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Directional Control-Response Compatibility Relationships Assessed by Physical Simulation of an Underground Bolting Machine

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Abstract

Objective—The authors examine the pattern of direction errors made during the manipulation of a physical simulation of an underground coal mine bolting machine to assess the directional control-response compatibility relationships associated with the device and to compare these results to data obtained from a virtual simulation of a generic device.

Background—Directional errors during the manual control of underground coal roof bolting equipment are associated with serious injuries. Directional control-response relationships have previously been examined using a virtual simulation of a generic device; however, the applicability of these results to a specific physical device may be questioned.

Method—Forty-eight participants randomly assigned to different directional control-response relationships manipulated horizontal or vertical control levers to move a simulated bolter arm in three directions (elevation, slew, and sump) as well as to cause a light to become illuminated and raise or lower a stabilizing jack. Directional errors were recorded during the completion of 240 trials by each participant.

Results—Directional error rates are increased when the control and response are in opposite directions or if the direction of the control and response are perpendicular. The pattern of direction error rates was consistent with experiments obtained from a generic device in a virtual environment.

Conclusion—Error rates are increased by incompatible directional control-response relationships.

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Application—Ensuring that the design of equipment controls maintains compatible directional control-response relationships has potential to reduce the errors made in high-risk situations, such as underground coal mining.

Keywords

control errors; machinery; safety

INTRODUCTION

Underground coal mining remains a domain in which the manual control of equipment, such as bolting machines, is ubiquitous. The risks of these activities are well documented and include injuries associated with direction errors, that is, operating a control in a direction that produces the opposite effect from that intended (Burgess-Limerick, 2011; Burgess-Limerick & Steiner, 2007; Helander, Krohn, & Curtin, 1983; Miller & McLellan, 1973).

One means of reducing the probability of such errors is to ensure directional compatibility between control movement and response. Previous research into directional stimulus-response compatibility provides robust and consistent evidence that compatible relationships between stimulus and response directions result in faster and more accurate performance (Chua, Weeks, Ricker, & Poon, 2001; Fitts & Seeger, 1953; Proctor & Reeve, 1990). It has been argued that this compatibility effect occurs because compatible arrangements have "properties in common, and elements in the stimulus set automatically activate corresponding elements in the response set" (Kornblum, Hasbroucq, & Osman, 1990, p. 253). It has also been suggested that "if stimuli share features with responses or, more precisely, with the perceptual effects these responses produce, they are able to prime these responses, which facilitates response selection in conditions of stimulus response compatibility but hampers response selection under incompatible conditions" (Hommel, 2005, p. 10). Although performance in consistently incompatible situations improves with practice, even after extensive practice, performance has not been found to reach that of consistently compatible relationships (Dutta & Proctor, 1992; Fitts & Posner, 1967).

Although this area has a long history of study (e.g., see Loveless, 1962, for a review), the research has almost without exception involved relatively artificial laboratory tasks and reduced cue environments. Although such paradigms may be satisfactory for application to topics such as aircraft attitude displays (e.g., Yamaguchi & Proctor, 2010), the findings may not translate well to the complex combinations of movements inherent in equipment such as underground bolting rigs.

Industrial equipment, such as that used in mining, provides examples of equipment design that appear to violate the principles obtained in previous research. For example, it is relatively common to find situations in which downward movement of a horizontal control lever causes upward movement of the controlled element, such as a boom, timber jack, or drill steel. Some authors (e.g., Helander, Conway, Elliott, & Curtin, 1980) have suggested that this design is a violation of compatible directional control-response relationships. Simpson and Chan (1988), however, suggested on the basis of an examination of participants' reported expectations that this directional control-response relationship is compatible and that operators assume a "see-saw" mental model of the situation whereby moving the near end of the control downward causes the far end (and the controlled element) to move upward.

Burgess-Limerick, Krupenia, Wallis, Pratim-Bannerjee, and Steiner (2010) addressed this discrepancy 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 consistent with the data reported by Mitchell and Vince (1951) and not with the participant expectations reported by Simpson and Chan (1988). This discrepancy raised the possibility that self-reported directional expectations are not necessarily predictive of behavior. Hoffmann (1997), and Chan and Chan (2003) have similarly reported discrepancies between reported directional expectations and actual behavior.

