An evaluation of sound restoration hearing protection devices and audibility issues in mining[1),2)]

Amanda S. Azman[a)] and Roberta L. Hudak[b)]

(Received: 23 May 2011; Revised: 29 September 2011; Accepted: 29 September 2011)

Despite advancements in engineering noise controls and the use of administrative controls, miners are still dependent on hearing protection devices for prevention of noise-induced hearing loss. However, miners often complain of reduced audibility or confusion about identifying spoken words when wearing conventional hearing protectors. This leads to an increased risk of miners being struck by moving equipment or errors in communication with co-workers. Miners will often remove their hearing protectors to overcome these obstacles. To address this problem, electronic technology exists that allows some amount of sound to pass through the hearing protector, therefore restoring some audibility of the passively attenuated sounds. This paper will present the results of testing completed on a selection of four sound restoration hearing protection devices, with the objective of determining if they provide improved speech intelligibility to workers near certain types of mining equipment.

Primary subject classification: 36; Secondary subject classification: 63.3

1 INTRODUCTION

The mining workforce experiences high levels of noise exposure and in turn suffers from high rates of noise-induced hearing loss (NIHL). In fact, the mining sector has the highest prevalence of hazardous workplace noise exposures (76%) among all industrial sectors[1]. Despite engineering and administrative controls implemented to reduce noise, miners continue to exhibit a high prevalence (24%) of hearing difficulty[2]. Therefore, it remains necessary for miners to use hearing protection devices (HPDs) to reduce their chances of acquiring NIHL.

HPD manufacturers have recognized the problems associated with working in environments with high noise levels and the need for workers to hear for proper job performance and safety. In response, technology has been developed aimed at selectively restoring some of the sounds that are normally blocked when conventional HPDs are worn. The devices into which this technology has been integrated are referred to as sound restoration hearing protection devices (SRHPDs).

Because miners often work in noise while still needing to be aware of safety hazards around them, they could benefit from information about the applicability of SRHPDs to their situation. This paper evaluates a selection of SRHPDs to determine if they provide improved speech intelligibility to workers near certain types of mining equipment.

1.1 Background

Hearing protection devices have several drawbacks, including unreliable attenuation unless worn correctly, discomfort for some users, and attenuation that blocks desired sounds along with noise. Specifically, miners have expressed concerns that wearing HPDs inhibits their ability to communicate with co-workers and reduces the audibility of alarms and other auditory warnings. Decreased audibility is not only a communication nuisance but can also contribute to unsafe working conditions. For miners who exhibit hearing loss, the degradation in audibility while wearing hearing protection can be even greater.

Audibility is also degraded by the presence of background noise. This occurs because background noise interferes with the human auditory system's ability to distinguish and process speech and other meaningful sounds. This phenomenon is known as masking. Masking is the interference with a person's ability to detect

[1)] This is the second paper published in NCEJ on the special topic of Noise in Mines.

[2)] The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

[a)] NIOSH, 626 Cochrans Mill Rd, P.O. Box 18070, Pittsburgh, PA 15236, USA; email AAzman@cdc.gov.

[b)] NIOSH, 626 Cochrans Mill Rd, P.O. Box 18070, Pittsburgh, PA 15236, USA; email: RHudak@cdc.gov.

and process one sound because of the presence of a second sound. Further, the masking effect of noise becomes more pronounced as the sound pressure level of the background noise increases and the frequency of the background noise decreases. When the background noise reaches a certain level, speech becomes totally inaudible[3]. The high levels of noise that are often present in the mining environment can mask both speech and warning signals, leading to confusion and potential danger.

1.2 Current HPD and SRHPD Technology and Research

SRHPDs are just one of several types of electronic hearing protectors available today. Each type of electronic hearing protector has a fundamentally different mode of functioning and different intended purposes, therefore an important distinction between the types must be made.

SRHPDs, also known as level-dependent hearing protectors, have one or two microphones outside of the ear cup and a speaker inside. This design allows for the ambient sound to be selectively amplified, thus enabling the audibility of certain sounds while maintaining protection to the worker from hazardous noise levels. The devices are designed to amplify sounds that are considered to be safe for the human ear, typically those below 80 or 82 decibels[3)] sound pressure level (L_p). Below this sound pressure level threshold, the devices provide adjustable amplification to potentially improve audibility. As ambient sound approaches the device's threshold of amplification, the electronic circuitry performs limiting, compression, or other processing to keep the sound transmitted to inside the protector below hazardous levels. The National Institute for Occupational Safety and Health (NIOSH) definition of a hazardous noise level is any noise exposure reaching at least 85 dBA, as an 8-hour time-weighted average. Most of these devices can also be worn in a passive mode with the electronics turned off, functioning as a conventional (passive) hearing protector.

