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Visual feedback system to reduce errors while operating roof bolting machines

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Abstract

Problem—Operators of roof bolting machines in underground coal mines do so in confined spaces and in very close proximity to the moving equipment. Errors in the operation of these machines can have serious consequences, and the design of the equipment interface has a critical role in reducing the probability of such errors.

Methods—An experiment was conducted to explore coding and directional compatibility on actual roof bolting equipment and to determine the feasibility of a visual feedback system to alert operators of critical movements and to also alert other workers in close proximity to the equipment to the pending movement of the machine. The quantitative results of the study confirmed the potential for both selection errors and direction errors to be made, particularly during training.

Results—Subjective data confirmed a potential benefit of providing visual feedback of the intended operations and movements of the equipment.

Impact—This research may influence the design of these and other similar control systems to provide evidence for the use of warning systems to improve operator situational awareness.

Keywords

Mining; Control compatibility; Equipment design; Situational awareness; Visual feedback system

1. Introduction

Roof bolting stabilizes the roof of the mine after coal extraction, reducing the risk of injury or fatality associated with a roof fall. However, the task is performed in confined space with the operators of roof bolting machines in close proximity to moving parts. Errors in the operation of roof bolters have caused many fatalities and injuries. Injuries caused by intentional control operation can be divided into the following categories: the wrong control

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was operated; the correct control was operated in the wrong direction; the intended control was operated in the intended direction while the injured employee (a roof bolter operator or another person) was in a position of danger (Burgess-Limerick, Krupenia, Zupanc, Wallis, & Steiner, 2010; Burgess-Limerick & Steiner, 2006, 2007, 2011).

According to the analyses of the U.S. Mine Safety and Health Administration (MSHA) injury database analyses of the roof bolter accidents from 1984 through 1994, 11 of the 16 fatalities involved the inadvertent (by the operator, roof fall, etc.) activation of a control (MSHA, 1994). Of the 16 fatalities, 14 involved the moving boom. Including victims being crushed between the boom and the mine roof, victims being crushed between the boom and the canopy, victims being crushed between the boom and the machine frame, and one victim being crushed between the boom and the automated temporary roof support (ATRS). Two of the 16 fatalities involved a drill mast head where the victims were crushed between the drill head and the machine frame. Additional interviews with experienced roof bolters mentioned the swing lever when controls were inadvertently operated.

There has been much discussion about the idea of standardizing control design to help reduce the probability of such errors. Miller and McLellan (1973) reported that there was a need to redesign roof bolter machines. Helander et al. (1980) suggested that “poor human factors principles in the design and placement of controls and inappropriately designed workstations contribute to a large percentage of injuries” (p. 18). A report by Klishis et al. (1993) confirmed that injuries due to incorrect operator control remain a problem.

1.1. Selection errors

In response to several roof bolter operator fatalities, in 1994 MSHA formed a committee called the “Coal Mine Safety and Health Roof Bolting Machine Committee” to investigate and report causes for these fatalities. The first author served as one of the U.S. Bureau of Mines contributors to this investigation. The committee found that one of the leading causes was the unintentional operation of controls. A specific suggestion was a recommendation to provide the industry with distinct and consistent knob shapes for the controls of the machine. From this committee was proposed rule-making in 1997 titled “Safety Standards for the Use of Roof-Bolting Machines in Underground Mines” which suggested that design criteria were being developed, but no rule making was ever published (MSHA, 1997). Ten years later, the New South Wales Department of Primary Industries published Mining Design Guideline 35.1, (NSW DPI, 2009), in which a standard set of knob shapes are recommended for the primary bolting controls.

Although these documents report the apparent need for shape coding of controls to reduce inadvertent activation of the wrong control (selection error), there is little scientific evidence that shape coding is effective as a control. Many human factors textbooks refer to the need to shape code, however the empirical evidence of the effectiveness is not recorded or it could not be substantiated that the shape coding was the main discriminating factor to improving performance (Chapanis, 1999, p. 15–16; Roscoe, 1980; p. 274).

Weitz (1947) described experiments in which participants operated levers under varying shape coding conditions. No differences were found in the number of selection errors

between coded and non-coded conditions in situations where the layout of the controls remained constant during the experiment. In situations when the controls were altered during the experiment, fewer selection errors were made by the participants who were assigned to shape coded conditions. Similarly, in a more recent series of experiments utilizing a virtual reality analogy of bolting involving a bank of four levers (Burgess-Limerick, Krupenia, Wallis, Pratim-Bannerjee and Steiner, 2010), shape coding was only found to reduce selection errors when the spatial arrangement of levers was altered during the experiment.

