i.e. noise components located behind the truck were shielded. It was thus demonstrated that near-field, phased-array measurements of the landing gear noise straight under the gear are not suitable. The array was also placed in the far-field, on the rear-arc of the landing gear. From this position, other noise sources such as the strut could be identified. This result demonstrated that noise from the landing gear on the flyover path cannot be characterized by only taking phased array measurement right under the gear. The noise reduction potential of various streamlining devices was estimated from phased array measurements (by integrating the beam forming maps) and using the linear array of individually calibrated microphones. Comparison of the two approaches showed that the reductions estimated from the phased array and a single microphone were in good agreement in the far-field. However, it was found that in the near-field, straight under the gear, phased array measurements greatly overestimate the attenuation.

Participant Overview. Lab-based study performed only by the researcher. No participants required.

<http://scholar.lib.vt.edu/theses/available/etd-04102007-105321/>

Sarkar, Sourish. “The Effect of Advance Demand Information on a Pull Production System with Two Customer Classes” (2007)

(Supported with funds from Decision Support Tool for Ergonomic Design Project)

In many situations, different consumers have different degrees of willingness to wait to get delivery of a product. So, consumers can be segregated based upon the demand lead time they are providing. In this paper, two types of consumers have been considered. The first category needs immediate delivery of the product, so there is no demand lead time; whereas for the other category, demand lead time is positive. A manufacturer, which produces the items using a base stock policy, can benefit from the advance demand information that the second category of consumers are providing. Early fulfillment for a particular order means fulfilling the order before the demand lead time. In this research, it is shown that a restrictive early fulfillment policy can help the firm to reduce the chances of order loss. A production control approach for restrictive early fulfillment is discussed and the factors that may affect the early fulfillment policy are examined.

Participant Overview. Lab-based study performed only by the researcher. No participants required.

<http://scholar.lib.vt.edu/theses/available/etd-05302007-162144/>

Schwartz, Kyle. “Acoustic Characterization and Preliminary Noise Control of Pneumatic Percussion Tools” (2006)

(Supported with funds from Noise Vibration Project)

Pneumatic percussion tools are extensively used in the construction industry. They are one of the noisiest machines in the construction industry generating noise levels above 110 dBA which are well beyond the permissible exposure limit (PEL) of 85 dBA. This work presents a comprehensive methodology for the acoustic characterization and noise source identification of these percussion tools. The methodology is applied to a representative pneumatic tool and the characterization results are described in detail. A mechanical analysis was performed on a chipping hammer finding mode shapes and natural frequencies of individual components. The mechanical analysis included modal hammer measurements and creating FE models. Fluid measurements were performed on the chipping hammer to find the velocity of the exhaust and pressure in the upper and lower chambers. The fluid tests found that the velocity of the exhaust is approximately Mach 1.0 or greater. Noise measurements were carried out on the chipping hammer to determine the spectral characteristics, overall sound power level, and spatial source strength maps of the tool. A spherical array of microphones was used to obtain an accurate estimate of the overall sound power levels and the directivity. The overall sound power radiation was found to be in the range of 110-115dBA. An advanced 63 microphone phased array was used to successfully locate and identify the major sources of noise from this tool via the use of beam-forming maps. This thesis also presents a preliminary noise control method employing commercial-off-the-shelf pneumatic silencers. The outcome of the tests is illustrated in detail in this thesis.

Participant Overview. Lab-based study performed only by the researcher. No participants required.

<http://scholar.lib.vt.edu/theses/available/etd-08242006-180234/>

Thomas, C. “Influence of Acculturation and Individual Differences on Risk Judgments of Construction Laborers” (2006) *(Supported with funds from Training Needs Project)*

In 2002 the number of reported nonfatal injury and illness cases in the construction industry involving days away from work was over 98,000 for European-Americans (non Hispanic) and 26,000 for Hispanics. Disproportionate to the number of injury and illness cases, the construction industry is comprised of 68% European-Americans, 7% African-Americans and 23% Hispanics (BLS, 2004a). Based on the expected increase in employment of construction laborers and the increase in the number of injuries and fatalities among specific ethnic groups, a need exists to study disparities across cultural groups to determine the basis for injury and fatality differences between these ethnic groups. The purpose of this research was to contribute

to the literature, an effective method for predicting the risk judgments of laborers employed by small construction firms. Predicting the risk judgments of laborers will assist in developing training programs to address these risk factors, which ultimately will reduce injury and fatality rates. Thirty-six construction laborers, 18 European-American and 18 Hispanic, were recruited for the research. Both ethnic groups were divided into two groups; the control and experimental groups. The control groups viewed a generic concrete construction video and the experimental groups viewed a People-Based Safety video. Each of the participants completed a demographic form, questionnaires, and the narrative simulations (pre-test). Following the narrative simulations the participants rated the narrative simulations, watched a video designated by group, and completed the narrative simulations (post-test). The narrative simulations were used to assess their ability to make risk judgments based on the information presented in the video. The questionnaires completed measured various individual differences, and were administered to detect confounding factors that may not be directly attributed to ethnicity. These questionnaires included: Phinney's (1992) Multigroup Ethnic Identity Measure, Leonard, Hill, and Karners' (1989) Risk Perception Scale, Janicak's (1996) Accident Locus of Control Scale, Rooney and Osipow's (1992) Self-efficacy Measure, and Zohar's (1980) Safety Climate Measure. Participant prior exposure to incidents as well as experience in the construction industry was also included. These measures were used to determine if differences in risk perception, locus of control, experience, acculturation, incident exposure, education, self-efficacy, and safety climate had an influence on the ability to make safe risk judgments. Information on topics construction laborers would like included in safety training as well as the preferred method of training was obtained through the use of focus groups. Eleven participants from the experimental group were recruited for the focus groups; 5 European Americans and 6 Hispanics. One focus group was conducted for each ethnic group. Six hypotheses were tested in this study: (1) there would be no difference in the risk judgments of European-American and Hispanic construction workers when given a choice of language, (2) more experienced construction workers would have more difficulty making safe judgments, (3) construction workers who have had more experience with safety related critical incidents in the workplace would have more difficulty making safe judgments, (4) construction workers who have lower levels of risk perception would have more difficulty making safe judgments, (5) construction workers who have an internal locus of control would have more difficulty making safe judgments than those who have an external locus of control, and (6) high acculturation participants would score higher on the narrative simulations than low acculturation participants following the video intervention. The first and fourth hypotheses were supported by the research. There were no significant differences found between the risk judgments of European-American and Hispanic construction workers, and risk perception was positively correlated to risk judgments. The remaining hypotheses were not supported by the research. The major findings of the research are (1) there were no differences in the risk judgments of European-American and Hispanic construction laborers, (2) risk perception and safety climate were significant predictors of construction laborer risk judgments, and (3) the risk judgments of participants were significantly higher for individuals viewing a People-based Safety intervention. There are several advantages of having this information. First, the lack of differences between the two ethnic groups, demonstrates that both groups are able to make safe risk judgments when given the appropriate information in the correct form and language. Secondly, regression analysis using independent

variables risk perception and safety climate, may be used to predict narrative simulation risk judgments. The positive relationship between risk perception and safety climate on safe risk judgments should encourage employers and trainers to increase employees' awareness of hazards on the job and increase employees' perception of the company safety climate. Hazards should be identified in addition to their consequences. Trainers should aim to increase workers' perception of risk by relying on past negative outcomes that have a personal nature even if they are infrequent events. Third, experience was positively correlated to participants' confidence in their risk judgments on the narrative simulations. Trainers should not exclude the more experienced employees during training. Continuous training will allow more experienced employees to re-familiarize themselves with old hazards and become aware of new hazards. It is just as important for more experienced employees to be updated on risks because they are more confident in how they react to hazardous situations. It is in the best interest of the company for the confident employees to be confident in safe risk judgments.

Participant Overview. Field-based study using 36 participants, 18 European-American construction workers and 18 Hispanic construction workers, male and female ages 18-52 years old. They were from small construction companies with little or no safety training. Methods used were questionnaires and narrative simulations
<http://scholar.lib.vt.edu/theses/available/etd-06272006-224309/>

Examples of Outreach to Professionals and Practitioners

In June of 2009, the Center sponsored a Construction Safety Symposium at the 21st International Society for Occupational Ergonomics and Safety (ISOES). Ten papers were reviewed and accepted based on abstract. Authors were invited to submit their papers for consideration to be published in the Open Occupational Health & Safety Journal, edited by Nussbaum, Smith-Jackson and Kleiner.

ISOES Construction Safety Symposium Participants.

	Name / Institution	Title
1	Hu, K., Rahmandad, H., Smith-Jackson, T.L., and Winchester W. Virginia Tech	Factors Influencing Risk of Falls: A Review of Evidence in Construction
2	Yuan ¹ ,L., Buchholz ² ,B., and Dale ³ , A.M. ¹ Southeastern Louisiana University ² University of Massachusetts Lowell ³ Washington University School of Medicine	Examination of Occupational Knee Disorders Among Carpenters in the St. Louis Area
3	Abdelhamid, T.S., Schafer, D., and Narang, P. Michigan State University	Hazard Identification Using Fuzzy SDT
4	Irizarry, J. Georgia Institute of Technology	Enhancing Hispanic Safety Training with Interactive Computing Technologies
5	Smith-Jackson, T.L., Artis, S., Hung, Y., Kim, H., Hughes, C., Kleiner, B.M., and Nolden, A.N. Virginia Tech	Safety Critical Incidents and Small Construction Contractors: A Prospective Study
6	Arezes, P. M. and Bizarro, M. School of Engineering of University of Minho, Portugal	Alcohol Consumption and Risk Perception in the Construction Sector
7	Ranasinghe, S. and Penney, J. Atkins Inc.	Application of Established Safety Processes from Overseas to the U.S. Construction Industry
8	Haro, E. ¹ , Littlejohn, R. ² , and Kleiner, B.M. ¹ ¹ Virginia Tech ² Mississippi State University	Safety Climate in Homebuilding Construction
9	Hung, Y. ¹ , Haro, E. ¹ , Yoo, H. ¹ , and Littlejohn, R. ² ¹ Virginia Tech ² Mississippi State University	Blame Allocation of Accidents Across Organizational Components (Worker, Supervisor, and Organization)
10	Knoll, P. and Lutey, W. Montana State University	An Overview of Teaching Construction Safety to College Students: Montana State University - Construction Engineering Technology Perspective

ISOES Symposium Abstracts

1. Hu, K., Rahmandad, H., Smith-Jackson, T.L. and Winchester, W.

Falls are a significant public health risk and a leading cause of nonfatal and fatal injuries among construction workers. Fall accidents also lead to a tremendous burden of work-related injuries costs, project delays, and reputational damages. In this paper, we surveyed the available literature on different factors contributing to risk of falls. 270 empirical and theoretical papers were reviewed and 117 qualified research papers were coded into a database. We identified major root causes of falls at multiple levels of analysis, from workplace design factors to cultural, organizational, physical and psychological characteristics, training and education, and incentives related to safety measures. We found that the homogeneity of the literature is not appropriate for conducting a structured meta-analysis. In response, we aggregated the current knowledge in a causal model. These findings can contribute to a better design of data collection and modeling studies, support engineering prevention efforts, organize the knowledge base, and inform policy and intervention design to reduce the risk of falls in the construction industry.