A second common type of electronic hearing protection device involves technology called active noise reduction (ANR), which uses the concept of phase cancellation to reduce the presence of noise under the ear cup. ANR technology reduces or cancels unwanted noise by the addition of a 180-degree out-of-phase electronically generated sound wave. Some ANR devices are designed to provide passive sound isolation and attenuation, while others provide little noise reduction when turned off.

A third common type of HPD technology uses electronic processing to provide protection from impulse noise. These HPDs are designed to block short duration (less than 1 second), high amplitude sound bursts such as gunfire, explosions, or industrial stamping processes. The current study evaluated SRHPDs, but not ANR or impulse HPDs.

Previous research has examined the benefit of SRHPDs for enhanced audibility as compared to conventional hearing protectors or the open ear. Two studies using the Hearing in Noise Test (HINT) found that performance of SRHPDs was approximately the same[4] or worse[5] by comparison to conventional hearing protectors. Other research has shown that subjects with normal hearing perform better on word recognition tasks when using SRHPDs than with the open ear[6] when tested in a loud environment. It is important to note, however, that these studies varied greatly in their research methods, devices tested, and subject population.

1.3 Objective

Based on the above cited research on HPDs and SRHPDs, it has been proposed that SRHPDs may improve audibility for miners as well as for workers in other noisy industries. The objective of the current research is to determine the effect of four types of SRHPDs on the speech intelligibility scores of normal hearing people exposed to three background noises common in the mining environment. Specifically, it is hypothesized that subjects will perform better with an SRHPD in its active electronic mode than when it is functioning as a passive protector. It is also hypothesized that subjects will perform better when exposed to a lower volume background noise than a higher volume background noise. Finally, it is hypothesized that the device with the most sophisticated processing system would have the highest speech intelligibility score.

The current study is the second of two NIOSH studies of the performance of SRHPDs in mining noise. In the first study, an instrumented acoustic test fixture (ATF) was used to measure the output of nine SRHPDs and predict audibility in various background noises with various device settings using the Speech Intelligibility Index (SII)[7]. The experimenters sought devices that had a stated purpose (in their marketing materials or packaging) of improved audibility or communication in high noise environments. Candidate devices were identified through an extensive search of the Internet and contact with known manufacturers of HPDs and other safety products which took place during the spring and summer of 2009. All devices were

[3)] SRHPD specifications vary by manufacturer, therefore the actual limit to amplification varies between 80 and 82 dB L_p on either a linear or A-weighted scale.

purchased in new condition from standard consumer vendors. The results obtained from the SII were used to select a reduced set of devices (from the original group of 9) and conditions for human subject testing in the second stage of research, described here. Because the first study required unweighted sound pressure levels for application of the SII, the second study was also conducted using unweighted values for consistency in methods and results. All references to decibels or sound pressure level (L_p) throughout the paper are unweighted unless otherwise specified.

2 METHODS

2.1 Subjects

This laboratory experiment evaluated the audibility performance of four types of SRHPDs set to specific outputs as tested on human subjects in mining background noise. Potential subjects were recruited from a subject pool maintained by NIOSH. The pool consisted of non-NIOSH employees who had been recruited through postings at local businesses and by word of mouth. An otoscopic exam of each potential subject's ears was conducted to rule out any blockage, infection, or other condition that could affect audibility. Normal hearing sensitivity was required for participation. To ensure that each potential subject had hearing sensitivity better than or equal to 20 dB HL, audiometric testing that followed the modified Hughson-Westlake procedure[8] was conducted using a Welch Allyn GSI 61 2-channel clinical audiometer[9] and TDH-50 earphones. Middle ear function was assessed by a licensed audiologist using a Welch Allyn GSI 33 middle ear analyzer. All potential subjects with normal hearing sensitivity also exhibited middle ear function within the range of normal. All screening procedures were conducted by a licensed audiologist or CAOHC-certified occupational health nurse. The NIOSH-required Human Subject Review Board approvals were obtained prior to the start of subject testing. Thirty subjects aged 18 to 55 (mean 32 years old, median 30 years old, with 22 females and eight males) passed the required screening measures and were enrolled in the study. The subjects were reimbursed at a standard rate for their participation.