1.2. Directional errors

As noted above, another cause of injury is directional compatibility errors. Directional errors are those errors where the correct control is operated but in the opposite direction than what was needed to produce the intended outcome. A contributing factor to this type of error may be that the directional control-response relationship is not compatible with the direction of movement or with the mental model of the operator. The directional control response relationships currently in use across mining equipment vary, even within manufacturers, and within similar functions, and sometimes change with changes in vehicle direction (Zupanc, Burgess-Limerick, & Wallis, 2007). Helander et al. (1980) also found design deficiencies and violation of control direction stereotypes associated with mining equipment and suggested that these design flaws contributed to increased injury risks.

Though it is agreed that it is important to ensure the compatibility of directional control-response relationships, the design is not always clear-cut. For example, it is relatively common on mining equipment to find situations in which downward movement of a horizontal control lever causes upward movement of the controlled element, such as a boom, stabilizer jack or drill steel. While some authors (e.g. Helander et al., 1980) have suggested that this is a violation of compatible directional control-response relationships, Simpson and Chan (1988) suggested that the response may be compatible if the operators assume a ‘see-saw’ mental model of the situation, where moving the near end of the control downwards causes the far end (and the controlled element) to move upwards. These issues have been examined more recently using a virtual simulation (Burgess-Limerick, Krupenia, Zupanc, et al., 2010).

1.3. Situational awareness

Improving the situational awareness of roof bolter operators is one way to help reduce selection and directional compatibility errors. Situational awareness can be defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” (Endsley, 1988). Expanding this definition Endsley (1995) describes three levels of situational awareness as perception of elements in the environment, comprehension of the current situation and projection of future status. When an inadvertent activation of a control occurs, the earlier this error is detected, the better. To improve the operator’s situational awareness, i.e. detecting errors then correcting them, a feedback control to allow for errors to be caught would be beneficial. The control feedback would enable the operator to improve performance and reduce the probability of harm to either himself/herself or to another individual nearby.

Currently, the operator must “notice” that the roof bolter arm appendage is moving in the wrong direction before he/she can correct the action. At that point, it may already be too late and the result can be catastrophic. Operational errors become even more critical when the error is performed out of the context of their routine job of placing roof bolts. For instance, the operator may get himself/herself caught between the drill mast and ATRS (relating to the drill feed control) or between the rib and the boom (relating to the swing control). In that moment, there is no room for an incorrect activation and yet, it may be highly probable for an error to be made when the motion is not in the context of the normal routine of placing roof bolts. Any feedback or warning information as to the correct directional movement would be invaluable.

A visual feedback system may serve to improve situational awareness by providing the operator with feedback prior to machine movement. A current technology being developed at the NIOSH Office of Mine Safety and Health Research (OMSHR) gave promising results of reducing time for subjects to detect and identify the direction of movement of a continuous mining machine when operators were standing in different operating positions during backing out and tramming tasks (Sammarco, Gallagher, Mayton, & Srednicki, 2012). The results indicated that in a dark environment, such as found in a mine, the visual feedback system on the continuous mining machine in this study “vastly improves an individual’s ability to quickly detect machine motions, in many cases by well over one second”. The research suggests that such a system could be an important tool to alert underground miners to impending or active machine motion which could prevent struck-by or pinning accidents in underground mining, such as the type of accidents involved with roof bolting machines. This same technology may be helpful for roof bolter operators when used in the context of operating controls. With accurate and improved situation awareness, roof bolter operators can react and respond more rapidly and with higher accuracy. An improvement in the feedback mechanism may provide the additional benefits of situational awareness.

1.4. Objectives

The aims of this research were (i) to determine whether the patterns of selection errors and direction errors observed while operating a real bolting machine in a laboratory are consistent with previous research using a virtual simulation analogous to bolting, and (ii) to determine whether a visual feedback intervention could improve the operators ability to recognize and correct a lever selection or direction error before adverse effects of the incorrect action are realized.