It has also been observed that reported directional expectations derived from drawings were not entirely consistent with reported preferences derived from the use of a computer-generated version of the same situation (Kaminaka & Egli, 1984). Although an expectation that a vertical lever would be pushed to cause vertical movement was reported on the basis of a drawn representation of the situation, no consistent preference was reported from a situation in which a lever was used to cause a virtual image to be raised or lowered.

Burgess-Limerick et al. (2010) 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.

Virtual environments have also been used to assess directional control-response relationships for other situations. Zupanc, Burgess-Limerick, and Wallis (2007, 2011) and Burgess-Limerick, Zupanc, and Wallis (2012) used a virtual analogy of a shuttle car used in underground coal mines to assess directional compatibility of steering wheel and joystick steering systems, respectively.

Although experimental paradigms involving a virtual environment have a number of advantages, the lack of ecological validity is potentially problematic. It may be that the behavior exhibited when controlling physical objects may differ from that observed during the manipulation of objects in a virtual movement. Consequently, it could be that the conclusions reached by Burgess-Limerick et al. (2010) on the basis of investigations in a virtual environment are not applicable to a specific application within a physical environment.

Objectives

The aim of this experiment was to examine the pattern of direction errors made during the manipulation of a physical simulation of an underground coal mine bolting machine to assess the directional control-response compatibility relationships associated with the device and to compare these results to data obtained from a virtual simulation of a generic device.

METHOD

Apparatus

A physical simulation similar in configuration to a single-boom Fletcher Roof Ranger I bolting machine was used. The apparatus consisted of a bank of five levers that controlled a simulated boom (Figure 1). Four of the five levers controlled hydraulic actuators that caused the physical simulation to move in the following directions: (a) slew (swing) of the boom about a vertical axis of rotation toward or away from the operator; (b) elevation or depression of the boom via rotation about a transverse axis of rotation, which caused the simulated drill head to raise or lower; (c) sump (horizontal translation) of the boom in-bye (in this case, to the operator’s left) or out-bye (to the operator’s right); and (d) raising or lowering of a simulated stabilizing jack. The remaining lever caused a light mounted on the end of the boom to become illuminated in one of two colors (red or yellow). The levers were orientated either horizontally or vertically.

Two sets of directional control-response relationships were defined. In Control-Response Relationship 1 (CRR1), an upward movement of a horizontal lever, or a movement of a vertical lever away from the participant, caused either (a) the color to change to red; (b) the boom to slew toward the participant; (c) the boom to elevate, raising the drill head; (d) the boom to sump (translate) in-bye; or (e) the stab jack to lower. These relationships were reversed in Control-Response Relationship 2 (CRR2).

Participants and Procedure

Forty-eight participants (32 male and 16 female; ages 21 to 61, M = 45.3, SD = 12.9) were randomly assigned to (a) one of two direction compatibility conditions (CRR1, CRR2) and (b) vertical or horizontal levers.

Following a demonstration of the function of the levers, each participant completed six blocks of 40 trials. In each trial, the participants were presented with a short video clip of the simulated roof bolter arm responding in 1 of the 10 possible ways. The participants were required to choose a lever and move it in one of two directions to attempt to achieve the response indicated by the video clip. Equal numbers of each stimulus video clip were presented in random order in each block of trials.

Following each response, the participant returned the bolter arm back to the starting position using the control bank and depressed a button located to the right of the control bank to indicate that he or she was prepared for the next trial. The next stimulus was presented 2 s later. Each trial lasted approximately 10 s. A 1-min break was provided every 40 trials (approximately every 6 min).

Analysis

Direction errors were defined as a movement of the lever in the direction opposite to that required by the stimulus. A direction error was determined to occur if the participant both chose the wrong lever and moved it in the wrong direction.

Direction errors were expressed as percentages. Error data are bounded by zero, and the distributions were consequently skewed. Hence, median and interquartile ranges for these data are presented graphically, and inferential statistical analysis (factorial ANOVA) was undertaken on log transformed accuracy (100% error) data.

RESULTS AND DISCUSSION

Two-way ANOVA (Lever Orientation × Control-Response Relationship) for direction errors are provided in Table 1.

Color

No significant effects of orientation or directional control-response condition were found for the color lever, indicating that the randomization was effective in providing equivalent groups of participants in the four conditions. The median direction error for the color lever was 2.1%. This median direction error rate is higher than the 1.25% median rate reported by Burgess-Limerick et al.’s (2010) Experiment 2. This difference may reflect differences in experimental protocol or participants.