2.2 Devices Under Test

Based on the results from the prior evaluation of nine devices by Azman and Yantek[7], four devices were selected for subject testing. These devices were labeled as devices 1, 2, 3, and 4. Two of the devices had output adjustment knobs and two had buttons. Device 1 was the most expensive with many proclaimed advanced features. Device 2 was from a widely known hearing protector manufacturer. Device 3 is permissible for use in underground coal mines. Device 4 was manufactured by a company that produces a variety of mining health and safety products.

Three samples of each type of device were used, for a total of 12 sample devices. All 30 subjects were tested using all four devices in all research conditions. A subject used the same device sample for all tests of that particular device, and each device sample was used by 10 subjects.

2.3 Experimental Paradigm and Stimuli

The Modified Rhyme Test (MRT) was the testing paradigm implemented. The procedure in ANSI S3.2-2009[10] was used as guidance; however deviation from the standard was necessary. The lengthy practice and training time required within the standard was not implemented because it, in addition to multiple conditions of testing would have led to an overly long test protocol that could have created concerns for subject fatigue. Even without the training and practice time stated in the standard, the test sessions neared six hours for some subjects. Also the minimum number of talkers stated within S3.2-2009 was not implemented because it requires an equal number of talkers and listeners. For this situation, it was more important to have a consistent speech stimulus and was not realistic to have 30 talkers to equal the 30 listeners (subjects) participating in the study.

The MRT is useful for this purpose because it is designed to determine speech intelligibility of communication systems. This closed-set response test was developed by House et al.[11] and has been shown to yield self-consistent and reliable results[12]. The MRT has demonstrated sensitivity to degraded speech and has been used successfully with human and digitally altered speech stimuli both in reverberation and in noise. Other standard hearing protector tests, such as ANSI S12.6-2008[13], determine the attenuation of hearing protectors, but were not implemented because quantification of attenuation was not the purpose of this study.

The MRT consists of 50 six-word sets of monosyllabic English words that vary on either the first or the last sound. The listener is shown a printed list of 50 six-word sets from which to choose a pre-recorded, spoken target word, which is always among the six listed words. The target word is presented, then there is a brief pause while the listener chooses between the options, then the next target word is spoken. This is repeated for all 50 targets of a particular list. Figure 1 illustrates an example of three six-word sets from an MRT list that was used in this study. A full test list

List 7

1	shop	mop	cop
	top	hop	pop
2	ray	raze	rate
	rave	rake	race
3	wick	sick	kick
	lick	pick	tick

Fig. 1—Example of the first three six-word sets of list 7 of the modified rhyme test. One word from each set is the spoken target word which was circled or highlighted by the subject.

contains 50 of these sets. The 50 six-word sets were randomly ordered into 40 lists, each set with a randomly-determined target (spoken) word.

Listener responses can be scored as (1) the number of words heard correctly; (2) the number of words heard incorrectly; or (3) the frequency of particular confusions of consonant sounds. For the purposes of the current study, the MRT was scored by percentage of correct responses (e.g., 35 correct out of 50 stimuli would be 70% correct). This provides a simple means for comparing performance across devices.

The MRT stimuli were recordings of spoken target words generated during previous NIOSH work. For the current project the MRT target words were adjusted to 82 dB L_p as measured by a Bruel and Kjaer 4188-A microphone hanging in the center of the booth routed through a National Instruments PXI 4462 4-channel data acquisition system, and analyzed by a Nelson Acoustics *Trident* acoustic analysis software package. The *Trident* software provides a real-time display of the sound pressure levels in the booth as well as one-third octave band data.

It is recognized that this stimulus sound pressure level is louder than the volume at which speech would typically occur. However, speaking with a raised voice is a realistic occurrence in noisy environments, and this level is in accordance with the standard speech spectrum level of 82 dB L_p identified as "shout" in ANSI S3.5-1997[14]. This was also the speech level used for the prior NIOSH SII study; therefore the same level was used in the current human subjects study for consistency.

Sounds from the mining environment served as the background noise for the MRT testing. These noises were recorded by NIOSH researchers during earlier field studies. The recordings consisted of noise from continuous mining machines (CMM) and roof bolting machines (RBM), which are common sources of noise overexposure in underground coal mining. The original recordings consisted of sound from operating modes of the CMM and RBM, but also occasionally included workers' voices and other extraneous sounds. The sound files were edited for time and content to contain 30 seconds of the sound emitted during the desired mode of operation of the machine. The background noise levels were adjusted to 80 dB 30-second L_{eq} for the CMM cutting/conveying and the RBM drilling, and to 78 dB 30-second L_{eq} for the CMM tramming. The range of L_p within the 30-second L_{eq} for the CMM cutting/conveying and the RBM drilling was 79.5–80.5 dB while the range of L_p for the CMM tramming was 76.5–79 dB. These levels were measured in the center of the booth by the same 4188 microphone and the *Trident* software. The 30-second clips were looped to yield background noise files that were 4.5 minutes in length. Spectral analysis of the noise files showed that the noises varied in spectral content as well as L_p. Figure 2 shows that the RBM noise contains relatively more high frequency content than the two CMM noises.