2. Methods

2.1. Participants

Sixteen adult male participants (age range of 22 to 56 years, mean=37, SD=11) who were practicing, experienced roof bolter operators (underground mining experience range of one month to 36 years, mean=10.1 years, SD=11.4 years) were recruited using word of mouth with the United Mine Workers of America and other mines. All participants had experience working with a roof bolter machine (range of 1 months to 20 years, mean=4.7 years, SD=5.5

years). Thirteen of the 16 participants had experience on the Fletcher Roof Ranger II machine, the machine used in these tests. An equal mix of union and non-union roof bolter operators were recruited to ensure all types of operations were included. All participants had normal, or corrected to normal vision, and were right handed. All participants provided written informed consent prior to the commencement of testing and were free to withdraw at any point in the experiments. Ethical approval to run all studies was given by the National Institute for Occupational Safety and Health (NIOSH) Human Subjects Review Board.

2.2. Apparatus

All experiments were conducted in the Human Performance Research Mine (HPRM) at the NIOSH, OMSHR in Pittsburgh, PA. The HPRM is a simulated underground mine environment with various testing apparatuses, data acquisition and control systems, and networked computers. The HPRM is large enough to house actual working mining equipment.

Participants were tested on an actual Fletcher Roof Ranger II Roof Bolter machine provided by Fletcher Manufacturing for a three-month period (Fig. 1a and b). The roof bolter was modified by Fletcher and NIOSH to provide additional safety precautions as indicated through the HSRB procedures and enable comparison with previous experimental testing (not yet published) on a mock-up bolter arm. The original machine had only 4 levers and a joystick. The joystick controls the rotation and the drill feed. For this experiment, the joystick control was decoupled and replaced with two levers to separate the controls for rotation and drill feed. Therefore a total of six mechanical directional hydraulic control valves were available. The directional hydraulic control valves operate the canopy, stabilizer jack, boom extension, boom swing, drill rotation and drill elevation. Additional changes were made to the roof bolter machine on-site in order for participants to encounter different lever assignments and directional operation than they were expecting so that errors could be measured.

These changes mostly involved reversing and rearranging the hydraulics to change the direction of movement of machine appendages. Fig. 2a and b show the experimental arm and one test subject using the experiment set-up. Fig. 3a and b illustrate the original and reconfigured testing layout of levers.

2.3. Instrumentation

For these experiments the roof bolting machine was equipped with two LED indicator lights within view of the operator to designate the operation of the boom swing out/away and the drill raise functions. The swing out/away used a red LED light that was placed just above the control bank and was directed towards the outside of the machine so that while the boom was swinging outward, its light would illuminate the rib and could be seen by workers coming onto the section; from this location the operator was able to easily see this swing light peripherally. The drill feed used a blue LED light located on the drill feed mechanism pointing upwards toward the drill hole. The operator can easily see this light while using the control bank. When a small amount of pressure was applied to the lever, the light was activated. When more pressure was applied to the lever the machine appendage moved. Both

LED light interventions could be turned off or on to match a given testing condition. The choice of providing an LED light to the drill feed and swing out/away control directions were based partially on MSHA accident data and partially on the authors' discussions with several experienced roof bolter operators (MSHA, 1994). These two LED lights comprised the visual feedback system intervention. Additionally, because roof bolts were not actually placed during the tests, incandescent lights (green and yellow) were added to the drill head to represent the rotational directions of the roof drill. It was not possible to show the action of rotation on the video stimuli so the light colors substituted for these actions. A green light was used for clockwise rotation and yellow for counterclockwise.

Instrumentation was also added to the Fletcher Roof Ranger II Roof Bolter to record the operator's actions during the laboratory tests. Two micro switches were used to monitor each of the six mechanical hydraulic directional control valves to enable recording of the following: canopy raise/lower, stabilizer jack raise/lower, boom extend/retract, boom swing in/out, drill rotation CW/CCW, and drill feed raise/lower. The operator was also provided with a momentary push button to acknowledge he was ready for the start of each test.

The outputs from all the micro switches, operators acknowledge push button, and LED lights statuses were input into a DATAFORTH 16 channel analog I/O backplane (SCMPB02) containing 15 isolated signal input modules (SCM5B33-04D) which output 0 to 10 VDC. As each control was activated by the subject an electrical signal was sent to an analog-to-digital board (PCI-6033E National Instruments, Austin, TX) and a control signal was sent to a hydraulic valve to move the arm in the corresponding action. The A/D board was controlled by Matlab's Data Acquisition toolbox (MATLAB®; The MathWorks, Inc, Natick, MA) and data were collected at 1000 Hz. A computer controlled Samsung 24″ Syncmaster 245BW LCD display (Microsoft PowerPoint 2004, Microsoft, Seattle, WA) was placed on a cart in front of the bolter to produce a visual stimulus (described in the stimulus section below). Subjects were asked to use the six control levers to move the roof bolter arm to match those of the visual stimulus. The levers were either identical, length coded, or shape coded according to the recommendations of MDG35 and either in a vertical or a horizontal orientation (Fig. 4a and b).

