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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.

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 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,

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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