The use of simulation for the human-centred design of underground coal mine bolting machines

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This paper describes a series of experiments addressing questions related to the design of underground coal bolting machine controls. The ecological validity of the experiments increased from the movement of an arbitrary device within a virtual environment, albeit connected with physical controls, through a hydraulically operated physical simulation of a specific bolting machine, to a real bolting machine within a physical simulation of an underground mine. Collectively, the results of the experiments illustrate the potential role for virtual and physical simulation in achieving human-centred design of mining equipment.

Keywords: Simulation, human-centred design, mining equipment.

1. Introduction

Previous research has highlighted potential control errors which may give rise to injuries to the operators of underground mining equipment (Burgess-Limerick & Steiner, 2006; Steiner & Burgess-Limerick, 2007) including the operation of an incorrect control (a selection error), or operating a correct control in an incorrect direction (a direction error).

Examples of typical bolting controls are illustrated in Figure 1. A variety of lever orientations, locations, and directional control-response relationships are evident. Standardising the controls on equipment such as bolting machines as a way of reducing the risk of such injuries has been suggested many times. Miller and McLellan (1973) commented on the “obvious need” to redesign roof bolting machines, suggesting, for example, that of 759 bolting machine related injuries, 72 involved operating the wrong control, while Helander et al (1983) determined that 5% of bolting machine accidents were caused by control activation errors. Improvements to guarding to prevent accidental control operation, standardisation of mining equipment controls, especially drilling and bolting controls, and the use of shape and length coding has been suggested on numerous occasions over the past 40 years.

Hedling and Folley (1972) noted (in the context of continuous miner controls) that “the widespread use of traditional round control knobs regardless of function being controlled is another source of error in operation”. Similarly, 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 the reported injuries” (p. 18). In particular, a lack of standardisation of controls was noted, with more than 25 different control sequences being identified, and differences existing even on similar machines produced by same manufacturer. A lack of control coding, violations of direction stereotypes, a mixture of mirror image and left/right arrangements, and the possibility of inadvertent operation was also noted.

Helander and Elliott authored a proposal in 1982 for a Society of Automotive Engineers standard titled “Human Factors Guidelines for roof drills” which addressed these issues. The proposed standard was later subsumed within a later proposed standard titled “Human factors design guidelines for mobile underground mining equipment” which was defeated at a ballot in 1984. (Both proposals are provided as appendices to a report by Gilbert, 1990). The standard was not issued despite meetings continuing until 1990. Klishis et al., (1993) again noted the lack of standardisation of bolting machine controls, even among machines from the same manufacturer, and commented on the potential for injuries due to incorrect control operation.

In a six week period in 1994, three operators of roof-bolting machines in the USA were killed. Two were crushed between drill head and machine frame while rib bolting, the third crushed between drill head and canopy. A “Coal Mine Safety and Health Roof-Bolting-Machine Committee” was formed by MSHA to investigate, and a report released (MSHA, 1994) which determined the causes to be the unintentional operation of controls. The solutions proposed in this report were: 1. Two-handed fast feed; 2. drill head raise shutoff; 3. auxiliary controls; 4. guarding; 5. pinch point identification; 6. self-centering controls; 7. hands-off drilling; 8. insertion/retrieval devices; 9. standardised control layouts; 10. pre-operational inspection. Other suggestions included in this report included: “Provide industry-wide accepted distinct and consistent knob
shapes and relative handle lengths to identify corresponding control function” and “Standardize machine control lever movement and corresponding machine function movement.”

Figure 1: Examples of bolting rig controls
These conclusions are consistent with a safety alert issued by the NSW Department of Primary Industries in 2005 which noted serious injuries occurring as a consequence of unintentional and intentional bolting control activation. The safety alert included the following as potential control measures: two handed control for fast speed operation; minimisation of pinch points; guarding to reduce inadvertent operation; shape coding; and standardised control layouts. These measures were also included in the Machine Design Guide 35.1 “Guideline for bolting and drilling plant in mines. Part 1: Bolting plant for strata support in underground coal mines”. The guideline includes suggested knob shapes for primary bolting controls (rotation, feed and timber jack).