2.4. Stimuli

Video clips of all possible movements of the machine were recorded without the levers in the video. These stimuli were used to show the operator the movements of the machine that they would mimic using the physical levers in front of them. The clips were all independent movements of the machine and were uniform in time, distance and aspect ratio. They were taken from the perspective of where the operator would stand. These stimuli were triggered when the administrator clicked a computer mouse after the participant acknowledged, through the pressing of the audible momentary button, that they were ready for the next stimulus. A signal was recorded when the stimulus was initiated and the test started. The stimuli were shown to the participant via the Samsung 24″ LCD monitor located at eye level within 7 feet of the participant's standing position.

2.5. Experimental design and procedure

Each participant was individually tested on the Fletcher Roof Ranger II machine located in the HPRM. The participant's age, handedness, demographics and expected control-response relationship for all machine movements were recorded. Additionally normal or corrected-to-normal vision was confirmed. A randomized experimental condition was used for each subject (Table 1). Each subject was asked to complete a total of 288 trials of 12 different actions (six levers with two directions each). The tests were blocked into 6 separate sections around 6 minutes each with a two to three minute break in between each section. Each section consisted of 48 trials with four repetitions of each action presented in a randomized order.

Prior to testing, each participant was shown the set-up and a set of standard instructions was read to each participant. They were each told that they would be operating the roof bolting machine and would be required to face the computer screen, operating six different controls using their right hand only. They were asked which way they believed the lever should be activated to make the appendage move in a particular direction. This was recorded as the perceived stereotype of the directional relationship. The instructions about the task were given with the emphasis on that it should be carried out as fast and accurately as possible. Because of the relatively simple nature of the task the participant was not given any practice time prior to commencement of the experiment. The subjects were then asked to stand by the bolter controls station with their right arm depressing the button on the control arm and their left arm at their side, the subjects were only allowed to use their right hand for testing. A testing session trial was then started provided the audible button was depressed. For each trial a short pause of a still picture of the video was given as a pre-cue and then a 2 to 3 second video was shown on display. The subjects were instructed to release the button once they made a decision as to what lever was needed to duplicate the action. They then traveled to this lever to choose the direction to operate the lever in order to duplicate the action shown on the screen. The stimulus was only shown once and only one action was shown for each trial (i.e. no sequence of actions). If an error was made, the operator had time to recover the error. Only one correction attempt was recorded. The subjects were asked to return the bolter arm to the starting position and activate the audible button with their right hand in preparation for the next trial. At the end of all trials, baseline motor movement times were established by asking participants to move a lever in a particular direction while recording response time (i.e. no choices involved). For these trials the subjects were instructed to release the red button and activate one of the six levers in a particular direction once they hear the command to do so. This was repeated three times for each lever/direction combination. Structured pre and post experiment questions were asked regarding the operation of roof bolting machines in the mine and the light interventions they experienced in the experiment.

2.6. Dependent measures

Control selection errors (SEs), and direction errors (DEs) were recorded. A control SE was identified when the wrong lever was selected for completion of the task. A control DE was identified when the correct lever was operated, but in the wrong direction. For this

experiment participants were permitted to correct an error if they made one on their first attempt.

3. Results

3.1. Error data

Fig. 5a presents selection error by block and coding. While there was a significant effect of block [$F(5,65)=11.6$, $p<0.0001$], there was no significant effect of coding [$F(2,65)=1.055$, $p=0.376$]. While the median selection error rate for length and shape coded groups was lower than the group with identical levers for blocks 2 and 3 (as might be predicted if coding is a training aid), the interaction between block and coding was not significant [$F(10,65)=0.5806$, $p=0.8239$].

Direction error rates as a function of lever, and lever orientation is presented in Fig. 5b. A significant main effect of control lever was evident [$F(5,84)=3.551$, $p=0.0058$], however there was no significant effect of lever orientation [$F(1,84)=0.2818$, $p=0.5969$], nor was there a significant interaction [$F(5,84)=0.2477$, $p=0.0399$].

Fig. 5c presents direction error rates as a function of lever, and of whether the light intervention was enabled (for swing and drill functions). No significant effects of the light intervention were noted.