2. Yuan, L., Buchholz, B., and Dale, A.M.

Construction workers, especially carpenters, have a significant number of complaints about knee disorders. Thus, it is desired to identify incident cases of knee disorders and to examine the distribution of specific knee disorders. Clinically, sensible algorithms were developed to investigate the medical claim data from the union health plan for carpenters in St. Louis. As a result, 4,900 incident cases of knee disorders were identified among 23,245 medical claims during 1998-2008 and the incidence rate was approximately 153 per 10,000 FTEs. The distribution of knee disorders was 33.1% for acute, 37.1% for subacute, and 29.8% for chronic of the total cases. The majority of carpenters among the total incident cases were Outside Journeymen. However, it was also noteworthy that Floor Layer Journeymen were diagnosed with more bursitis (32.1% of their total cases) and Outside Apprentices had a higher percentage of ACL or PCL sprain (13.6%).

3. Abdelhamid, T.S., Schafer, D., and Narang, P.

Safeguarding construction workers from occupational hazards, whether arising from traumatic, ergonomic, and/or exposure accidents involves training workers to recognize such hazards. Earlier research presented at the Annual Construction Safety Conference explored the need for an assessment of the process of identification and applied Signal Detection Theory (SDT) to assess the ability of a worker to detect unsafe conditions. This research applies Fuzzy SDT to increase the applicability of conventional SDT analysis to construction settings where the definition of a signal event and its associated response do not follow a binary or dichotomous structure. Application of the methodology is demonstrated using a pilot study involving structural steel workers. Results from the sample of 10 ironworkers indicated the average sensitivity in identifying hazards was above average and that workers generally adopted a conservative strategy. Data analysis using conventional SDT model showed a marginally increased sensitivity, but with a very high variation. This study indicates that the fuzzy SDT model was

a better fit when quantifying and analyzing the ability of construction workers to recognize workplace hazards.

4. Irizarry, J.

As a growing number of Hispanics continues to enter the construction industry workforce, contractors face a range of opportunities and challenges, particularly in providing safer workplaces. Addressing safety practices can present a special challenge for companies who employ people from different cultural backgrounds. This research presents initial work in the development of a framework for the development of technology-based training that addresses safety issues among the Hispanic construction workforce. The proposed framework compliments current safety training practices and provides an interactive training solution that is tailored especially for the Hispanic worker. The proposed training solution makes use of video, images, and computer graphics that are incorporated in a graphical user interface that allows interactive assessments of concepts explained. The proposed framework assesses a worker's risk perception and measures learning outcomes that result in a "diagnosis" of potential safety issues the worker face in the work environment.

5. Smith-Jackson, T.L., Artis, S., Hung, Y., Kim, H., Hughes, C., Kleiner, B.M., and Nolden, A.N.

According to a 2006-2007 Bureau of Labor Statistics (BLS) report, approximately 90% of construction companies 20 or fewer workers; of these, 30% specialize in residential construction. Contractors with 10 or fewer employees are exempt from OSHA reporting requirements, unless a fatality occurs or an injury/illness leads to lost workdays for three or more employees (29 CFR 1904.1, Subpart B). These policies make it difficult to address safety challenges faced by small construction contractors who account for disproportionate numbers of injuries and fatalities. A prospective study was conducted in which construction workers logged critical incidents for four weeks. Definitions and examples of critical incidents were given to workers, along with a data logging notebook with structured questions. Workers could report the events immediately upon occurrence or after the workday ended. Critical incident analysis and influence diagrams were used to analyze the reports. Results included event types, triggers, work dynamics, and time-of-day.

6. Arezes, P.M. and Bizarro, M.

Even empirically, it seems reasonable to assume that alcohol consumption may represent an important risk factor for accident occurrence. Previous studies have shown that some workers tend to ignore the risk that may arise from developing of an activity under the effect of alcohol. The main objective of this study was to assess the relationship between the risk perception of construction workers and their, reported and measured, alcohol consumption. Risk perception and self-reported consumption were evaluated through a questionnaire applied to a sample of 100 construction workers. Simultaneously, the identification of the amount of alcohol in blood was carried out amongst all the study subjects. From the obtained results it was possible to

conclude that workers with a lower risk perception seem to be also the highest alcohol consumers. The obtained results will, hopefully, help companies to establish reliable programs to eradicate alcohol consumption at work.

7. Ranasinghe, S. and Penney, J.

By applying non-US regulatory processes to US projects, Atkins have sought to improve safety reporting and performance in the design of major offshore installations. This paper discusses the successful application of these processes and potential implication to the US construction industry. UK safety case and verification requirements were implemented throughout the design of a major offshore installation. This provided formal evidence of the activities undertaken to identify and mitigate risks associated with operation of the facility for its intended application and environment. There is no formal requirement in the US for these processes. From this principle, this paper will focus on the benefits the construction industry in the UK has seen from implementing mandatory safety processes defined within the Construction Design and Management (CDM) regulations. Through comparison with the US OSHA (Occupational Safety and Health Administration) regulations and the principles involved in the two systems, the implications on the US construction industry are discussed.

8. Haro, E. and Kleiner, B.M.

Construction is a temporary undertaking for which a new organization is established for every project. The difference in contractor approaches can introduce variability in safety processes. Construction worker health and safety continues to be at the forefront of concerns for the industry. Although the causes of injuries and illnesses in construction have long been tracked, reported and researched, the industry continues to lead the occupational related fatal and non-fatal injuries. Safety climate refers to shared perceptions regarding safety policies, procedures and practices among members of an organization. It is the degree to which employees believe priority is given to organizational safety performance. The purpose of this research is to increase the understanding of safety climate among crews working for the same general homebuilding contractor. Understanding perceptual safety climate scores can lead to the design of safety interventions, and consequently, the reduction of injuries and fatalities.

9. Hung, Y., Haro, E., Yoo, H., and Littlejohn, R.

The objective of this study is to examine blame allocation of accidents across organizational components (workers, supervisors, and organization). An accident blame allocation instrument was used to measure the participant's blame allocation, which included accident scenarios with and without pictures of male and female faces of European Americans, African Americans and Latinos. A total of 66 students, aged from 18-23 participated in the study. Results of the Accident Blame Allocation revealed gender effects across organizational components.

10. Knoll, P. and Lutey, W.

This article illustrates the need to teach that construction safety is NOT intuitive. In the MSU CET program, we start teaching safety principles and practices in the student's junior year and continue to emphasize construction safety throughout the student's junior and senior years, ending in the student's capstone graduating class. The key is to get our students understanding that in construction safety, we are talking about human life. Many safety laws are dictated based on results from severe accidents or even death (e.g. OSHA Fatal Facts). Understanding these laws is not easy, especially for a 20 to 22 year old who does not have industry experience. This article reports the trends in our CET students' scores on the Constructor's Qualification Examination (CQE) Level I Exam as well as student responses to a locally developed survey relating to safety. The article also recounts the various means that the MSU CET program uses to not only teach construction safety principles and practices but to instill the fact that safety is not intuitive and must be learned and practiced.

Examples of Recognition, Awards and Service

As an objective indicator of the Center's ability to provide impact, a Center project was awarded the prestigious national Alexander C. Williams, Jr., Design Award in 2008. This award recognizes "those who have made outstanding contributions to the conception or design of any product, service, or system that has had a significant impact on users."

In another visible opportunity, the Center was responsible for ensuring the safety and health of workers on an episode of the nationally syndicated ABC television show, Extreme Makeover Home Edition. We used this opportunity to perform and disseminate work organization research, in this case, focused on the design of rapid-build or fast-track construction systems (Kleiner, Smith-Jackson, Mills, O'Brien, and Haro, 2008). The two-hour special episode for which the Center designed and managed the safety system received international exposure. The Department of Energy's Solar Decathlon project has also received international attention and culminated with a fast track design and build competition on the Mall in Washington, D.C. Center faculty have also been regular contributors to such trade periodicals as Modern Contractor Solutions and Construction Equipment.

As a NIOSH-funded construction center under a cooperative agreement, the Center's materials were part of the evidence package provided to the IOM review of the Construction Program. The Center is proud that the NIOSH Construction Program received the impressive scores of "5" for Relevance and "4" for Impact. Additionally, Center director Kleiner and Associate director Smith-Jackson served on the IOM Traumatic Injuries Committee and IOM Personal Protective Technologies Committee, respectively. Kleiner was also assigned as a reviewer for the final "Review of NIOSH Research Programs" report.

Conclusion

It is well accepted that there is a shortage of safety and health professionals in the United States. The Center's unique positioning within a University, created the opportunity to create OSH professionals and refocus existing researchers on construction OSH in the human supply chain. The diversity of disciplines needed to perform valid OSH research has been mobilized

and has grown from multidisciplinary to interdisciplinary work. The science of socio-technical systems theory guided multidisciplinary integration initially and more recently, NORA goals have provided strategic direction. Through its actions and activities, the Center and sub-project personnel sincerely valued and served the end user - the American construction workers, their families and friends. Additionally, the Center valued and involved its strategic partners through such vehicles as an internal and external advisory committee and NIOSH was valued and involved as a full partner in the achievement of the Center's vision.