Boom Elevation

Significant effects of both directional control-response relationship and lever orientation were found for the elevating and depressing of the boom of the simulated single arm bolter (Figure 2A). Very few directional errors were made by participants assigned to the horizontal lever and CRR1 condition in which raising the horizontal lever caused the boom to elevate. When the controls were oriented vertically, fewer errors were also made by participants assigned to the CRR1 condition. In this case, moving the vertical lever away from the participant caused elevation of the boom and drill head; however, more errors were made in this situation than in the horizontal CRR1 condition.

These results are consistent with those obtained from the virtual simulation of a generic device (Burgess-Limerick et al., 2010). The comparable situation examined in the previous virtual simulation is clockwise elevation of the virtual device controlled by horizontal and vertical levers located to the participants’ right (Experiment 2, Burgess-Limerick et al., 2010). These data are plotted in Figure 2B for comparison. An identical pattern of direction errors is observed, although as for the color lever, the magnitude of error rate is greater in the current experiment.

These results reinforce the importance of optimized directional control-response compatibility for reducing directional error probability. This is particularly important for the drill feed function given the history of fatalities in the United States arising from bolter operators being crushed between the boom and roof or between boom and bolting machine structure (Mine Safety and Health Administration, 1994).

Slew

A significant interaction was found between lever orientation and directional control-response relationship for the slew lever (Figure 3). When lever orientation was horizontal, fewer directional errors were made by participants assigned to the CRR1 condition in which an upward movement of the horizontal lever causes the boom arm to swing toward the participant. When the lever orientation was vertical, fewer directional errors were made by those participants assigned to the CRR2 condition in which moving the vertical lever away from the participant caused the boom to swing away from the participant. In both situations, however, the direction of the lever movement, whether horizontal or vertical, was perpendicular to the movement of the boom rotation. Consequently, the median direction errors were greater than 5% in all situations examined, indicating that controlling rotation of the boom in the transverse plane (about a vertical axis of rotation) with either horizontal or vertical levers mounted as illustrated in Figure 1 is a relatively error-prone situation. These results are consistent with those obtained from the virtual simulation of a generic device (Burgess-Limerick et al., 2010) in that slew was generally associated with relatively high error rates; however, there was no directly comparable situation in the virtual simulation. Given that the operator is located between the slewing boom and the mine wall, direction errors of this nature have potential for serious unwanted consequences.

Sump

A significant effect of directional control-response condition was found; however, there was no significant effect of lever orientation, nor was the interaction significant (Figure 4). The fewest direction errors were made by participants assigned to the vertical lever orientation and CRR2. In this situation, a vertical lever was moved away from the participant to cause the model boom to move out-bye (to the right). When the lever orientation was horizontal, relatively many directional errors were made regardless of the control-response relationship condition. Although this situation is not directly comparable to any of the relationships examined in the previous experiments, the results are consistent with the principle of consistent direction and demonstrate that error rates are increased when the lever movement is perpendicular to the response direction.

Stabilizer Jack

Fewer errors were made in the horizontal lever condition when raising the horizontal lever caused the stabilizer jack to be raised. When the lever orientation was vertical, fewer errors were made when moving the vertical lever away from the participant caused the stabilizing jack to be raised. These differences were not statistically significant, however, illustrating variability in the participants' interpretation of the control response. This variability arises because activating the stab jack lever may be interpreted as lowering the stab jack, or it may be interpreted as stabilizing or raising the bolting machine in preparation for bolting. This situation is not comparable to any of the movements of the virtual device examined in the previous experiments. It does serve to illustrate the difficulty in determining an optimal design when the user's interpretation of the response may vary.

CONCLUSIONS

The pattern of direction errors observed during the use of the physical simulation of a specific piece of underground coal mining equipment is consistent with those observed in previous experiments involving a 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. The results provide evidence to support the validity of other experiments conducted in virtual environments (e.g., Burgess-Limerick et al., 2012; Zupanc et al., 2007, 2011) as a means of examining directional control-response relationships. These findings have been adopted in guidance material, such as Mining Design Guide 35.1 (Industry & Investment NSW, 2010), which provides assistance to designers of such equipment.