The background noises were then digitally merged with MRT stimulus words so that synchronization of the words in relation to the start and stop of the background noise was consistent for all test lists. This was done to yield 40 test lists that had equal timing for the start and stop of the target words as well as equal timing for the start of each individual test word in relation to the background noise. The background noise started 10 seconds prior to presentation of any target words of the MRT test list and stopped 10 seconds after the end of the list. The combined background noise/MRT stimulus test lists were saved as 40 individual files for use during the subject testing.

2.4 Testing Apparatus

All research took place in the Auditory Research Laboratory located at the NIOSH Pittsburgh facility. All testing occurred in a double-walled sound-treated hearing test booth. The stimuli sound sources were stored as lossless digital files and were played from a desktop personal computer. Sound sources were routed into the test booth through an MPX 300 amplifier and a GSI clinical audiometer. The audiometer was used to adjust stimulus intensity to 1 dB accuracy. The sound-treated booth was outfitted with two diagonally-situated Cambridge Soundworks Model 6 speakers from which the test stimuli were presented. Sound pressure levels of the combined stimulus words and background noise inside the test booth were confirmed using the same microphone and data acquisition system mentioned previously.

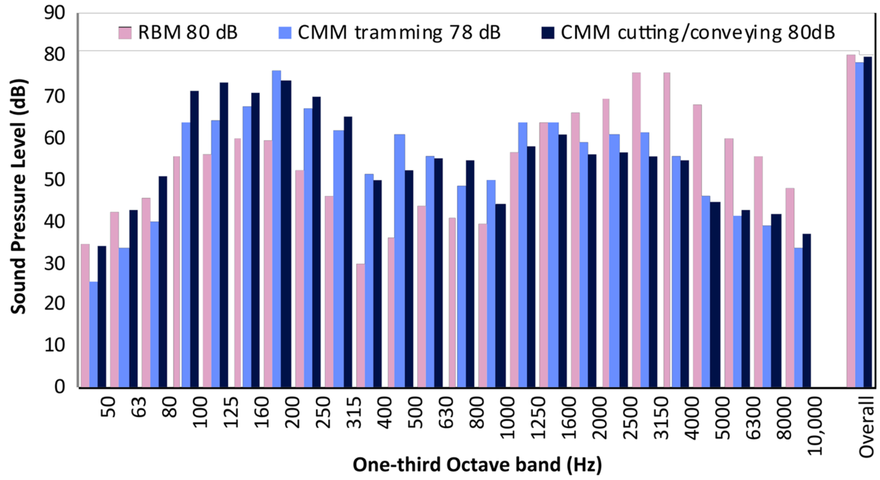

Fig. 2—Unweighted frequency spectra of the 3 background noise sources. Notice that the CMM noises contain more low frequency content than the RBM noise.

3 PROCEDURE

Subjects were tested using the MRT while seated in the center of the test booth in a non-absorptive chair with a small desk on which their response sheet and writing tool were located. All SRHPDs were fitted on the subjects by a researcher. The researcher also manipulated the output control of the SRHPD to the desired position. Each subject was tested in nine conditions for each of the four devices across either one or two sessions. The conditions for testing each of the four devices were the three noise types (CMM cutting and conveying 80 dB, CMM tramming 78 dB, or RBM drilling 80 dB) by the three device settings (passive, 1/4 output, 3/4 output) which resulted in 36 conditions. For each condition, a separate test list was used. Four additional test lists were used as practice lists before beginning testing.

In accordance with the MRT, the subjects selected, by circling or highlighting, a spoken target word from a closed set of words that were visually displayed on sheets of paper. The test lists were presented from the speakers in the test booth. The spoken target words began after 10 seconds of background noise with each utterance lasting approximately 1.5 seconds with a 3-second pause between each utterance. The carrier phrase *mark the* ____ *now* was used in all conditions. During the 3-second pause between words, the background noise continued. Subjects were instructed to mark the target word from a response list containing the 50 six-word sets. The sets were numbered 1–50 and matched the auditory presentation order. There was a 1–3 minute break between each word list while the hearing protector and response sheet were changed by the researcher. Testing was monitored through a window in the test booth to ensure that the subjects remained on the correct six-word set as the list progressed. Subjects were instructed to guess at the word when they could not discern it. This procedure was done for all 36 test lists and the practice lists. The list order, SRHPD model used, SRHPD setting used, and background noise were all randomized. Although subjects often made comments regarding test conditions or their performance, no feedback was given by the researchers regarding correctness of responses or difficulty of listening conditions.