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<http://scholar.lib.vt.edu/theses/available/etd-08172007-142231>
2. Experimental data; Recommendations and design requirements to support the adoption and use of safety training within small construction firms.
NIOSH Closeout Report for Tonya L. Smith-Jackson
3. Low fidelity paper construction safety training system prototype; Recommendations for safety in small construction companies; Recommendations on future use of Contextual Design for developing training systems.
<http://scholar.lib.vt.edu/theses/available/etd-09262006-160427/>
4. Recommendations for the identification & assessment phase of total safety management implementation.
<http://scholar.lib.vt.edu/theses/available/etd-06272006-224309/>
5. Risk – taking behavior assessment between different cultures (American, Asian, Latin-American)
<http://scholar.lib.vt.edu/theses/available/etd-10312007-234714/>
6. Experimental data; Guidelines for establishing safe working envelopes to help accommodate the hearing needs of construction workers; Recommendations and guidelines for backup alarm standards
NIOSH Closeout Report for John G. Casali
7. Experimental data; Software (MatLab code) for biomechanical models; Recommendations to improve the construction work environment.
NIOSH Closeout Report for Maury A. Nussbaum

APPENDICES

Appendix A: Project Co- Investigators' Affiliations

Appendix B: Construction Industry Questionnaire

Appendix C: Informed Consent Forms

Appendix D: Amplitude-Sensitive Earmuffs Measures in Pink Noise

Appendix E: Comfort and Alarm Detectability Rating Scales

Appendix F: Procedures for the Backup Alarm Detection Study

Appendix G: Chipping Hammer Operation

Appendix H. Calculation of Stack Drop-Off Locations

Appendix A: Project Co- Investigators' Affiliations

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** Life was taken in the tragic events of April 16th 2007*

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Kevin P. Granata Occupational Safety and Health Pilot Research Program
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Virginia Tech

Appendix B: Construction Industry Questionnaire

☐ Center for Innovation in Construction Safety and Health

www.ictas.ise.vt.edu

Jeff A. Lancaster, Ph.D.

Phone: (540) 231- 2680 FAX: (540) 231-3322

Research Assistant Professor and Auditory Systems Laboratory Manager

Electronic mail address: jlancast@vt.edu

Questionnaire about Speech Communication and Signal Detection in the Construction Industry

Instructions:

Please complete the enclosed questionnaire as completely and accurately as you can. Your answers will remain strictly confidential, and your name will not be associated with your answers in any way. Please contact Dr. Jeff Lancaster @ 540-231-2680 if you have any questions about this questionnaire.

Background Information:

Age: _____

Gender: Male _____ Female _____

Job title: _____

Construction work experience, in years: _____

Hours worked per week: Now: _____ hours/week

At maximum: _____ hours/week

Section I: Your Job and the Worksite

1. Check any of the following equipment that you feel contributes to noise in your worksite and for each, also indicate if this equipment has any type of signal or alarm which sounds and if so, what it is for. This includes signals inside the cab for the operator as well as outside the vehicle for other personnel to hear.

☐ Motor grader	Signal or alarm? _____	What for? _____
☐ Air compressor	Signal or alarm? _____	What for? _____
☐ Asphalt/paving/concrete equipment	Signal or alarm? _____	What for? _____
☐ Crane	Signal or alarm? _____	What for? _____
☐ Crawler loader	Signal or alarm? _____	What for? _____
☐ Dozer	Signal or alarm? _____	What for? _____
☐ Excavator	Signal or alarm? _____	What for? _____
☐ Forklift	Signal or alarm? _____	What for? _____
☐ Loader backhoe	Signal or alarm? _____	What for? _____
☐ Pipelayer	Signal or alarm? _____	What for? _____

- ☐ Scraper Signal or alarm? _____ What for? _____
- ☐ Skid steer compact loader Signal or alarm? _____ What for? _____
- ☐ Trencher/boring machine/cable plow Signal or alarm? _____ What for? _____
- ☐ Truck Signal or alarm? _____ What for? _____
- ☐ Water pumping equipment Signal or alarm? _____ What for? _____
- ☐ Wheel loader Signal or alarm? _____ What for? _____
- ☐ Other equipment (specify): _____ Signal or alarm? _____ What for? _____

2. In your job, do you have to communicate, by voice and hearing, with other personnel?

☐ Yes ☐ No

If yes, what is the purpose of this communication? _____

During the communication, do you have trouble hearing or being heard? _____

If yes, please explain why: _____

3. Does your employer provide hearing protection for you to use while at work (e.g., earplugs, earmuffs)?

☐ Yes ☐ No

If so, do you wear the hearing protection provided by your employer while at work?

☐ Yes ☐ No

If you do not wear hearing protection while at work, please explain why you do not:

Questionnaire Ratings:

In the section below, please list worksite tasks in which you feel communicating with the crew is important. Please rate the *importance of completing the task safely* (Column 1), and then rate the *importance of hearing to the completion of that task* (Column 2), where:

1 = Unimportant, 2 = Somewhat Unimportant, 3 = Neutral, 4 = Somewhat Important, and 5 = Important. Circle the choice that best corresponds to your opinion.

	Column 1	Column 2
Tasks in which <i>COMMUNICATION</i> is important:	Importance of completing the task safely	Importance of hearing to completion of task
<i>WITH THE CREW</i>	<u>the task safely</u>	to completion of task
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5

In the section below, please list worksite tasks in which you feel directing equipment operators is important. Please rate the *importance of completing the task safely* (Column 1), and then rate the *importance of hearing to the completion of that task* (Column 2), where:

1 = Unimportant, 2 = Somewhat Unimportant, 3 = Neutral, 4 = Somewhat Important, and 5 = Important. Circle the choice that best corresponds to your opinion.

Tasks in which	Column 1	Column 2
<i>DIRECTING EQUIPMENT</i>	Importance of <u>completing</u>	Importance of <u>hearing</u>
<i>OPERATORS</i> is important:	<u>the task safely</u>	to completion of task
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5

Tasks in which	Column 1	Column 2
<i>DIRECTING EQUIPMENT</i>	Importance of <u>completing</u>	Importance of <u>hearing</u>
<i>OPERATORS</i> is important:	<u>the task safely</u>	to completion of task
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5

In the section below, please list worksite tasks in which you feel safe activity around mobile equipment is important. Please rate the *importance of completing the task safely* (Column 1), and then rate the *importance of hearing to the completion of that task* (Column 2), where:

1 = Unimportant, 2 = Somewhat Unimportant, 3 = Neutral, 4 = Somewhat Important, and 5 = Important. Circle the choice that best corresponds to your opinion.

Tasks in which

Column 1

Column 2

SAFE ACTIVITY AROUND

Importance of completing

Importance of hearing

MOBILE EQUIPMENT is important:

the task safely

to completion of task

	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5
	1	2	3	4	5		1	2	3	4	5

Questions about the use of New Technology:

Are any of the following technologies being used at your worksite? If so, is there sound involved or hearing required to properly use the technology? Please add any new technologies that are not listed.

<u>Have available or use?</u>	<u>Hearing component?</u>	
☐ Cellular phone ("hands-free" -- <i>not</i> push-to-talk)	☐ Yes	☐ No
☐ Cellular phone (push-to-talk)	☐ Yes	☐ No
☐ Computer interface with main office	☐ Yes	☐ No
☐ Collision avoidance system	☐ Yes	☐ No
☐ GPS (Global positioning system)	☐ Yes	☐ No
☐ Truck dispatching system	☐ Yes	☐ No
☐ Walkie-talkie	☐ Yes	☐ No
☐ _____	☐ Yes	☐ No
☐ _____	☐ Yes	☐ No
☐ _____	☐ Yes	☐ No

Worksite Problems:

When the following worksite problems are encountered, how do you usually first detect their occurrence? Please add any problems you know of that are not listed.

Circle V for Visual, H for Hearing, S for Smell, F for Feel or Handling, O for Other, or NA for Not Applicable

Hearing-related problems between personnel:

Co-worker requests emergency help	V	H	S	F	O	NA
Co-worker requests work assistance	V	H	S	F	O	NA
General co-worker conversation	V	H	S	F	O	NA

Hearing related problems between ground personnel working around equipment:

Other vehicles dangerously close	V	H	S	F	O	NA
Load shift or loss	V	H	S	F	O	NA
Hearing backup alarms	V	H	S	F	O	NA
Hearing a vehicle's forward horn	V	H	S	F	O	NA
Hearing other vehicle alarms	V	H	S	F	O	NA
Load too close to ground personnel	V	H	S	F	O	NA

Hearing related problems for equipment operators:

Hydraulic failure	V	H	S	F	O	NA
Low equipment fuel/oil	V	H	S	F	O	NA
Overheating of engine	V	H	S	F	O	NA
Load shift or loss	V	H	S	F	O	NA
Mechanical adjustment needed	V	H	S	F	O	NA
Other vehicles dangerously close	V	H	S	F	O	NA

Hearing a vehicle's forward horn	V	H	S	F	O	NA
Hearing other vehicle alarms	V	H	S	F	O	NA
Load too close to ground personnel	V	H	S	F	O	NA

Critical incidents:

Can you think of any particular examples in which you feel that your hearing played an important role in a critical worksite situation, either because you couldn't hear something, or because you did hear something? If so, please describe each incident as fully as possible. Examples might be near-misses or accidents. (Use back of sheet if more room is needed.)

Incident 1:

Incident 2:

Incident 3:

Section II: Your hearing

1. Are you concerned about your noise exposure at work?

☐ Yes ☐ No

If yes, please explain: _____

2. Are you concerned about your ability to hear warning signals at work?

☐ Yes ☐ No

If yes, please explain: _____

3. Are you concerned about your ability to hear co-workers at work?

☐ Yes ☐ No

If yes, please explain: _____

4. Do you feel that hearing is important in your job?

☐ Yes ☐ No

5. If you feel that hearing is important, do you feel that it is also necessary?

☐ Yes ☐ No

6. Do you feel that your worksite is loud?

☐ Yes ☐ No

7. After a workday, do you sometimes have difficulty hearing others talk or find it difficult to hear things (e.g., radio/TV)?

