Implications of directional control-response compatibility for the design of mining equipment

Robin Burgess-Limerick¹ Christine Zupanc¹ Guy Wallis¹ Veronica Krupenia¹ Lisa Steiner²

¹School of Human Movement Studies, The University of Queensland ²National Institute for Occupational Safety and Health, USA

Abstract

Incompatible relationships between control and response direction increase the probability of errors, with serious injury potential. This paper describes the results of experiments conducted within the virtual environments laboratory at the University of Queensland, and at Mining Injury Prevention Branch of the National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory, USA which examine the directional control-response compatibility.

An investigation of the steering relationships found in underground coal shuttle cars in use in Australian mines indicates that the alternating compatible and incompatible steering relationship creates a situation in which the likelihood of steering direction errors is relatively high. This incompatibility may have contributed to a recent fatality, and alternative steering mechanisms should be implemented.

ACARP project C16013 "Principles for the reduction of errors in bolting control operation" investigated directional control-response relationships through use of both a virtual generic control situation (UQ), and a physical model of a bolting machine (NIOSH PRL). The results indicate that the simplistic recommendations found in standards are insufficient to capture the complexity of the possible combinations of control orientation and equipment response. Recommendations for the design of bolting rigs are made, and the principles are applicable to other items of mining equipment.

Introduction

The probability of moving a control in the wrong direction is increased when the relationships between control movement direction and equipment response do not correspond to principles of control-response compatibility. This paper concerns two examples of underground coal mining equipment in which these errors may contribute to serious injuries.

Shuttle car steering

The majority of Australian shuttle cars are driven using a steering wheel located to one side, and between, the two facing seats, attached to the inside wall of the cab adjacent to the shuttle car's conveyor (Figure 1). Two facing seats allow the driver to change seats with each change of direction and always face the direction of travel.



Figure 1: Typical shuttle car in use in Australian underground coal mines

When the car is full of coal, the driver will move to the left hand seat of the cab illustrated in Figure 1, and drive the car to the boot end where the coal is unloaded. When driving away from the face in this shuttle car, if the driver wishes to turn the car to the right, he rotates the steering wheel clockwise, pushing the top of the steering away from the body. To turn left, the driver pulls the top of the steering wheel back towards the body, an anti-clockwise rotation. This relationship between control direction and vehicle response is "compatible", and is typically executed without error or delay.

However, when the driver has emptied the car at the boot end, and changes seat to return to the face, the task is more difficult. The driver is now sitting in the right hand seat seen in Figure 1. Now, if the driver wishes to execute a right hand turn, he must push the top of the steering wheel away from himself (anti-clockwise rotation), and to turn left he must pull the top of the steering wheel towards from his body (a clockwise rotation). As pointed out by Worringham (2003), this is an "seriously incompatible" control-response relationship.

The consequences of incompatible control-response relationships generally are an increase in errors, and/or a reduction in the speed with which tasks can be performed, and this conclusion has been confirmed in a series of experiments in a virtual reality simulation situation of the situation (Zupanc, 2008; Zupanc et al., 2007). The injury potential of such

errors is considerable because shuttle cars (of the order of 3m wide) are frequently operated in close proximity to continuous miner operators, cable hands, and other pedestrians within the restricted space of a heading (typically 4.5-5.5 m). This risk was highlighted by a fatality in Queensland in 2007 in which a continuous miner operator was crushed between a shuttle car and the rib.

One solution to the steering incompatibility problem is to provide a single rotating seat and a steering mechanism which remains always compatible such as that provided in the "Ergo pod" shuttle car illustrated below (Figure 2). These cabs can be retrofitted to existing vehicles.



Figure 2: "Ergopod" shuttle car cab

Bolting controls

A second example in which directional control errors have serious injury potential is roof rib bolting rigs (eg., Figure 3, Burgess-Limerick & Steiner, 2006). Machine Design Guideline 35.1 "Guideline for bolting and drilling plant in mines. Part 1: Bolting plant for strata support in underground coal mines" (NSW DPI, 2009) requires that "The direction of operation of manual controls should be consistent with the direction and response/movement of the actuator or the plant, where practicable".

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Figure 3: Examples of bolting rig controls

The importance of ensuring "compatible" directional control response relationships is unanimously agreed. However, determining the appropriate directional relationship in any specific circumstance is not always straight forward. As in MDG35, directional compatibility is frequently expressed as what might be called the "principle of consistent direction" and this principle is generally reflected in current standards.

Worringham and Beringer (1998) modified this general principle to accommodate situations in which an operator uses a control located to one side, or behind, while looking straight ahead. In this case, the compatible directional relationships were ones in which the movement direction of the control in the virtual visual field (as if they were looking at the control) was consistent with the movement of the controlled element. This was referred to a "visual field compatibility", that is, "the direction of motion of a control, as defined by its movement when viewing the control, should correspond with the movement of the controlled object in the operator's visual field, while viewing the object" (Worringham, 2003 p.14).