3.1.1. Subjective data—Participants were exposed to either the visual feedback system (light on drill feed up and light on swing out/away condition) or not. However, participants who did not have the visual feedback system condition were shown the lights and how the system would work on the machine after the end of their trials. The participants were asked the following questions pre and post experiment:

Pre-test questions

1. Have you ever grabbed the wrong control when operating the bolter?
   - If so, was it while bolting or tramming?
   - What control(s) did you grab incorrectly?
   - Why do you think that happened?
2. Have you ever activated a control in the wrong direction?
   - If so, was it while bolting or tramming?
   - What control(s) did you operate in the wrong direction?
   - Why do you think that happened?

All participants (100%) responded yes to #1 pre-test question ‘Have you ever grabbed the wrong control when operating the bolter?’ Majority of the participants indicated doing this while bolting (14 of the 16 participants, or 87.5%). 12.5% (2 of 16) reported grabbing the wrong control during both bolting and tramming. Participants erroneously grabbed the swing (56%), the extend control (25%), the canopy and drill feed (both 12%) and the

rotation control (.06%). When asked ‘Why do you think this happened?’ majority of participants report not looking at the controls while operating the roof bolter (12 of the 16 participants, or 75%). 31% of participants reported grabbing the wrong control because they were rushing or not paying attention to the task and 19% said they either couldn’t see the controls or made a mistake because of the position of the controls.

Majority of participants (69%) also responded yes to pre-test question #2, ‘Have you ever activated a control in the wrong direction?’ Participants indicate doing this primarily while bolting (73%) and erroneously grabbing the swing (64%). When asked ‘Why do you think this happened?’ Participants reported activating a control in the wrong direction because they were either not paying attention (45%) or in a hurry doing the job (27%).

Post-test questions

1. Did you find that the light feedback helped you to choose the correct, direction or to help you correct your error if you made one?
2. Would a light feedback system be useful for you on the job? When would it be most useful?

For post-test question #1, ‘Did you find that the light feedback helped you to choose the correct direction or to help you correct your error if you made one?’ 43% (3 of 7) of the participants who were NOT exposed to the light feedback said they would find the light helpful while 78% (7 of 9) of the participants who were exposed to the light feedback found it useful.

Prior to seeing the light feedback, one participant indicated that the light “…would be distracting”. He thinks they would cover it up if it were on the machine. He also did not think it would be helpful. After the experiment was complete, he was shown the visual feedback lights and thought “it very well could be helpful for training.”

For post-test question #2, ‘Would a light feedback system be useful for you on the job? When would it be most useful?’, the majority of participants in both conditions indicated that having a light feedback system would be useful for them on the job. 100% of those participants exposed to the light feedback found it useful while 71% of participants not given light feedback found it useful (5 of the 7 participants responded yes in this condition while one participant refrained from responding).

Participants who thought the light feedback system would be useful for their job indicated the system would be most useful during training (6 of 16 participants – 38%), as a warning system (4 of 16 participants – 25%) and as a signal that the roof bolting arm was swinging (3 of 16 – 23%; one participant chose not to respond to this question).

4. Discussion

The selection error data were consistent with those previously gathered from an examination of shape coding in a virtual simulation (Burgess-Limerick, Krupenia, Wallis, et al., 2010), and with the previous literature. Selection errors are likely to be made, particularly in the early stages of learning a new lever layout, even by experienced operators. Shape coding

may be beneficial if it is consistently applied to the same machine functions across different machines.

The direction error data similarly confirm that directional error rates are relatively high, but that the error rates vary considerably across functions. Where directional control response compatibility is maintained (e.g. drill feed) the direction error rate was very low. Sump (extension) movements of the bolter arm required movements of the control levers which were perpendicular to the direction of the response, and this lack of compatibility resulted in higher direction error rates. Directional error probability can be reduced by, as far as possible, ensuring directional control-response compatibility. This finding is consistent with the previous literature and the examination of a virtual analogy of bolting (Burgess-Limerick, Krupenia, Zupanc, et al., 2010).

Although the direction error rate was not significantly different between groups with and without the visual feedback system, the qualitative data indicated that the workers generally found the lights helpful. The control that most operators said they selected incorrectly was the swing control. Most operators report they do not look at the controls when operating their equipment. Other explanations include being in a hurry or selecting the wrong control because of the positioning of the controls. Since the controls all look and feel the same as each other, it is difficult to distinguish between controls. Operators said they “count” or “feel” for the right control in terms of its position or order and sometimes make a mistake. They also reported that when they operate the controls in the wrong direction it is while they are bolting and mostly with the swing control. This further establishes that the swing is a control that gives the operators the most difficulty and may not match their mental models of directional compatibility. The swing (left and right motion) moves in a different plane than the action direction of its control lever (up and down). The drill feed, as evidenced by the MSHA injury and fatality data, and the swing as evidenced by discussions with roof bolter operators and answers to these experimental questions, are the two controls which can be confused and may result in catastrophic events when operated at the wrong time or in the wrong direction.