☐ Yes ☐ No

8. Which of the following devices do you use while on a worksite? What brand and model? Please estimate what percentage of the time that you use them during a typical workday.

- ☐ AM/FM/CD (loudspeaker type) brand/model _____ % of workday used _____
- ☐ AM/FM/CD (walkman-type, lightweight headset) brand/model _____ % of workday used _____
- ☐ AM/FM/CD (walkman-type, earmuff headset) brand/model _____ % of workday used _____
- ☐ Communications Radio (walkie/talkie) brand/model _____ % of workday used _____
- ☐ Cell phone brand/model _____ % of workday used _____
- ☐ Earmuff (for hearing protection) brand/model _____ % of workday used _____
- ☐ Earplugs (for hearing protection) brand/model _____ % of workday used _____
- ☐ Other type of hearing protector (specify) _____ % of workday used _____

9. Do you have any known hearing loss? ☐ Yes ☐ No

If yes, how would you categorize the loss?

☐ Mild ☐ Moderate ☐ Severe ☐ Total Deafness

If you have a loss, what do you believe may have caused it (for example, hunting, noisy hobbies, spectator sports, work-related noise, hereditary, other)? _____

Have you had a hearing test? _____
 When was your last hearing test? _____
 What type of test was it?

☐ Audiometric (headphones) ☐ Whisper or similar test ☐ Other _____

What was the result? _____

Do you own a hearing aid? ☐ Yes ☐ No

Do you wear a hearing aid while at work? ☐ Yes ☐ No

Do you wear a hearing aid when *not* at work? ☐ Yes ☐ No

10. Check any of the following hobbies or home activities that you have been involved in:

- ☐ Participation in or live attendance at car races, tractor pulls, etc.
- ☐ Hunting
- ☐ Target shooting, skeet shooting, etc.
- ☐ Woodworking, metal working
- ☐ (Outside of work) using a chainsaw, gas-powered trimmer, snow-blower
 If so, please list make/model _____
- ☐ (Outside of work) using farm and/or construction equipment

If so, please list make/model _____

☐ Riding an all-terrain vehicle, snowmobile, or motorcycle

☐ Other 'noisy' hobbies: _____

11. Check any of the following occupations you have worked in and approximately for how long:

☐ Military how long? _____ ☐ Lumber/furniture industry how long? _____

☐ Boiler operator how long? _____ ☐ Quarry & mining operations how long? _____

☐ Machine shop how long? _____ ☐ Automobile/truck repair how long? _____

☐ Other 'noisy' occupations (specify): _____ how long? _____

12. Do you currently wear any sort of hearing protection device when you are exposed to noise:

At work? ☐ Yes ☐ No

In leisure activities? ☐ Yes ☐ No

Type worn: ☐ Earmuffs ☐ Earplugs ☐ Other (specify) _____

Brand/model worn (if known): _____

THANK YOU FOR YOUR COOPERATION WITH THIS RESEARCH EFFORT.

Appendix C: Informed Consent Forms

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)
AUDITORY SYSTEMS LABORATORY

Informed Consent for Participants of Investigative Projects

Title of Project: Quantification of and Solutions to the Impediments to Speech Communication and Signal Detection in the Construction Industry (Phases 1, 2, 3)

Principal Investigator: Dr. J. G. Casali, Grado Professor & Lab Director, ISE

Research Manager: Dr. Jeff A. Lancaster, Research Assistant Professor & Lab Manager, ISE

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a research study aimed at evaluating the impact of all types of construction noise on the hearing of speech and signals in the construction worksite. The researchers hope to ultimately contribute to the improvement of construction safety in jobs that are hearing-critical in nature. Basically, the research aims to: a) determine what impediments exist to speech communication and the ability to hear other auditory signals (e.g., enunciators, warnings, vehicle reverse alarms and horns, or incidental sounds) on the jobsite, b) quantifying the magnitude of the problems associated with *not* hearing speech and signals, c) determining the types and levels of construction noise from various sources, and ultimately, d) determining and/or developing appropriate interventions aimed at mitigating or removing the impediments, and d) evaluating the interventions to empirically determine their effectiveness. A total of about 100 individuals (both males and females) involved in various aspects of the construction industry are being recruited for the various aspects of this research.

II. PROCEDURES

As a participant in this research, you may be asked to do some or all of the following: provide your opinions in an interview with the experimenter, allow the signals or communications from your work environment to be recorded, allow the work to be observed and/or videotaped, wear a

device that measures noise levels, and perform an audiometric (hearing) test to determine your hearing ability. None of these procedures entails any known risk to you as a participant.

a. Interviews and Observations

An experimenter who is skilled in acoustics and noise issues will conduct all interviews and observations. You should answer honestly and freely in interviews and, in the case of your work and/or equipment being observed or videotaped, you should go about your tasks in normal, routine fashion. In no case will your name or any other identifier be associated with your answers or your observation or recording. If taping is used, those tapes will only be reviewed by the researcher team involved in this study, and will not be available to anyone else, including your employer. The tapes and interview notes will be destroyed after the results are compiled.

b. Dosimetry (personal noise measurements)

You may be asked to wear a portable dosimeter during your workday. A dosimeter is a simply sound level meter which records noise exposure. These devices do not have the capability to record what you say. You may have used one of these devices before, since they are routinely employed to determine noise exposures for OSHA compliance. (Dosimeters will also be placed in noisy areas and in the vicinity of noisy machinery to determine the dose for any individual who must work near the machine for an entire work shift.) These dosimeters are miniature sound level meters that are intended to be worn, are unobtrusive and noninterfering, and they simply record noise levels (nothing else) over the workday. You should not touch the microphone or tap on the keys of the dosimeter as this could ruin the measurement data. There is no danger in dosimeter use.

c. Audiometry (hearing) Tests

You may be given a hearing test to determine your ability to hear faint tones through earphones. As a precursor to this test, you will be asked several questions to assess the general health and condition of your ears. Then you will be given an examination in which the experimenter will look into your ears using an otoscope (a lighted microscope-like device) to determine the condition of your ears. Next, your right and left ear hearing will be tested with very quiet tones played through a set of headphones. You will have to be very attentive and listen carefully for these tones. **Depress the button on the hand-held switch and hold it down whenever you hear the pulsed-tones and release it when you do not hear the tones.** The tones will be very faint and you will have to listen carefully to hear them. No loud or harmful sounds will be presented over the headphones.

It may also be necessary to obtain a bone-conduction threshold in addition to the air-conduction threshold described above. The procedures and your responses will be identical to those described above. The only difference between the two tests are that, instead of wearing headphones, you will be wearing a small vibration transducer placed against the mastoid bone behind your ear or against your forehead. You will hear the same tones you heard during the air-conduction audiogram and you are asked to respond in exactly the same manner. Again,

the tones will be very faint and you will have to listen carefully to hear them; no loud or harmful sounds will be presented during this test.

III. RISKS

There is no risk to you posed by any of the interview or observation techniques that may be employed in gathering information about the nature of construction work with respect to sound and worker hearing, such as hearing of signals and noise. This part of the research is simply to ascertain what important things workers in construction need to hear, and how noise affects that. Likewise, as described above, the dosimeter noise measurement device poses no risk and is routinely used in industry for the same purpose as in this study – to measure noise exposure over the workday.

The audiometric (hearing) tests described above will be conducted in a soundproof booth with the experimenter sitting outside. The door to the booth will be shut but not locked; either you may open it from the inside or the experimenter may open it from the outside. You may communicate with the experimenter by simply talking. You should also know that the earphones for the audiometer are sanitized prior to use for each new participant.

There is no risk to your well being posed by these hearing tests or by the visual ear inspection. Also, realize that they are not designed to assess or diagnose any physiological or anatomical hearing disorders.

You may ask to see and examine any of the instruments used, which would include the audiometer and its earphones, the otoscope, the bone conduction tester, and the dosimeter.

IV. BENEFITS OF THIS RESEARCH

Your participation in this study will provide information that will ultimately be used to assess the impact of noise on hearing signals and speech in construction, and to develop ways of improving worker hearing in construction situations.

No guarantee of benefits has been made to encourage you to participate. You may also receive a summary of the results of this research when completed. Please leave or send a self-addressed envelope if you are interested in the summary. To avoid biasing other potential participants, you are requested not to discuss the study with anyone until six months from now.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. At no time will the researchers release the results of the study to anyone other than the individuals working on the project without your written consent. The information you provide will have your name removed and only a participant number will identify you during analyses and any written reports of the research. Also, as stated above, you will not be identified by name with any tapes that may be recorded in this research, and those tapes will only be reviewed by the research team, after such time they will be destroyed.

VI. COMPENSATION

For participation in this experiment, you will receive \$5.00 for each hour that you participate outside of normal working hours, if this is acceptable to your employer. You will not be compensated for participation during your workday. For example, hearing tests may be conducted outside of your normal working hours (such as before and after work), and would be compensated. Wearing a dosimeter during your workday would not qualify for compensation.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time you have spent in the study. There may also be certain circumstances under which the investigator may determine that you should not continue as a participant of this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the requested activities, and unforeseen danger to the participant, experimenter, or equipment.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial and Systems Engineering.

IX. PARTICIPANT'S RESPONSIBILITIES

I know of no reason why I cannot participate in this study. I have the following responsibilities:

- To answer interview questions accurately and to the best of my ability
- To proceed with my work tasks in routine fashion when being observed
- To wear the dosimeter throughout the requested period and not tamper with its microphone or keypad.
- To listen attentively to the sounds during the hearing tests and to press and release the button with relative accuracy and to follow instructions to the best of my ability.
- To notify the experimenter at any time about discomfort, any concerns, or desire to discontinue participation.

Signature of Participant

X. PARTICIPANT'S PERMISSION

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. Then if you decide to participate, please sign your name on this page and the following pages.

I have read a description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so, being paid only for the portion of the time that I spend in the study.