The issue may be more complex however. It is relatively common to find on mining equipment situations in which downward movement of horizontal control causes upward movement of the controlled element such as a boom, timber jack or drill steel. While some authors (eg., Helander et al., 1980) have suggested this is a violation of compatible directional control-response relationships, Chan et al., 1985 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.

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, using 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 element. 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"

More recently, the issue has been examined in a series of experiments involving both virtual and physical simulations (Burgess-Limerick, 2009; Krupenia, 2008). The apparatus illustrated below was used in experiments in which the orientation of the control levers was varied between horizontal and vertical, the location of the levers was varied between left, front and right, and the directional relationships between the lever movement and the response of the physical or virtual model were altered (Figure 3).





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Figure 4: Virtual reality simulations (above) and physical simulation (below) of bolting controls.

Large differences were demonstrated in the rate of direction errors (and magnitude of reaction times) between different directional control-response relationships. These findings reinforce the importance of this aspect of control design. The results also indicate that directional compatibility effects are not as straightforward as current standards and guidelines suggest.

In most, but not all, situations, it is important to ensure that control-response relationships correspond spatially, and the general recommendation that the direction of movement of a control should be in the same direction as the response is sound. In particular, in contrast to the data provided by Chan et al. (1985), consistently fewer directional errors were made when a horizontal lever was moved upwards to cause an upwards rotation of a controlled device, regardless of the plane of the rotation and the location of the controls (ie., regardless of whether the plane of movement of the rotated device was coincident with the plane of movement of the control). This raises the possibility that self-reported directional *expectations* are not necessary predictive of actual *behaviour*.

In situations where the movement of the control and the response are in different planes there are some control-response relationships which are associated with lower direction error rates than others. For example, when controlling elevation and depression with a vertical lever, the results were more complex. Where elevation of the controlled device involved rotation of the controlled image directly back towards the operator, fewer directional errors occurred when a vertical lever was pulled back towards the operator, regardless of whether the location of the lever was to either side or directly in front. Where the elevation involved clockwise or anti-clockwise rotation in the plane of the screen, and the vertical controls were located in front of the participant, neither directional control-response condition was effective in reducing directional error rate. Where the vertical controls were located to the participants' right or left, the directional error rate was lower when the direction of movement of the vertical lever corresponded to the rotation of the controlled device ie., pushing a vertical control located to a participant's right caused clockwise rotation and vice versa. However, in many cases the error rates were higher than the corresponding horizontal control conditions.

In contrast, the use of horizontal levers to control slew left and right was associated with generally high directional error rates, regardless of the directional control-response relationship. The only situations in which low directional errors rates were observed for slew control was when the direction of movement of the control corresponded to the direction of the response, eg., when pushing a vertical lever located on a participant's right away from the participant caused right slew of the controlled device (and vice versa).

A further general observation which is particularly relevant to the design of bolting rigs on integrated bolter-miners is that very few directional errors occurred when extension (lengthening) of the virtual device was caused by raising a horizontal control. The only exception occurred when a horizontal lever located to a participant's right was used to cause extension horizontally to the left.

However, the following recommendations for the design of bolting rigs are justified:

- ★ Where horizontal levers are used to control the extension of a timber jack to either the roof or rib, an upward movement of a horizontal control should be employed to cause extension
- ★ Where horizontal levers are used to control drill feed to roof or rib, an upward movement of a horizontal control should be employed to cause feed

Similarly, when extension was controlled by a vertical lever, fewer directional errors occurred without exception when lengthening of the device was caused by a movement of the vertical lever away from the operator. Consequently, the following recommendations for the design of bolting rigs are justified:

- ★ Where vertical levers are used to control extension of a timber jack to roof or rib, a movement of the vertical lever away from the operator should be employed to cause extension
- ★ Where vertical levers are used to control drill feed to roof or rib, a movement of the vertical lever away from the operator should be employed to cause feed

In general, the lowest error rates for extension occurred when raising a horizontal lever, or pushing away a vertical lever, to cause extension was also consistent with the principle of common control response direction eg., pushing a vertical lever located to a participant's left to raise extension to the left, or raising a horizontal lever to cause extension vertically. An optimal design of bolting rigs would ensure that the maximally compatible relationships between control and response were always maintained.

These recommendations apply to the design of new bolting rigs. A variety of directional control-response relationships are found on bolting rigs currently in use. The consequences of making alterations to those existing rigs which do not conform to the above directional control-response relationships are unknown. It may be that for operators who are accustomed to operating controls which have directional control-response relationships which differ from those recommended here, a change may increase the probability of a directional error, at least in the short term, and changes to existing equipment may consequently be undesirable. Alternately, it may be that the changes would be accommodated without difficulty and that changing existing equipment is desirable.

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