The lack of significance in the quantitative data may be due to the simple nature of task and the lack of other distractions during the experiment. Since there are limited action choices as a roof bolter operator, the simplicity of the task itself only generates a small number of errors even with the changes to the machine with which they had experience. The number of errors may have been reduced further depending on whether operators prioritized accuracy over speed.

The lower positive response rate to QUESTION #1 by the miners exposed and NOT exposed to the light feedback may be related to these same issues. The error rate of both these subject groups was low to begin with; therefore, it is less likely that they would feel the need for additional aid.

The anecdotal comment from one of the subjects NOT exposed to the light feedback adds credence to this thought; after exposure to the system, he responded more favorably. However, both groups responded positively to QUESTION #2 indicating that the light

feedback would be helpful even if it did not help them. They reported that it would have been very helpful when they were training to operate the roof bolter machine. This cue should likely be incorporated into the design of the machine to address the possibility of operators relying on that feedback while performing bolting tasks. There is evidence in the literature that cueing decreases error rates and that withholding a cue that a participant has been trained to use increases error rates (Ament, Lai, & Cox, 2011). Because error rates for both groups of participants was low to begin with, it can be speculated that participants did not need the additional aid because majority of the participants could be considered an expert at the task (median time working as a roof bolter=4.67 years).

The positive response to the use of the visual feedback system is encouraging because based on human factors principles the light feedback should improve attention (Lynas & Horberry, 2011 and Stanton, Chambers, & Piggott, 2001). The light feedback increases task attention spatially and temporally as well as providing feedback redundancy in conjunction with the bolter motion itself (Wogalter & Mayhorn, 2005). The additional lighting on the drill feed up motion will also provide additional lighting when placing the roof bolt, a request that several roof bolters have mentioned during underground discussions of roof bolting tasks.

5. Limitations and future direction

A limitation to this study was the small number of roof bolter operators that were available for this study. It is costly and difficult at this time of mine worker shortages to have workers tested. Other types of interventions could have been compared and tested along with placing the visual feedback system on controls other than the drill feed up and swing out/away. It may have been helpful to test selection errors and directional compatibility errors with a larger number of controls. This may help identify when shape-coding, length-coding and location coding is most beneficial. Also, it may be possible to compare error rates and reaction times of new bolter operator trainees with and without this feedback system as well as determine how such an intervention can change the way they do their jobs.

6. Summary and impact on Industry

The data illustrate the importance of multiple control barriers to both reduce the probability of errors (shape coding and compatible directional control-response relationships) and control measures aimed at making systems error tolerant, and allowing operators to detect and recover from errors before negative consequences are realized. The experiment confirmed the need for additional attention to the swing and drill feed. The visual warning system may be an acceptable and appropriate intervention while the standardization of controls is further examined. It is possible that this type of intervention is effective for times when there is little time for decisions and an error in direction of a lever could result in injury or even death. The situation where the operator is using the controls out of the context of their normal routine or when the operator is training for the first months of their jobs, this visual feedback can maximize safety and minimize learning time. It may be necessary to carry-on this feedback once the operator has used it for training. This cost-effective solution should be studied in the environment to ensure its intended use. Applications beyond mining

can extend to any control design where feedback is critical to the health and safety of the operator and there is a need to improve situational awareness.

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Biographies

Lisa J Steiner, Team Leader Cognitive Engineering, Center for Disease Control, National Institute for Occupational Safety and Health, Office of Mining Safety and Health Research

Lisa, a certified professional ergonomist, has worked for the Bureau of Mines and CDC NIOSH Office of Mining Safety and Research for 21 years. Her main areas of research are the reducing of musculoskeletal injuries in mining through ergonomics processes development and redesign of jobs, tasks and equipment. She currently is pursuing her PhD in Human Movement Studies at the University of Queensland concentrating on the cognitive engineering aspects of directional control response compatibility and selection errors of mining machine controls. She is the Team Leader of the Cognitive Ergonomics Team in the Human Factors Branch of NIOSH OMSHR in Pittsburgh, PA.