Signature _____

Printed Name _____

Date _____

The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory and Dr. Jeff Lancaster, Lab Manager. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory Dr. Casali: (540) 231-5073
Room 538 Whittemore Hall Dr. Lancaster: (540) 231-2680

Virginia Tech

Blacksburg, VA 24061

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Dr. David Moore

CVM Phase II (0442)

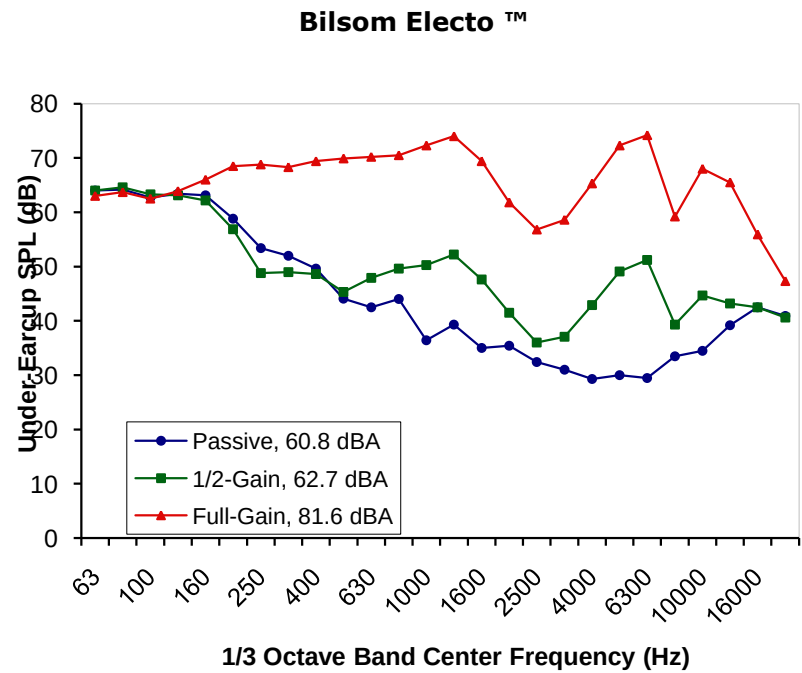
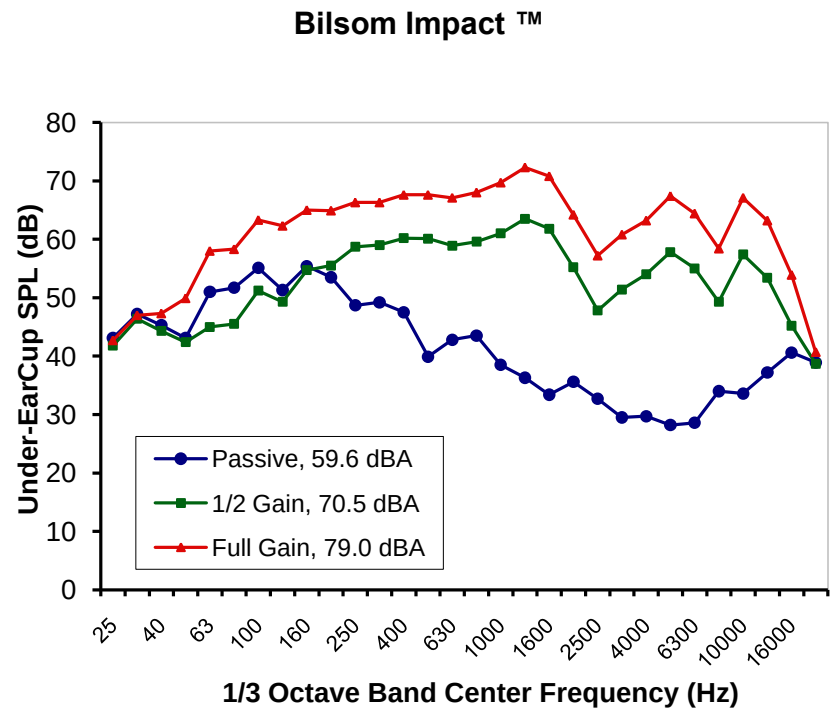
Virginia Tech

Blacksburg, VA 24061

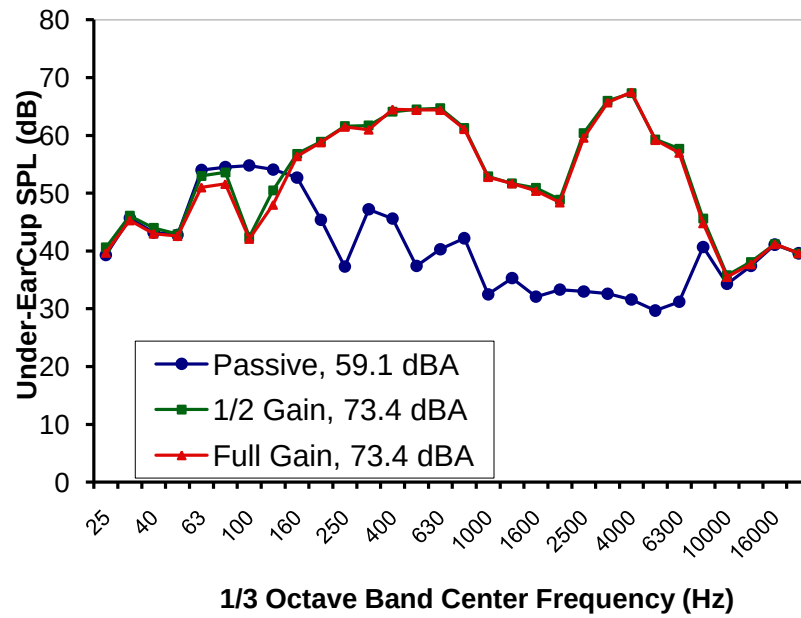
(540) 231-4991

Appendix D: Amplitude-Sensitive Earmuffs Measures in Pink Noise

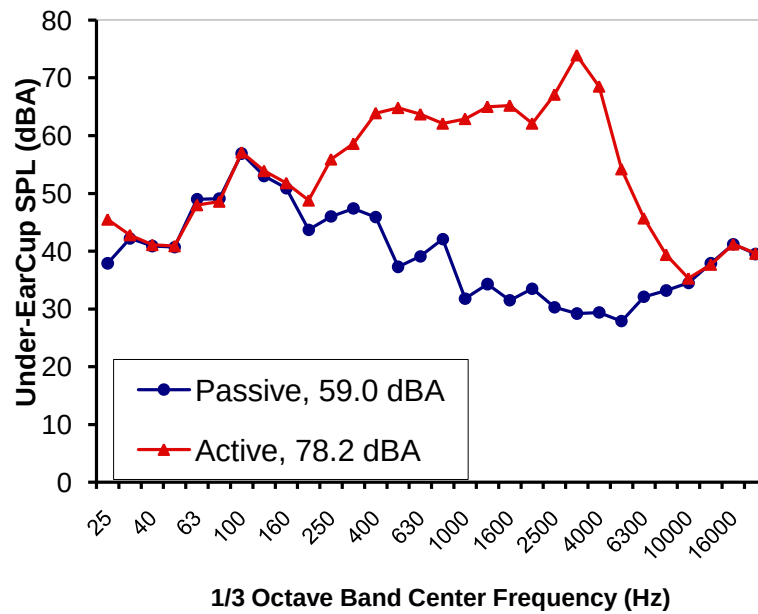
80 dBA Pink Noise: Under-the-headset Levels at Various Gain Settings



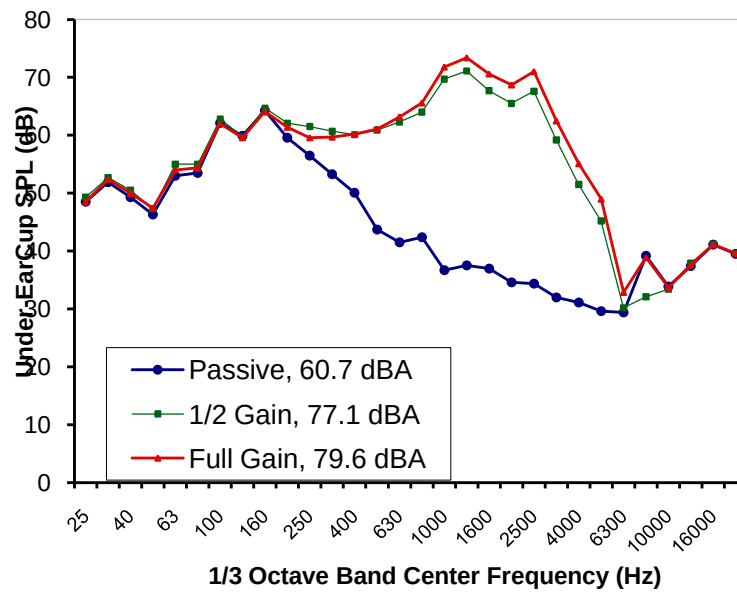
Peltor Tactical Pro™



Peltor Push-to-Listen (PTL™)