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Biographies

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KEY POINTS

- Discrepancies exist in the directional control-response relationships found in mining equipment.
- Previous experiments in a virtual environment have supported the general applicability of the principles of consistent direction and visual field compatibility; however, the applicability of these results to a physical environment is open to question.
- The patterns of direction errors observed in a physical simulation of a specific piece of underground coal mining equipment are consistent with previous experiments involving a virtual simulation of a generic device.
- The probability of direction errors is increased if the control and response movements are in opposite directions or if the directions of the control and response movements are perpendicular.

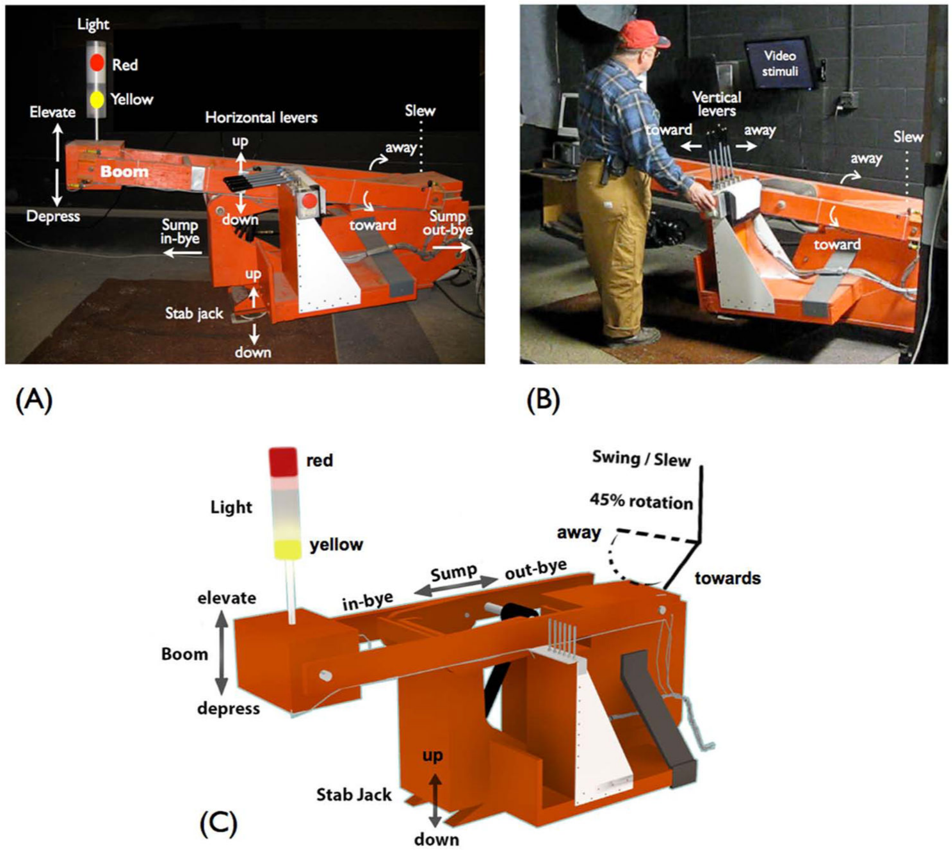

Figure 1.

(A) Simulated roof bolter arm, (B) participant performing the experiment, and (C) schematic representation of the bolter arm movements.

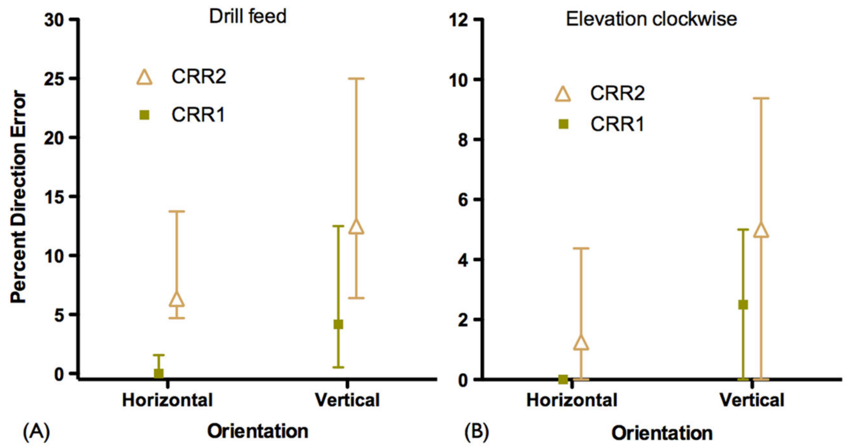

Figure 2.