Robin Burgess Limerick, Professor of Human Factors, Minerals Industry Safety and Health Centre, Sustainable Minerals Institute, The University of Queensland, Australia

A certified professional ergonomist, Robin is a past-president of the Human Factors and Ergonomics Society of Australia (HFESA), and the current chair of both the HFESA Minerals Industry Special Interest Group, and the International Ergonomics Association Technical Committee on Mining. Prof Burgess-Limerick’s research focuses in particular on reducing the risks to safety and health associated with the operation and maintenance of mining equipment. Robin is the author of more than 100 scholarly publications.

Brianna Eiter, Research Fellow Cognitive Psychologist, Center for Disease Control, National Institute for Occupational Safety and Health, Office of Mining Safety and Health Research

Brianna M. Eiter has been a research fellow at the National Institute for Occupational Safety and Health for approximately one year. She earned her PhD in cognitive psychology in 2005 from Binghamton University and then spent 6 years as a researcher and teacher at Hofstra University. She has participated in studies related to attention, reading, and decision making. Her area of expertise is the use of eye-movements to measure cognitive processes.

William Porter, Research Industrial Engineer, Center for Disease Control, National Institute for Occupational Safety and Health, Office of Mining Safety and Health Research

William Porter is a researcher in the Musculoskeletal Disorders Prevention Team of Human Factors Branch at the NIOSH Office of Mine Safety and Health Research. Bill has a B.S. in Bioengineering and a M.S. in Industrial Engineering from the University of Pittsburgh. Bill has worked for NIOSH for the past seven years as a research engineer. He has worked to test and operate the equipment needed for multiple field and laboratory studies including ingress/egress of mobile equipment, low-seam mining knee injuries, and haul truck related injuries. Along with colleagues at NIOSH he developed a training program for both managers and employees on normal processes of aging.

Tim Matty, Engineering Technician, Center for Disease Control, National Institute for Occupational Safety and Health, Office of Mining Safety and Health Research

Timothy Matty is an Electronics Technician in the Musculoskeletal Disorders Prevention Team of Human Factors Branch at the NIOSH Office of Mine Safety and Health Research. He formerly was a Master Electrician for a coal company where he repaired and rebuilt all types of underground mining equipment along with their control panels. At NIOSH, Tim's efforts include finite element analysis, testing set-up, data acquisitions and data reduction. He is trained and experienced in ProE and ProMechanica Solid Modeling and Mechanical Analysis software as well as developing 3D graphical models of mining equipment for computer simulations.

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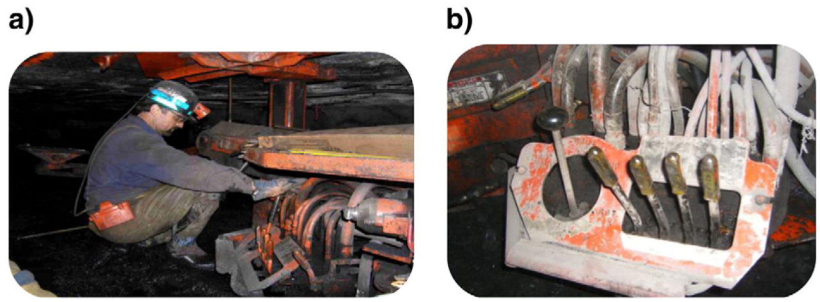

Fig. 1.
Operator on a RRII machine (a) and the joystick control on a RRII (b).

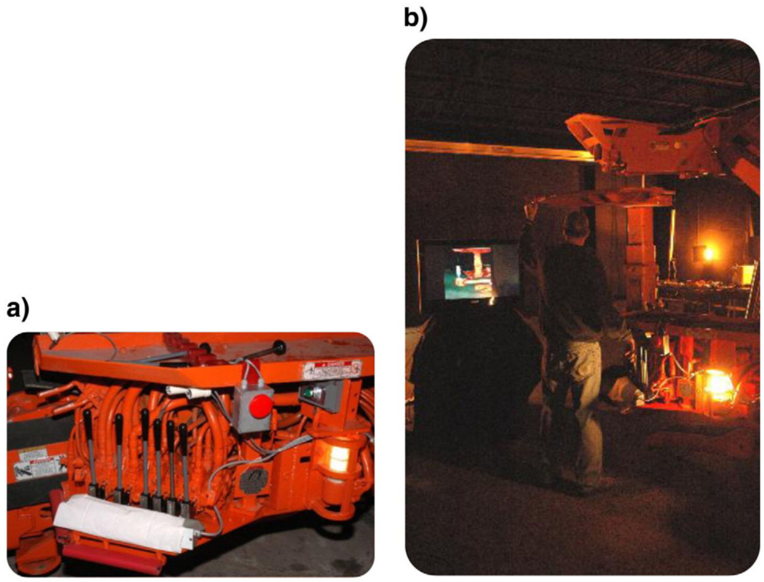

Fig. 2.
Experimental roof bolting controls (a) and Operator during experimental trials (b).