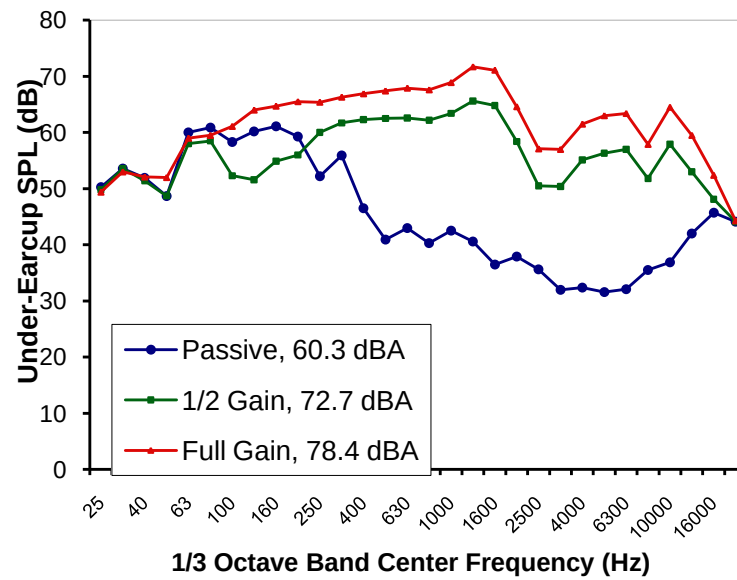


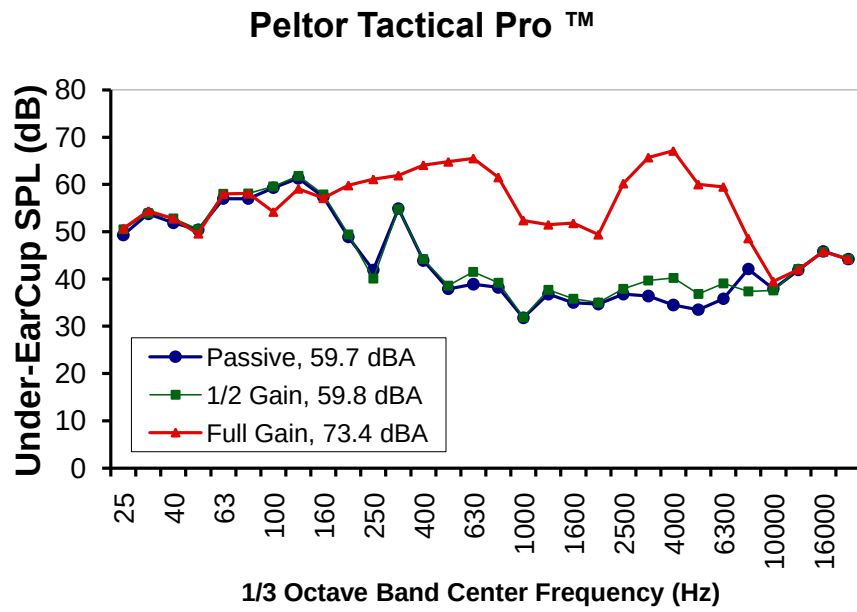
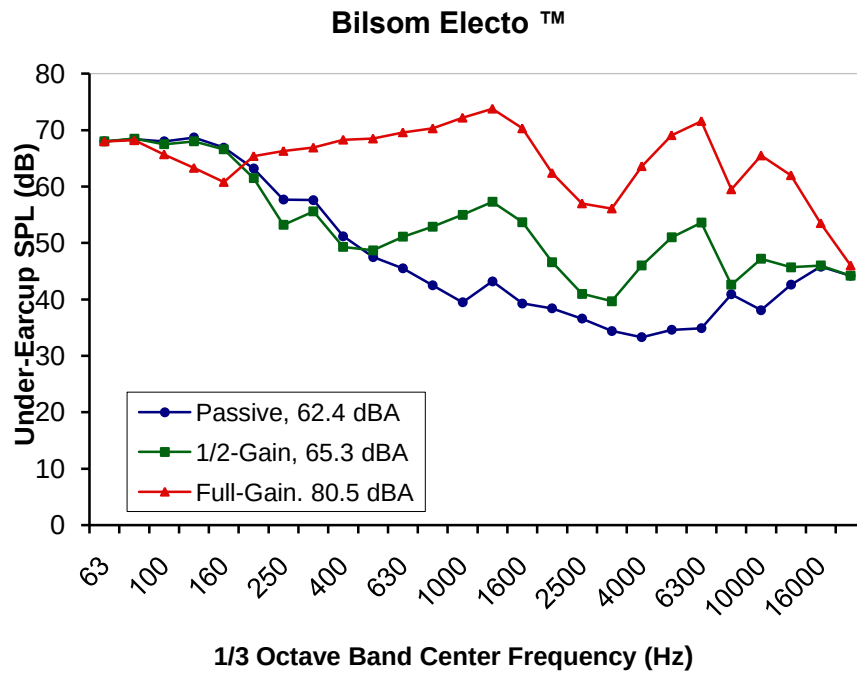
Deben Slim Electronic

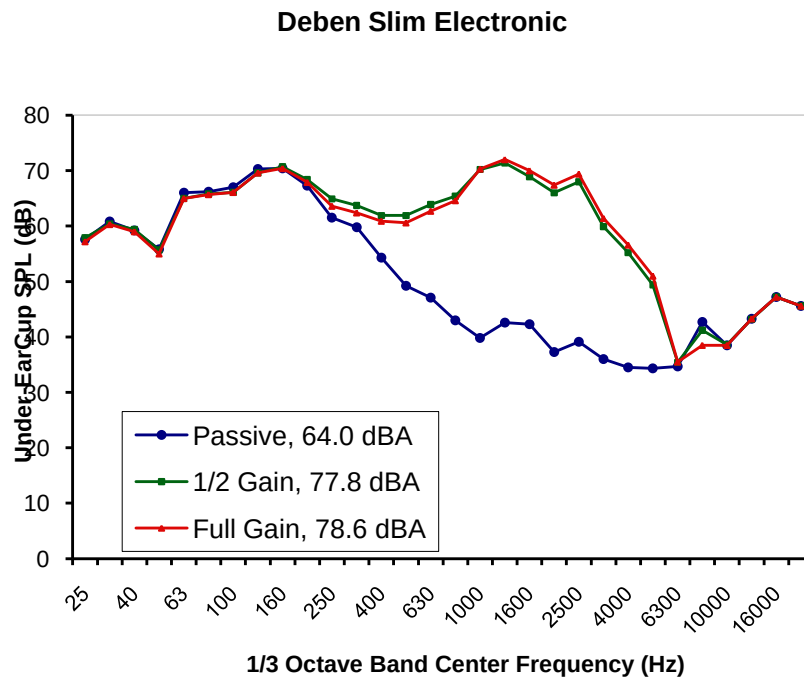
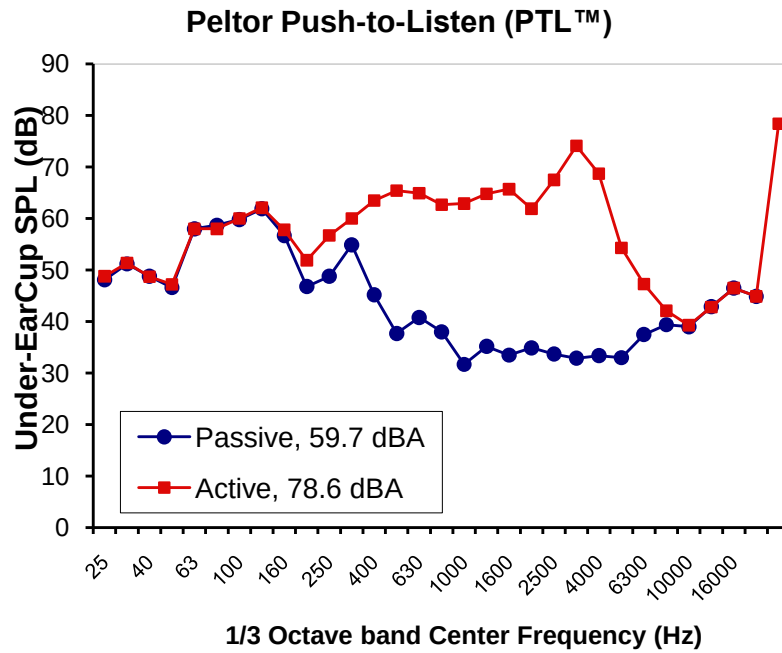


85 dBA Pink Noise: Under-the-headset Levels at Various Gain Settings

Bilsom Impact™







Appendix E: Comfort and Alarm Detectability Rating Scales

Subject: _____ Date: _____ HPD: _____

HOW DOES THE HEARING PROTECTOR FEEL NOW?

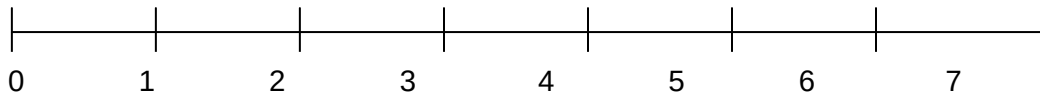
Uncomfortable		Comfortable
	0 1 2 3 4 5 6 7	
Painless		Painful
	0 1 2 3 4 5 6 7	
No Uncomfortable pressure		Uncomfortable pressure
	0 1 2 3 4 5 6 7	
Intolerable		Tolerable
	0 1 2 3 4 5 6 7	
Tight		Loose
	0 1 2 3 4 5 6 7	
Not Bothersome		Bothersome
	0 1 2 3 4 5 6 7	
Heavy		Light
	0 1 2 3 4 5 6 7	
Cumbersome		Not cumbersome
	0 1 2 3 4 5 6 7	
Soft		Hard
	0 1 2 3 4 5 6 7	
Cold		Hot
	0 1 2 3 4 5 6 7	
Smooth		Rough
	0 1 2 3 4 5 6 7	
Feeling of complete isolation		No feeling of complete isolation
	0 1 2 3 4 5 6 7	

Is there a specific feature of the hearing protector that would cause you not to wear it?

Yes _____ or No _____ If yes, what feature or features?

Subject: _____ Date: _____ HPD: _____

**RATE THE LEVEL OF DIFFICULTY IN DETECTING THE BACKUP ALARM SIGNAL UNDER
THE HEADSET YOU ARE WEARING**



Extremely
easy to detect

Extremely difficult
to detect

Appendix F: Procedures for the Backup Alarm Detection Study

1. BEFORE PARTICIPANT ARRIVES

- a. Turn on all of the equipment, and allow warming up for at least 15 min.
- b. Calibrate the testing room.
 - Position measurement microphone stand at head center position.
 - Turn on calibrator, insert microphone.
 - Ensure L/D 2800 analyzer reads 94 dB @ 1 KHz (adjust as needed).
 - Remove microphone from calibrator.
 - Ensure that microphone and stand are at head center position.
 - Adjust noise level of Infinity loudspeakers to pre-labeled volume setting on amplifier (**ensure that all four speakers are outputting noise**).
 - Measure volume setting and adjust amplifier to desired level.
 - Turn off noise.
 - Turn on Klipsch horn backup alarm.
 - Measure/verify frequency of backup alarm to be ~1250 Hz.
- c. Verify the noise spectra for the 1994 CMI PR-500B road-milling machine by referring to measured spectrum.