Whilst standardisation of bolting controls is desirable, differences between manufacturers in current designs make this a sensitive issue. All authors agree that coding by handle shape and/or length, and consistent arrangements of primary controls is desirable. However, the relative magnitudes of benefits associated with shape, length and location coding is unknown. This is necessary before evidence based recommendations may be made regarding the relative importance of each type of coding, and whether all methods should be employed, or whether a subset is sufficient to reduce the probability of selection errors to negligible levels.

A second question of interest is the appropriate directional control-response relationship of controls. The importance of ensuring “compatible” directional control response relationships is unanimously agreed, that is, the direction which the controlled element moves in response to a movement of a control should correspond to the operators’ expectations. Contraventions of this principle increase errors, increase reaction time, and increase the time taken to learn to use equipment proficiently.

Directional compatibility is often expressed as implying that the movement of a control should be in the same direction as the movement of the controlled element which results eg., “The single most important control optimisation is to have controls move in the direction of the component controlled”. Muldoon et al., (1980); p 41. This logic leads to the common recommendation that a horizontal control lever should be moved upwards to cause an upward movement of a controlled element.

This recommendation is reflected in ISO/TS 15077 which applies to controls for tractors and self-propelled machinery for agriculture and forestry, as well as AS4024 (via its reference to IEC 60447: 2004), although no evidence is provided. AS2956.1 (1988, also ISO4557) allows deviations from this arrangement: “The movement of the following controls in relation to their neutral position shall be in the same general direction as the movement they control unless customary usage or combining of controls dictates otherwise”.

The issue is not straightforward. A number of authors have noted the relatively common practice to reverse this situation on bolting rigs where downward movement of horizontal control is associated with upward movement of controlled element such as boom or a timber jack. While some reports note this as a violation of directional control-response relationships, Chan et al., 1985 noted that response may be compatible if the operators assume a “see-saw” mental model of the situation where moving the near end of the control downward causes the far end (and the controlled element) to move upward.

Chan et al. (1985; Simpson & Chan, 1988) investigated this situation through an experiment in which 144 people reported the direction they would move a control lever to achieve a specified effect, on a 1/10th model of a drill loading machine. The results indicated that while the majority of people reported responses consistent with a “see-saw” mental model, the stereotype was far from universal, and up to 33% of people reported expectations for “up=up”. Extremely strong expectations were reported for the movement of vertical controls however, with more than 90% of people expecting a backward movement of a vertical lever to cause an upward movement of a controlled device, and this is consistent with recommendations found in relevant standards. Chan et al (1985) suggested that “conflicting recommendations and gaps in the literature would need to be resolved before any standardisation of control-response relationships for mining machines was possible” This statement remains true, and this project aims to clarify the consequences of different orientations of controls and controlled elements to allow justifiable recommendations to be made for incorporation in standards.

2. Method

Three different simulated tasks of varying ecological validity were employed to assess questions related to the optimal design of bolting equipment to reduce injury risks. One set of experiments utilised a computer generated virtual simulation of a generic device capable of slewing left and right (rotation about a vertical axis of rotation), elevation & depression (rotation about a transverse axis of rotation), extension & retraction (lengthening or shortening), and changing colour (Figure 2). Experiments utilising the virtual simulation were undertaken within the Virtual Environments Laboratory within the School of Human Movement Studies, The University of Queensland.
The second set of experiments utilised a physical simulation similar in configuration to a single boom bolting machine (Figure 3). The physical simulation was located at the Mining Injury Prevention Branch, National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory (USA).

Figure 3: Physical simulation of a single boom bolting arm and visual stimuli (Steiner & Burgess-Limerick, 2013; Steiner et al., 2014)
The third experimental paradigm utilised a modified roof-bolting machine (Figure 4) located within the Human Performance Research Mine, National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory (USA).