The study resulted in 1080 response lists derived from testing 30 subjects on 36 different test lists (the practice lists were not used in the final analysis). The paper copies of all results were scored by two research assistants. There was no threat of bias in scoring based on knowledge of the test procedure, condition, or subject because the chosen word was either correct or incorrect. The results were coded and entered into electronic format by another researcher with 20% of the results checked for accuracy by the primary researcher. Devices were coded as 1, 2, 3, and 4; noises were coded as 1 for CMM tramming, 2 for RBM drilling, and 3 for CMM cutting/conveying; settings were coded as 0 for off/passive, 1 for 1/4 of output, and 3 for 3/4 of output.

4 RESULTS

A 3x3x4 analysis of variance (ANOVA) was used to test the hypotheses with *score* as the dependent variable and *noise*, *setting*, and *device* as the independent variables. ANOVA can also be used to detect interaction effects, although none were hypothesized. Table 1 shows the mean performance scores represented as speech intelligibility scores for each category of the

Table 1—*Mean performance scores represented as speech intelligibility for each level of the independent variables when collapsed across all other variables.*

INDEPENDENT VARIABLE	Mean Performance Score	Standard Deviation
NOISE		
Tramming	88.59	5.17
Drilling	73.14	6.79
Conveying	66.18	8.65
SETTING		
Passive	76.84	11.19
1/4 output	76.90	11.60
3/4 output	73.95	12.06
DEVICE		
1	76.15	11.66
2	76.60	11.28
3	76.20	11.33
4	74.92	11.76

independent variables. The largest difference in mean speech intelligibility scores was found between the categories of the *noise* independent variable (22% change from highest to lowest score). The difference is much less from the highest to lowest mean scores within the *setting* and *device* independent variables (3% for setting and less than 2% for device).

While the ANOVA found that all three main effects were statistically significant, no interaction effects reached significance. The first hypothesis predicted that performance scores would be the lowest (poorest) with setting 0 (passive) compared to settings 1 (1/4 output) and 3 (3/4 output). The analysis showed that the effect of *setting* reached statistical significance, F $(2, 1044) = 10.734$, $p < .001$, however the effect was small from a practical standpoint. The Bonferroni post hoc test[15] revealed that subjects scored 3% lower when using setting 3 (3/4 output) than either settings 0 (passive) or 1 (1/4 output). This result is contrary to the hypothesis that subject performance would improve when the SRHPDs were in the active mode.

The second hypothesis predicted that performance scores would be higher (better) in the background noise with the lower L_p than in the other background noises. Specifically, performance would be better in the CMM tramming background noise than the RBM drilling or CMM cutting/conveying background noises. The analysis revealed a statistically significant effect for noise F $(2, 1045) = 1018.251$, $p < .001$. The Bonferroni post hoc test revealed that subjects scored 15% better when exposed to background noise 1 (CMM tramming) compared to noise 2 (RBM drilling) and 22% better in background noise 1 than background noise 3 (CMM cutting/conveying). The difference in average scores of 7% between background noises 2 and 3 also reached statistical significance.

The third hypothesis predicted that performance scores would be higher (better) when subjects used device 1 than when using devices 2, 3, or 4. The analysis revealed a statistically significant effect for device F $(2, 1045) = 1018.251$, $p < .001$. Contrary to hypothesis 3, the Bonferroni post hoc test revealed that subjects using device 2 scored 1.7% higher than subjects using device 4. There were no other statistically significant differences between devices.

5 DISCUSSION

The most notable differences in speech intelligibility occurred between the three noise sources. When collapsed across all variables, better performance was obtained in the lower level background noise as illustrated in Fig. 3. The best speech intelligibility was obtained in the CMM tramming at 78 dB background noise regardless of device type or setting. Again, this was the background noise with the lowest presentation L_p. This suggests that regardless of the device used or the setting of the device, better performance occurs in relatively low background noise situations, which is contrary to user expectations that the devices are most beneficial in high noise settings. Also evident in Fig. 3 is that within each background noise, mean performance varied by approximately 5% or less. That is, little difference can be noted by device or device setting within each type of noise.