2. FAMILIARIZATION (THRESHOLD TRACKING TASK)

- a. The experimenter shall verify the noise intensity of the noise (Caterpillar tractor in operation, Sound Effects Vol. 5, Track 19) which should be set at 95 dBA.
- b. The experimenter shall also verify the level of the backup alarm intensity. This should be set at the 95 dBA Masking Noise level on the knob of the amplifier controlling the backup alarm gain.
- c. Once the participant comes in, s/he is greeted and seated in the chair where the threshold monitoring task will occur.
- d. The participant will be fitted with all hearing devices one at a time to make sure that all devices fit properly. If any device does not fit properly, reject participant.
- e. The experimenter will give a verbal description of the overall experiment and the of the threshold monitoring “familiarization” task to the participant.
- f. The participants will be presented with a Peltor H-10A earmuff, which will be fitted by experimenter to ensure proper fit.
- g. The experimenter shall make sure that the participant is seated upright with front leg of the chair directly above the crossed ‘x’ mark on the floor, and that the participant is seated at head center position. Participant is instructed to maintain their head/chin as close to the head center position as possible, and to not move during testing.
- h. The experimenter is seated behind the workstation desk.
- i. The experimenter makes sure that the backup alarm intensity is at its lowest intensity on the laptop wave volume control.
- j. The experimenter plays the backup alarm (looped on windows media player).
- k. The experimenter starts the wave graph on Labview software.
- l. Masking noise in the form of a caterpillar tractor in operation at 95 dBA will be presented.

- m. Once the Masking noise starts, the participant should silently count to five, and on the fifth count, the participant should begin the tracking task.
- n. Participant will track a backup alarm signal using a wheel scroll on a mouse.
- o. Participants given about 30 seconds to complete this task.
- p. The experimenter shall actuate the pause button on windows media player to stop the backup alarm signal
- q. The experimenter actuates the mute button on the amplifier to terminate the masking noise.
- r. The experimenter will save the recorded tracking graph on the computer, and label it according to participant and trial.
- s. The participant shall discontinue the tracking task
- t. Steps h through t are repeated 4 times, for a total of five tracking trials.

3. DATA COLLECTION SESSION

- a. The experimenter sets the specific Masking noise level/type for that session before the participant enters the room (i.e., Step 1 above).
- b. The experimenter shall set the specific level of the backup alarm intensity using volume knob on the amplifier controlling the backup alarm intensity.
- c. Once the participant comes in, s/he is greeted and seated in the chair where the threshold monitoring task will occur
- d. The experimenter will give a verbal description and procedure of the experiment. The participant is presented with the following script to read,
 - 1. *The purpose of the experiment is to investigate the detectability of a backup alarm signal while wearing the earmuffs in different kinds and intensities of noise.*
 - 2. *Once the earmuff is fit on your head, please do not touch or take off the device until you are told to do so by the experimenter.*
 - 3. *Please sit at the desk and position your head/chin such that it is within one inch of the head reference, and do not move your head at any time during the testing.*
 - 4. *Once the Masking noise is presented, please silently count to five and then start the auditory tracking task.*
 - 5. *You should use the mouse scroll wheel in front of you to increase and decrease the backup alarm noise. First, roll the scroll wheel forward to turn the backup alarm volume up to a level where you are completely sure that you hear the alarm. Then roll the scroll wheel backwards, until you no longer can hear the backup alarm. Then turn the backup alarm volume up again, this time to a level that you can just barely hear the alarm, but still sure you can hear the alarm. Then turn the volume down again to a level where you can no longer hear the alarm. Continue this process of increasing the volume of the alarm until you can hear it, and then decreasing the volume until you cannot hear it, over and over, until the noise stops.*
- e. The experimenter will fit the participant with the hearing device.

- f. Once the device is fitted, the experimenter shall raise the lower part of the cup to make sure that the participant's earlobes are completely within the earcup.

BILSOM IMPACT™

- If the hearing device is a Bilsom Impact™, the experimenter should make sure that the amplification knob is fully turned on to its highest level (i.e., full right turn).

PELTOR TACTICAL PRO™

- If the device is a Peltor Tactical Pro™, the experimenter shall press and hold the "on" button on the device for about 3 seconds. The participant is requested to listen for an audible 'beep,' indicating that the device is turned on.
 - The experimenter shall verify with the participant to make sure that the device is indeed on.
 - The experimenter shall press and hold the "+" button for 5 seconds to maximize the gain on the device.
- g. The experimenter shall make sure that the participant is seated straight with front leg of the chair directly above the crossed 'x' mark on the floor, and that the participant's head is centered with the head reference and is about 1 inch from it.
- h. The experimenter is seated behind the workstation desk.
- i. The experimenter makes sure that the backup alarm intensity is at its lowest intensity on the laptop wave volume control.
- j. The experimenter checks both of the amplifier gain settings controlling the Masking noise and backup alarm signal on the amplifiers to make sure they are at the appropriate levels.
- k. The experimenter initiates the backup alarm on windows media player (looped 'on').
- l. The experimenter starts the wave graph on Labview.
- m. The experimenter presents the specific Masking noise for the condition being tested for (i.e., either pink or milling machine noise).
- n. Once the Masking noise starts, the participant should silently count to five, and after the fifth count, the participant should begin the tracking task.
- o. Participant will perform the tracking task using a wheel scroll on the mouse located on the desk in front of them.
- p. Participants given 30 seconds to complete this task.
- q. The experimenter shall actuate the pause button on windows media player to stop the backup alarm signal.
- r. The experimenter actuates the mute button on the amplifier to terminate the Masking noise.
- s. The experimenter will save the recorded tracking graph on the computer, and label it according to participant and trial.
- t. The participant shall discontinue the tracking task.
- u. Steps g through t are repeated 4 more times.
- v. Upon completion of the Masking noise level conditions, the electronics are turned off (if the headset is a sound transmission device).
- w. The participant is asked to exit the room and sit on the chair located outside of the room. The following script will be read the participant before s/he leaves the room, "Please do not remove or adjust the hearing protector during this break. It is important that the fit of the hearing protector be consistent across all trials conducted during a single session." In the meantime, the experimenter sets and

verifies the next Masking noise level/type and the next backup alarm level (based on participant/condition ordering on page 1).

- x. Upon completion of next trial setup, the participant is called back in the room and seated in the chair.
- y. Steps g through v are repeated.
- z. Upon completion of all of the Masking noise level/intensity conditions of the specific headset, the participant is given the semantic differential scale to rate the device's ability to detect the backup alarm.
- aa. Upon completion of the aforementioned scale, the participant is then given a comfort rating scale and is asked to rate the subjective comfort of the hearing device.
- bb. Upon completion of both scales, the headset will be removed from the participant's head by the experimenter.
- cc. The experimenter shall fit the participant with the next headset (again, based on the participant/condition ordering on page 1.)
- dd. Steps d through bb are repeated.

Only on the last day of the experimental sessions

- ee. On the last experimental session, after the participant has completed all of the experimental conditions, s/he is presented with all of the headsets (placed on a table, side-by-side), and is once again given the semantic differential scale to rate the devices' ability to detect signals.

Appendix G: Chipping Hammer Operation

Here, one complete cycle of the piston from an impact to the subsequent impact is analyzed. Generally this type of hammers run at around 30 Hz, therefore one cycle of piston takes around 0.03 seconds. There are many events which happen during one cycle of the piston such as the impact between the chisel and piston, opening and closing of the upper exhaust ports and openings and closing of the lower exhaust ports due to the moving piston. All these events happen in a particular sequence. Therefore, it was important to know the exact and relative timings of opening and closing of the upper and lower exhaust ports and the impact between chisel and piston during a cycle. The opening or closing of the exhaust ports would produce very sharp changes in the exhaust jet velocities and therefore measuring these velocities would tell the exact time of closing and opening of the exhaust ports.

The displacement of the piston at the time of impact was considered as $x=0$. All other displacements are measured with respect to the impact position. The highest displacement of the piston is 102 mm. A number of CAD drawings of the impact hammer consisting of all the major components were prepared to scale as shown in Figure A1(a)-(i). Each drawing has the piston in a different position. The specific position of the piston was chosen very carefully by considering the positions of the exhaust ports as will be explained further. The different positions of the piston are cyclic in nature. Figure A2 illustrates the time history tracking operation of the impact hammer from experimental measurements of the exhaust jet velocities from the upper and lower ports and the chisel accelerations. Black vertical markers named as (a)-(i) drawn on Figure A2 validate the operation of the impact hammer as explained below.

Event (a): Impact ($x=0$)

Impact between the chisel and piston was chosen to be the first event. This was an obvious choice since data from the accelerometers clearly indicate the timings of the impact as can be seen from the instantaneous increase in the chisel accelerations in Figure A2-(a). Secondly the displacement of the piston (displacement at $x=0$) at the time of impact was also known. Also it was known that the piston moves upward after the impact. Figure A1(a) shows the position of piston and dynamic fluid flows routing in the impact hammer at the time of impact. At this point the lower exhaust ports are blocked by the piston, therefore the air jet velocity from lower exhaust ports is almost zero. The upper exhaust ports are open to upper chamber, however the pressure in the upper port is slightly more than atmospheric pressure, and therefore only a small amount of air is coming from the upper ports. At this position the air pressure is being supplied to the lower chamber. During impact, part of kinetic energy of the piston is transferred to the chisel which is then used in the impact process. It should be noted that there is fluid flow leakage around the as shown in Figure A1.

Event (b): Upper exhaust ports close ($x=0.035\text{m}$)

Due to impact the piston is rebounds and starts to move upwards. The supply pressure is still applied to the lower chamber. This high pressure in the lower chamber accelerates the piston in the upward direction. Therefore the piston eventually blocks the upper exhaust ports and the jet velocity through upper exhaust ports drop to zero instantaneously as seen in Figure A2(b).

Figure A1(b) shows the position of the piston and the corresponding dynamic fluid flow routing. Since the upper exhaust ports get blocked the upper chamber becomes a closed volume. After this point the upward moving piston will compress the air inside upper chamber and therefore increase the pressure. The lower exhaust ports are still blocked by the piston. As a result, the jet velocity through the lower ports remains almost equal to zero.