![Image](image-url)

**Figure 4:** Modified roof bolting machine (Fletcher Roof Ranger II) (Steiner et al., 2013).

3. **Results and Discussion**

3.1 Selection errors

Burgess-Limerick et al. (2010b) reported two experiments in which a bank of four levers was operated by participants to manipulate a generic virtual device under different coding conditions. The results provided no evidence that arbitrary shape-coding was effective in reducing the probability of selection errors when the layout and position of the controls remained constant. However, when the side of the participant on which the levers were placed was altered during the experiment, and for the block of trials immediately following this change, a significantly lower selection error rate was found for participants assigned to the shape-coded conditions. Another potential means of reducing selection error probability is to provide different lengths of levers. For a bank of five levers, for example, providing a longer handle length for the middle control may be an effective cue. Steiner and Burgess-Limerick (2013) partially replicated and extended these experiments to include length coding using a physical simulation of a single boom roof-bolting machine with five levers.

Collectively, the results of five experiments supported a conclusion that when operators are not under time pressure, attention is not divided, and operators are able to view the controls they are manipulating, any benefits of arbitrary shape-coding or length-coding for reducing selection errors are likely to be restricted to situations in which the arrangement of controls in relation to the participant is subsequently altered in some way, such as the operator moving from one machine to another with a different control layout. Even in this situation, the effect is likely to be relatively small. While the recommendation contained within MDG35.1 for arbitrary shape-coding is valid, the control measure may not, on its own, significantly reduce the risk of injuries associated with bolting operators inadvertently selecting the wrong control. If shape-coding is employed, measures should be taken to ensure that the relationship between shape and function remains consistent and that maintenance errors are prevented.

3.2 Direction errors

Burgess-Limerick et al. (2010b) addressed the issue of appropriate directional control response relationship is different control layouts in two experiments that involved a virtual simulation of a generic device controlled by a bank of four levers. The response of the virtual device included changing color, lengthening or shortening, slewing left or right, and elevating or depressing. The levers that controlled these
responses varied in orientation (horizontal or vertical) and in the direction of the resulting response. The position of the bank of levers with respect to the participants also varied across the experiments.

The results confirmed the general applicability of the principles of consistent direction and visual field compatibility (Worringham & Beringer, 1998). In particular, the finding that directional error rates were minimized when upward movements of a horizontal lever caused upward movements of the controlled device was not consistent with the participant expectations reported by Simpson and Chan (1988). Burgess-Limerick et al. (2010b) also noted that the control of slew (swing) was associated with a relatively high probability of direction errors in most of the situations examined, with the exception of situations in which a vertical lever located to a participant's right or left was paired with a directional control-response relationship such that moving the lever away caused the device to swing in the same direction. Directional error rates were relatively high when the direction of movement of the slew was perpendicular to the movement of the control, and it was concluded that these situations should be avoided.

The pattern of direction errors observed when these questions were addressed using the physical simulation of an underground coal roof bolting machine (Steiner et al., 2014) were consistent with those observed using using the virtual simulation of a generic device. This finding provides confidence that the principles derived in previous experiments in virtual environments may be generalized to physical environments. The results emphasize the importance of ensuring consistent direction of control and response movements to reduce the probability of errors, which may have serious consequences. The probability of direction errors is increased if the control and response movements are in opposite directions or, importantly, if the direction of the control and response movements are perpendicular. Designers of bolting equipment should avoid providing the directional control-response relationship that have been identified here as being associated with relatively high error rates.

3.3 Roof bolting machine experiment

In the final experiment in this series, 16 experienced roof bolter operators utilised a modified roof bolting machine to allow examination of the patterns of selection and direction errors, and to examine whether the provision of a lighting intervention which indicated to the operator the function and direction of movement commanded could improve the ability of an operator to recognize and correct a selection or direction error before adverse consequences occur (Steiner et al., 2013). The results were consistent with those previously obtained and suggested that the provision of visual feed-forward information may have potential to allow error correction.

4. Conclusion

The examination of the same design questions using of virtual simulation, physical simulation, and modified real equipment within an laboratory context provides a solid empirical basis on which to make recommendations for the design of equipment to improve operator performance and reduce injury risks. Virtual and physical simulation has a key role to play in achieving human-centred design of industrial equipment.

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References


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