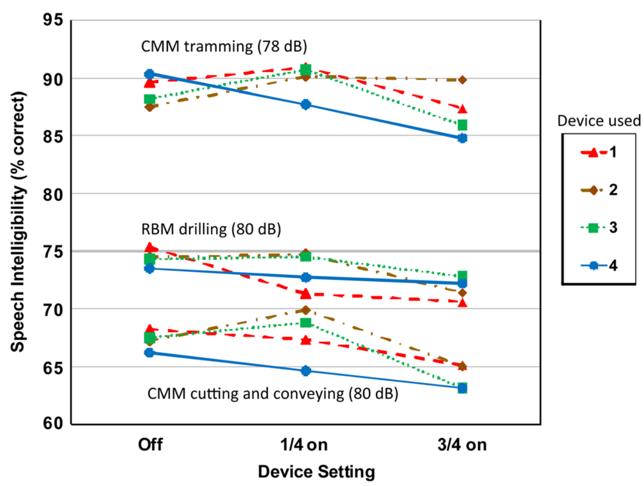

Fig. 3—Graph indicating that speech intelligibility results varied the most by background noise source.

Smaller differences are noted in speech intelligibility scores between device settings; however, these differences are contrary to an expectation that higher settings would increase performance. The best performance was found when the device was turned off or at 1/4 of its output. In working conditions, many users will be tempted to turn the devices to maximum output under the impression that they will receive maximum benefits. Clearly, this is not the case, as can be seen in Figs. 4, 5 and 6. For all of the noises and devices evaluated, performance was the worst when the device was at the maximum output setting.

While the results indicate statistical significance, one must also consider the practical significance of these findings. Many of the performance differences were on the order of 1–2 words, or 2–4 percentage points. This small difference in speech intelligibility is unlikely to have a dramatic effect on the ability of a miner to comprehend spoken language. Further, none of the devices or conditions neared 100% speech intelligibility, but they all remained at 50% or better.

Although there is a clause within S3.2-2009 to calculate MRT scores with a correction for subjects guessing the correct word, this calculation was not included in the analysis. The application of the correction factor reduces scores by a ratio of the number of incorrect choices. The correction for guessing would be applied to all test conditions and would affect all of them to approximately the same degree. Therefore, it is unlikely that that inclusion of the correction factor would change the relative results based on comparisons across conditions.

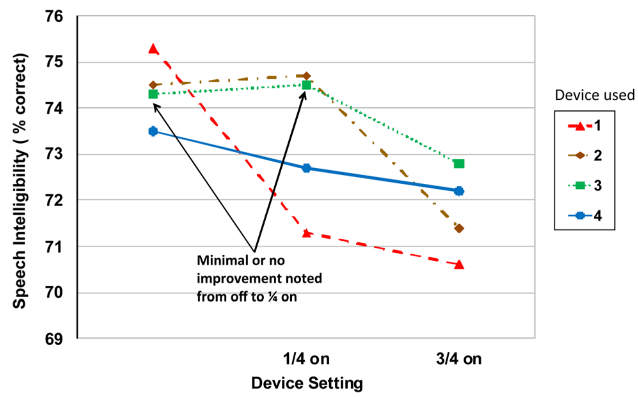

Fig. 5—Speech intelligibility scores for the various devices and settings in background noise source RBM drilling 80 dB .No improvements can be noted from off to 1/4 or 3/4 on.

The intent of this study was to evaluate SRHPD performance in various mining noises. The main noise characteristic of interest was the L_p at which the background noises were presented, however the frequency spectra varied as well (see Fig. 2), which is common with real-world noises. While the best performance was observed for the lowest noise L_p (as expected), a smaller effect was also found between noises at the same L_p, but with different spectral content. The current study was limited to just the three different noise samples, which is insufficient to fully explore the interaction between noise spectral content, L_p, device processing characteristics, and audibility. Future studies should consider including noise samples from more types of

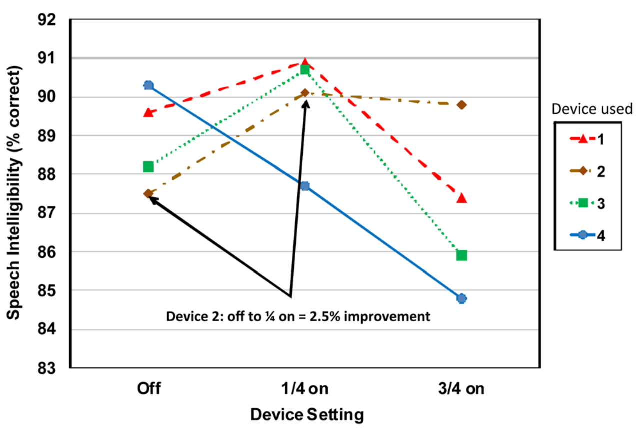

Fig. 4—Speech intelligibility scores for the various devices and settings in background noise source CMM tramming 78 dB. Small improvements can be noted with some devices from off to 1/4 on, but no additional improvement is noted from 1/4 on to 3/4 on.