Event (c): Lower exhaust ports open and pneumatic valve flips to apply pressure to upper chamber ($x=0.04\text{m}$)

Lower exhaust port opens up as the piston moves past it. Since the lower chamber is open to the supply pressure, the pressurized air exhausts through the lower ports very quickly and pressure in lower chamber exponentially decays down to atmospheric pressure. as can be seen from Figure A2(c) By this time the pressure in the upper chamber already started to increase due upward moving piston as explained earlier. The increase in upper chamber pressure and decrease in the lower chamber pressure causes the pneumatic valve to flip and now the supply pressure gets applied to the upper chamber. The position of the piston and fluid flow routing is explained in Figure A1 (c)

Event (d): Upper exhaust ports open ($x=0.09\text{m}$)

By this time piston has obtained enough momentum that it moves upwards against the supply pressure in the process increasing the pressure in the upper chamber above supply pressure. The upper exhaust valve opens up to the lower chamber releasing very small amount of air to atmosphere as shown in Figure A2 (d). Sometimes the piston may not able to move past the upper ports. Figure A1 (d) graphically represents the position of the piston and flow routing.

Event (e): Piston attains top position and stars to move down

The piston reaches the top position when its velocity goes to zero due to the resistance from increasing supply pressure, friction between piston and center body and gravity. Immediately it starts to move downwards. Figure A2 (e) represents the approximate timing of the piston reaching the top. The upper and lower exhaust ports remain uncovered at this time. The pressure inside the upper chamber reaches the maximum. The experimental results show that the piston never hits the top. Therefore the volume of the upper chamber never goes to zero which allows the pressure values to remain finite although slightly more than the supply pressure. Figure A1 (e) graphically represents the position of the piston and flow routing.

Event (f): Upper exhaust ports close ($x=0.09$)

The piston accelerates downwards and forces small amount of air out when it passes upper exhaust ports. Then it blocks the upper exhaust ports as shown in Figure A2 (f). The lower exhaust ports are still open. The downward moving piston starts to compress the air gradually in the lower chamber. So there is build up of pressure in the lower chamber. The position of the piston and fluid flow routing is explained in Figure A1 (f).

Event (g): Lower exhaust ports close ($x=0.04\text{m}$)

As the piston moves down the pressure in the lower chamber increases causing more and more air to be released from the lower ports. Finally the lower ports get blocked by the piston and

immediately the exhaust jet velocity goes to zero as shown in Figure A2 (g). After this point the lower chamber becomes a closed volume. The downward moving piston compresses the air in the chamber and therefore increases the pressure. The upper ports remain blocked during this time. As a result the jet velocity from both ports is almost zero. Figure A1 (g) shows the positions of the piston and dynamic fluid flow routing at the same time.

Event (h): Upper exhaust ports open and pneumatic valve flips to apply pressure to the lower chamber ($x=0.035\text{m}$)

Pressure at the top of the piston continues to accelerate it downwards. Upper exhaust ports now get uncovered. Therefore the extremely high pressure in the upper chamber gets released to the atmosphere and the air in the chamber charges out with very high velocity. The pressure in the upper chamber then drops to atmospheric instantaneously as seen in Figure A2 (h). At this point the pressure in the lower chamber already started to increase rapidly is high due to piston moving at high velocity. This creates a back pressure on the pneumatic valve causing it to flip. Therefore the supply pressure gets applied to the lower chamber. Figure A1 (h) graphically represents the position of the piston and flow routing.

Event (i): Impact ($x=0$)

By this point the piston attains very high velocity which allows it to overcome the resistance of the high pressure air in lower chamber. Finally it reaches the lowest point in its travel when it hits the chisel. As can be seen from the Figure A1 (i), the volume of the lower chamber doesn't go to zero at the time of impact due to the geometry of center body which keeps the pressure in the chamber to finite values.

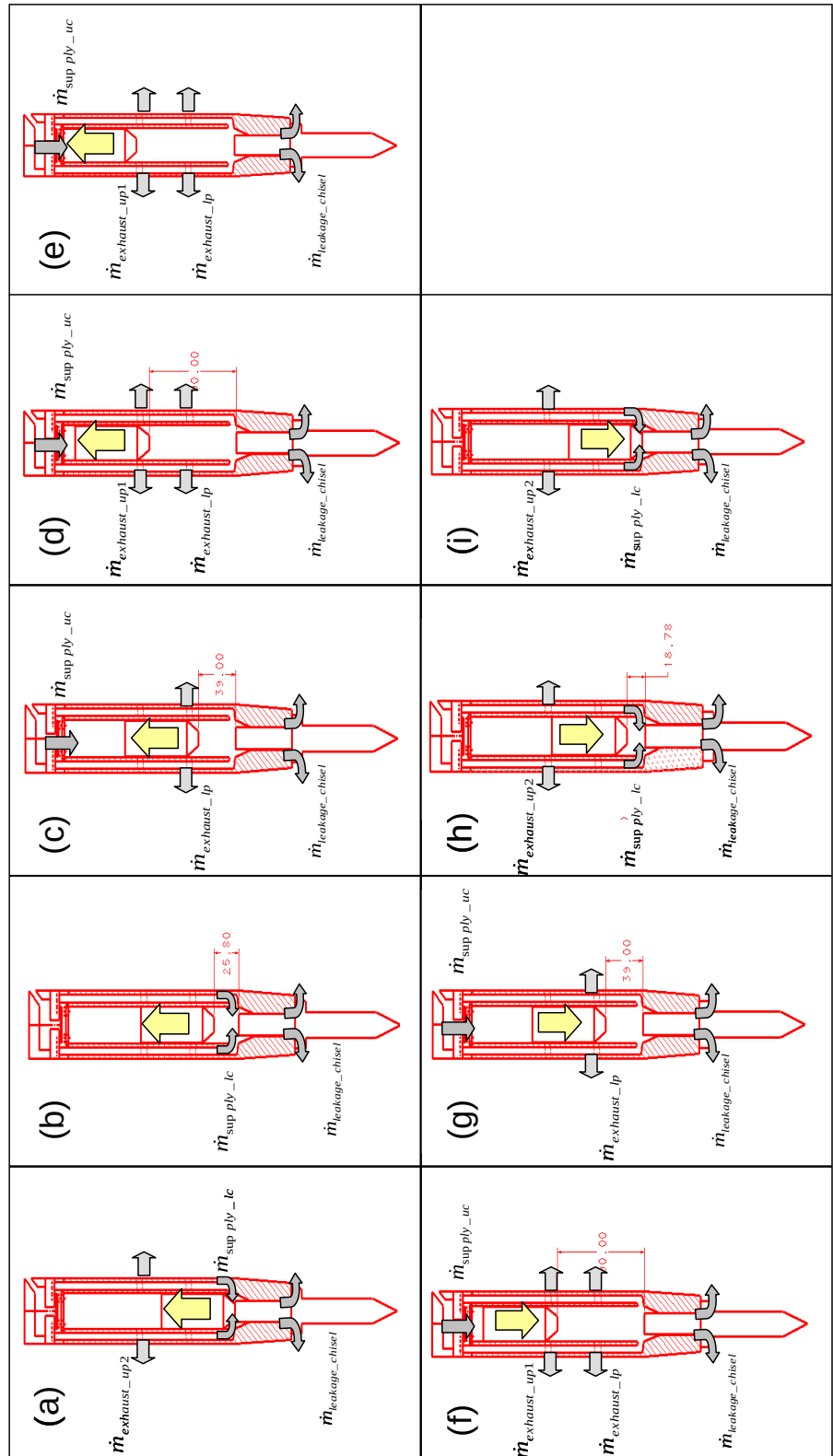


Figure A1: Impact hammers schematic showing its Time history tracking operation from event (a) to (i) and related fluid flow routing.

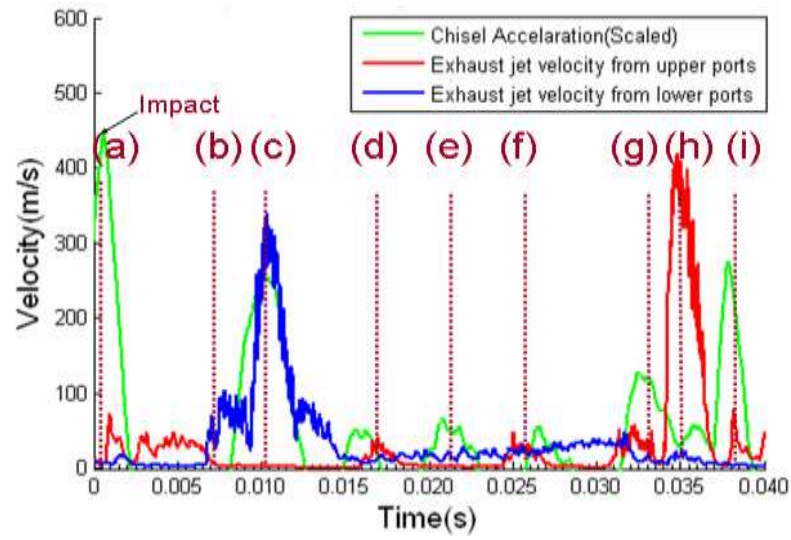


Figure A2: Experimental measurements (exhaust jet velocities and chisel accelerations) of impact hammer showing its Time history tracking operations from event (a) to (i)

Appendix H. Calculation of Stack Drop-Off Locations

For each stack, the drop-off location (x location along the dropping edge) is calculated using the following iterative algorithm. Let $\bar{y}$ = y location of each stack, q_i = x coordinate, final location of panel i (finished structure), v_i = y coordinate, final location of panel i .

1. Find initial stack x coordinate: $\bar{X} = \frac{\sum_i l_i q_i}{\sum_i l_i}$
2. Using $\bar{X}, \bar{Y}$ to calculate all $d_i = \sqrt{(\bar{X} - q_i)^2 + (\bar{Y} - v_i)^2}$
3. Find new $\bar{X}$ with d_i : $\bar{X} = \frac{\sum_i \frac{l_i q_i}{d_i}}{\sum_i \frac{l_i}{d_i}}$
4. If the stack location values have converged to an acceptable level, done. Otherwise go to Step 2.