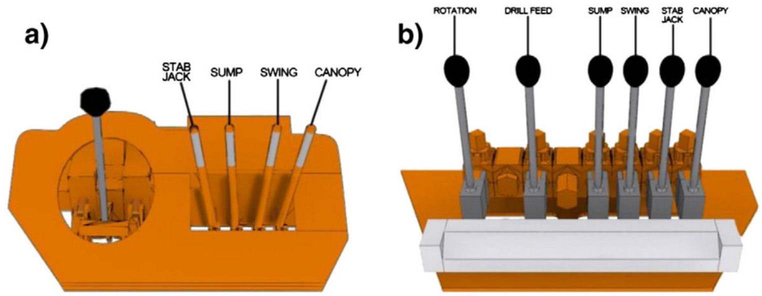

Fig. 3.
Actual roof bolter set up (a) and changed set up for experiment (b).

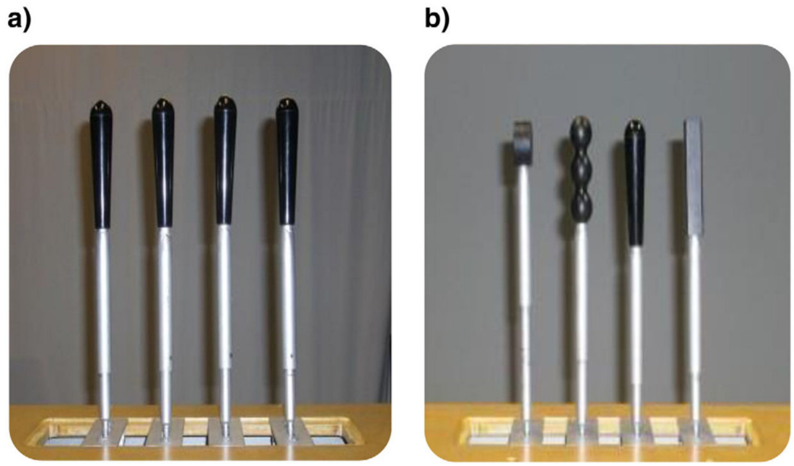

Fig. 4.
Typical lever shape (a) and suggested MDG35 shape-coded controls (b).

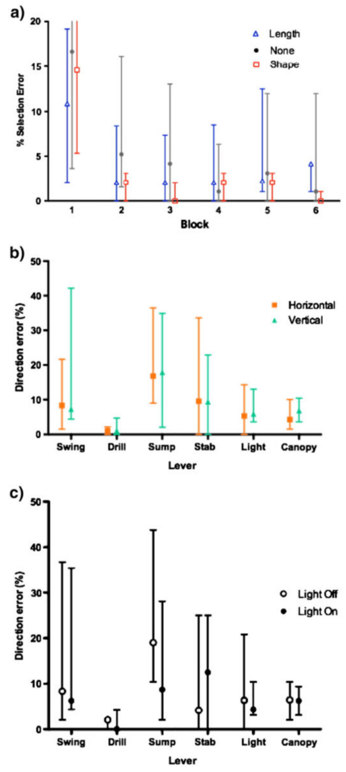

Fig. 5.
a. Selection error by block and coding (length, shape or non-coded). b. Directional error by control lever and orientation (horizontal or vertical). c. Direction error by control lever and visual feedback light intervention.

Table 1

Test Conditions.

Condition	Control layout
1	Light On, Length Coded, Horizontal
2	Light On, Length Coded, Vertical
3	Light On, Shape Coded, Horizontal
4	Light On, Shape Coded, Vertical
5	Light On, Non-Shape Coded, Horizontal
6	Light On, Non-Shape Coded, Vertical
7	Light Off, Length Coded, Horizontal
8	Light Off, Length Coded, Vertical
9	Light Off, Shape Coded, Horizontal
10	Light Off, Shape Coded, Vertical
11	Light Off, Non-Shape Coded, Horizontal
12	Light Off, Non-Shape Coded, Vertical