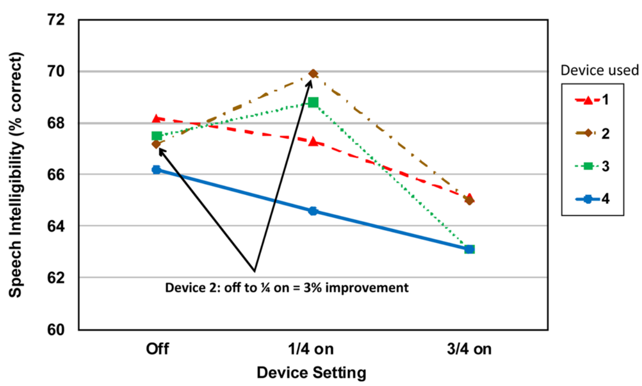

Fig. 6—Speech intelligibility scores for the various devices and settings in background noise source CMM cutting/conveying 80 dB. Small improvements can be noted with some devices from off to 1/4 on, but no additional improvement is noted from 1/4 on to 3/4 on.

machinery that encompass a broader range of spectral content and L_p. To gain more control over within-subject performance, future studies should also consider acquiring a baseline of speech intelligibility in a quiet setting to identify each subject's decrement due to noise and improvement (if any) due to SRHPD processing.

A final limitation lies within the presentation of the background noise and MRT words within the test chamber. The mining background noises and the MRT words were digitally mixed and presented as a monaural signal through the two loudspeakers in the test chamber. This presentation eliminated any opportunity for subjects to use spatial cues to differentiate between the speech and noise sounds. In some mining settings, workers are very close to a machine noise source while speech occurs at a distance. In other cases, machine noise may be at a distance while the worker is listening to speech from a nearby coworker. In each of these cases, directionality cues and cues related to the acoustic environment (e.g., reverberation) could affect the relative audibility of speech in noise. Greater control over these factors could be attained by simulating the environment through a multi-loudspeaker arrangement. Near field sounds (e.g., speech from a nearby colleague) could be represented by having the sound emanate from a single loudspeaker in the array. Although the simpler two-loudspeaker monaural configuration used in the present study could have lowered overall absolute audibility scores, it is unlikely to have resulted in any systematic bias in the relative findings. Because the study was intended to assess relative performance of SRHPDs in various conditions, a factor that has a uniform effect is not a significant concern. Still, a more realistic multi-loudspeaker setup would be useful in future studies, especially if devices are developed with spatial processing capabilities.

6 CONCLUSIONS

Sound restoration hearing protection devices, or level-dependent hearing protectors, do not appear to provide a simple across-the-board solution to improving audibility for workers in mining. The devices show small potential benefits when worn in specific ways in certain noise situations, but those situations must be carefully assessed for workers to enjoy the benefits of wearing SRHPDs, as follows:

- SRHPDs provide the most benefit for speech intelligibility in background noise levels that may not cause a worker to reach the NIOSH recommended exposure limit (85 dB(A) as an 8-hour time-weighted average with a 3 dB exchange rate). This testing was done with background noises of 78 or 80 dB L_p. The previous instrumented SII study[6] employed a background noise of 95 dB L_p, which is a more typical sound pressure level for operators of continuous mining machines. With the CMM noise at 95 dB, it was estimated that speech cues would be almost totally inaudible despite the processing technology because of the powerful masking effect of the noise.
- SRHPDs provide the most benefit at lower output settings. Wearers must be aware of the output levels to which they adjust the devices. Wearers should listen to ambient sounds through the devices while they adjust them and recognize that they can make additional output adjustments as the ambient noise changes.

A recent study investigating the benefits of active versus passive hearing protectors has revealed similar results[16]. The results of this study found that speech recognition of active and passive HPDs was highly dependent on the background noise implemented. Additionally, the passive hearing protectors improved speech recognition at higher stimulus sound pressure levels. Variation among devices and settings was found to which the authors recommended trial of the devices in various sound environments.