(A) Boom elevation (elevate-depress) direction error and (B) clockwise elevation direction error data from Experiment 2, Burgess-Limerick, Krupenia, Wallis, Pratim-Bannerjee, and Steiner (2010).

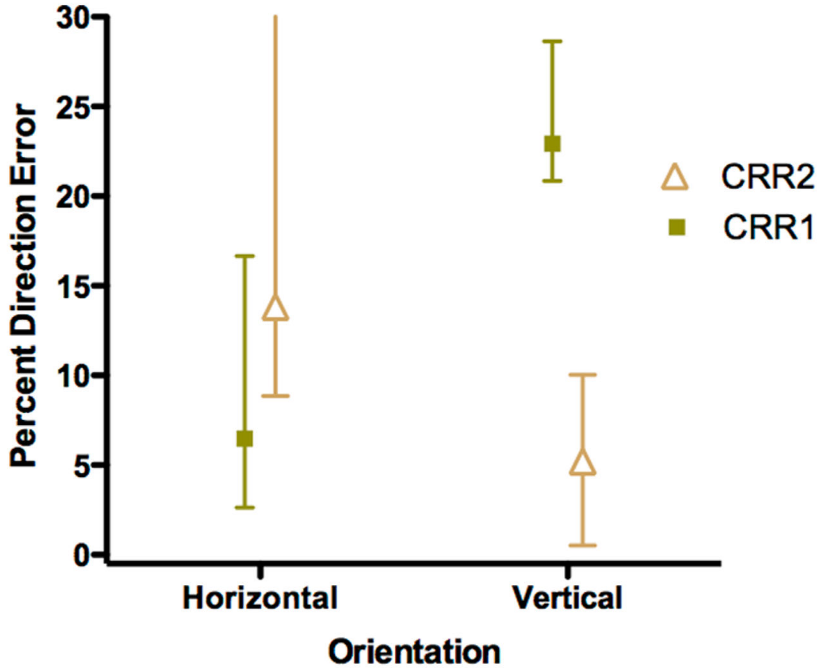

Figure 3.
Slew (swing) direction error.

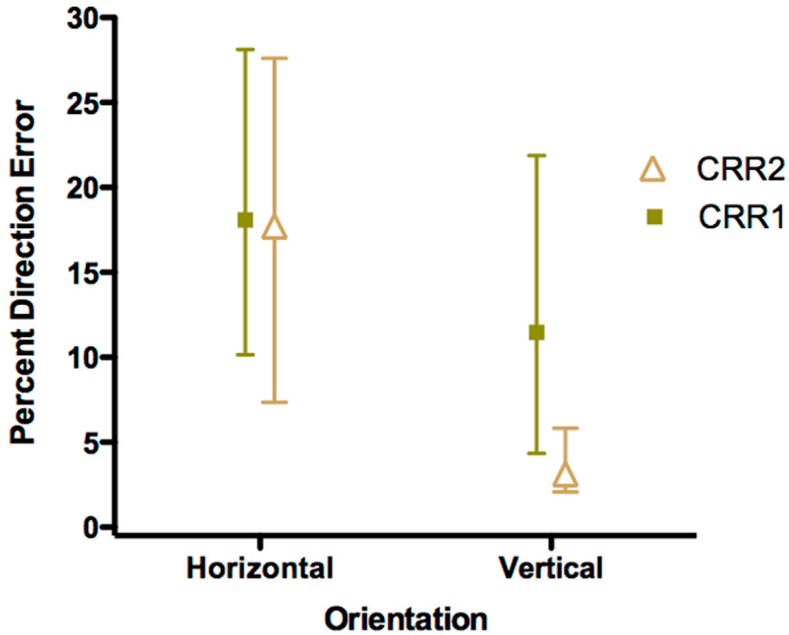

Figure 4.
Sump (in-out) direction error.

TABLE 1

Two-Way ANOVA Results for Direction Error

	Direction Errors					
	Orientation		CRR		Interaction	
Lever	***F***	***p***	***F***	***p***	***F***	***p***
Color	2.67	.110	3.90	.056	1.23	.275
Boom elevation	6.70	.013	6.08	.018	0.001	.941
Slew (swing)	0.278	.601	1.89	.176	25.43	<.001
Sump	2.45	.123	14.7	<.001	1.99	.165
Stabilizing jack	3.54	.066	2.85	.099	0.023	.879

Note. All degrees of freedom (1, 44). CRR = control-response relationship.