Although limited benefits may be obtained from SRHPDs by workers who are constantly exposed to high levels of noise, one must also consider the potential benefits of SRHPDs for workers who are intermittently but repeatedly exposed to hazardous noise throughout their working shift, or those who have noise exposure at the lower end of the hazardous continuum (85–89 dBA 8-hr TWA). Research has shown that in various heavy industries such as road construction, sheet metal stamping, and lumber milling, the use of hearing protection is highest when noise exposure is relatively high and exposure is continuous[17]. Workers who are only intermittently noise-exposed or those at the lower exposure levels are less likely to maintain HPD use, especially in situations where they feel that the noise has dropped below a hazardous level. The use of SRHPDs would allow for those workers to maintain some amount of audibility while protecting their hearing in intermittent or lower-level hazardous noise.

The results of this study show that when exposed to lower level noises, wearers of SRHPDs continue to identify speech well when the devices are set to a low output. Because the devices allow ambient sound to pass through, with proper training on device use, workers may be less likely to remove their hearing protectors to communicate when they are in relatively quieter conditions that they might consider non-hazardous. Continued use of hearing protectors in these conditions has two benefits to the worker. First, they will not forget to reapply their hearing protectors, nor reapply them incorrectly, if they have not been removed. Second, and perhaps most importantly, workers will not have to make judgments regarding the "safety" of a particular noise environment. Workers can continue to wear their hearing protectors and maintain levels of communication and protection in situations where they may have previously removed their HPDs.

7 REFERENCES

1. S. Tak, R. R. Davis and G.M. Calvert, "Exposure to hazardous workplace noise and use of hearing protection devices among US workers- NHANES, 1999-2004", *Am. J. Industr. Med.*, **52**, 358–371, (2009).
2. S. Tak and G. M. Calvert, "Hearing difficulty attributable to employment by industry and occupations: An analysis of the national Health Interview Survey- United States, 1997–2003", *J. Occup. Environ. Med*., **50**, 46–56, (2008).
3. G. Kidd, "Psychoacoustics", Chap 3 in *Handbook of Clinical Audiology*, 5th Edition, edited by Jack Katz, Lippincott Williams and Wilkins, Baltimore, MD, (2002).
4. T. Dolan and D. O'Loughlin, "Amplified earmuffs: Impact on speech intelligibility in industrial noise for listeners with hearing loss", *Am. J. Audiology*, **14**, 80–85, (2005).
5. P. Plyler and M. Klumpp, "Communication in noise with acoustic and electronic hearing protection devices", *J. Am. Acad. Audiology*, **14**(5), 260–268, (2003).
6. S. Arlinger, "Speech Recognition in Noise When Wearing Amplitude-Sensitive Ear-Muffs", *Scand. Audiology*, **21**(2), 123–126, (1992).
7. A. Azman and D. Yantek, "Estimating the performance of sound restoration hearing protectors by using the speech intelligibility index", *2010 Int. Mech. Eng. Cong. and Expos*., (2010).
8. R. Carhart and J. Jerger. "Preferred method for clinical determination of pure-tone thresholds", *J. Speech and Hearing Dis*., **16**, 340–345, (1959).
9. *Specifications for audiometers*, American National Standards Institute ANSI S3.6-1996, (1996).
10. *Method for Measuring the Intelligibility of Speech over communication systems*, American National Standards Institute. ANSI S3.2-2009, (2009).
11. A. House, C. Williams, M. Hecker and K. Kryter, "Articulation testing methods. Consonantal differentiation in a closed response set", *J. Acoust. Soc. Am*., **37**, 158–166, (1965).
12. C. Williams and M. Hecker, "Electing an intelligibility test for communication system evaluation", *J. Acoust. Soc. Am*., **42**(5), 1198, (1967).
13. *Methods for Measuring the Real-Ear Attenuation of Hearing Protectors*, American National Standards Institute ANSI S12.6-2008, (2008).
14. *Methods for Calculation of the Speech Intelligibility Index*, American National Standards Institute ANSI S3.5-1997 R, (1997).
15. G. Glass and K. Hopkins, "Multiple Comparisons and Trend Analysis", Chap 17 in *Statistical Methods in Education and Psychology, 3rd Edition*, Allyn & Bacon, Needham Heights, Massachusetts, (1996).
16. A. Bockstael, et al, "Speech recognition in noise with active and passive hearing protectors: A comparative study", *J. Acoust. Soc. Am*. **129**(6), 3702–3715, (2011).
17. W. Daniel, S. Swan, M. McDaniel, J. Camp, M. Cohen and J. Stebbins, "Noise exposure and hearing loss prevention programs after 20 years of regulations in the United States", *Occup. Environ. Med*., **63**, 343–351, (2006).