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Directional control-response relationships for mining equipment

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A variety of directional control-response relationships are currently found in mining equipment. Two experiments were conducted in a virtual environment to determine optimal direction control-response relationships in a wide variety of circumstances. Direction errors were measured as a function of control orientation (horizontal or vertical), location (left, front, right) and directional control-response relationships. The results confirm that the principles of consistent direction and visual field compatibility are applicable to the majority of situations. An exception is that fewer direction errors were observed when an upward movement of a horizontal lever or movement of a vertical lever away from the participants caused extension (lengthening) of the controlled device, regardless of whether the direction of movement of the control is consistent with the direction in which the extension occurs. Further, both the control of slew by horizontally oriented controls and the control of device movements in a frontal plane by the perpendicular movements of vertical levers were associated with relatively high rates of directional errors, regardless of the directional control-response relationship, and these situations should be avoided.

Statement of Relevance: The results are particularly applicable to the design of mining equipment such as drilling and bolting machines, and have been incorporated into MDG35.1 *Guideline for bolting & drilling plant in mines* (Industry & Investment NSW, 2010). The results are also relevant to the design of any equipment where vertical or horizontal levers are used to control the movement of equipment appendages, e.g. cranes mounted to mobile equipment and the like.

Keywords: control-response relationship; directional compatibility; equipment design; simulation; mining

1. Introduction

Mining remains a hazardous industry because of the close proximity of people to multiple sources of energy and adverse environmental conditions. Recent analyses of injury narratives have highlighted the potential for control errors to cause injury (e.g. Burgess-Limerick and Steiner 2006). One category of errors is 'selection' errors, when a control other than the intended control is operated (Burgess-Limerick *et al.* 2010). Another category might be called 'direction' errors, which occur when the correct control is operated, but in the opposite direction to that required to produce the intended outcome. A potential contributor to the probability of direction errors occurring is equipment in which the directional control-response relationships are not 'compatible'. The directional control-response relationships currently in use vary across equipment, even within equipment that have similar functions, and sometimes even change with changes in vehicle direction (Zupanc *et al.* 2007).

This is not a new observation. Helander *et al.* (1980) noted design deficiencies, including violation of direction stereotypes, associated with mining equipment and suggested that these deficiencies contributed to increased injury risks. 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 straightforward.

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, timber 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.

Simpson and Chan (1988) investigated this situation through an experiment in which 144 participants reported the direction they would move a control lever to achieve a specified effect, using a one-tenth model of a drill loading machine. Equal numbers of participants were drawn from three groups: equipment fitters/operators; design engineers;

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administrative and clerical staff. No significant differences were found between the groups for any of the directional relationships assessed, nor were responses found to differ as a function of experience. The results indicate that while the majority of participants reported responses consistent with a 'see-saw' mental model, the stereotype was far from universal and up to 33% of participants reported expectations for 'up = up'. Extremely strong expectations were reported for the movement of vertical controls, however, with more than 90% of participants expecting a backward movement of a vertical lever to cause an upward movement of a controlled element.

These expectations are not consistent with previous results, however (for a comprehensive review, see Loveless 1962). For example, Vince (1945 cited in Mitchell and Vince 1951) reported that participants' expectations are for an upward movement of a linear control to result in an upward linear movement of an associated display. This principle might be called the 'principle of consistent direction' and is generally reflected in current standards. Vince and Mitchell (1946) were similarly reported to have examined relationships between linear movements of control and displays in different planes, finding that a forward movement of a vertical control placed in front of participants was expected to cause an upward movement of an associated linear display.

Of relevance to the design of bolting controls, Humphries (1958) noted that directional expectations were influenced by operator position with regard to the control and displays. Participants were reported to expect a control movement to the right of the body to produce a display movement to the right of the field of view and for a control movement away from the body to produce an upward movement of the display.

More systematic investigations of the effect of operator orientation with regard to the display were undertaken by Worringham and Beringer (1989, 1998). The general principle of consistent direction was modified to accommodate situations in which an operator uses a control located to one side, or behind, while looking straight ahead. In this case (and consistent with Humphries 1958) the compatible directional relationships were reported to be ones in which the movement direction of the control in the virtual visual field (as if the participant was looking at the control) was consistent with the movement of the controlled element. This principle is referred to as 'visual field compatibility' and consistent results have been reported by Lulham and Burt (1999) and Chua *et al.* (2001).

Despite the definition of principles of 'consistent direction' and 'visual field compatibility', there remain combinations of lever movement and response direction for which designers have no evidence base upon which to make design decisions. This is complicated further by the apparently contradictory results reported by Simpson and Chan (1988). This paper provides a systematic and comprehensive examination of the association between directional control-response relationships and error rates for situations of varying control lever orientation, location and controlled element response. While the experiments were motivated by a particular industrial application, the results have more general applicability.

1.1. *Objectives*

The aim of this research was to determine appropriate directional control-response relationships as a function of control lever orientation (vertical or horizontal) and location (side-on and front-on). Two experiments were conducted in a virtual environment to address these questions. Control lever orientation and directional control-response relationship were manipulated in experiment 1, while control location was held constant in front of the participants. Control lever orientation, directional control-response relationship and lever location were manipulated in experiment 2.

2. Methods

2.1. *Apparatus*

A computer-generated simulation of a generic device (Figure 1) capable of slewing left and right (rotation about a vertical axis of rotation), elevation and depression (rotation about a horizontal axis of rotation), extension and retraction (lengthening or shortening of the virtual device) and changing colour, were created by a Silicon Graphics Onyx 3000® (SGI, Inc., Fremont, CA) equipped with InfiniteReality II graphics. The image was projected on to a reflective screen using a BARCO 808S analogue projector (Barco N.V., Kortrijk, Belgium) with a 24 Hz frame rate and screen resolution of 1280 × 1024 pixels. Participants used four levers to cause the movements of the virtual device (right image) to match those of the computer-controlled stimulus image on the left. The effect of each lever is described in Figure 2. The orientation of the control levers (horizontal or vertical) and location with regard to the participant (side-on and front-on) were manipulated.

2.2. *Procedure*

Each trial required correct operation of all of the four levers in different sequences, in response to four successive movements (or change in colour) of the

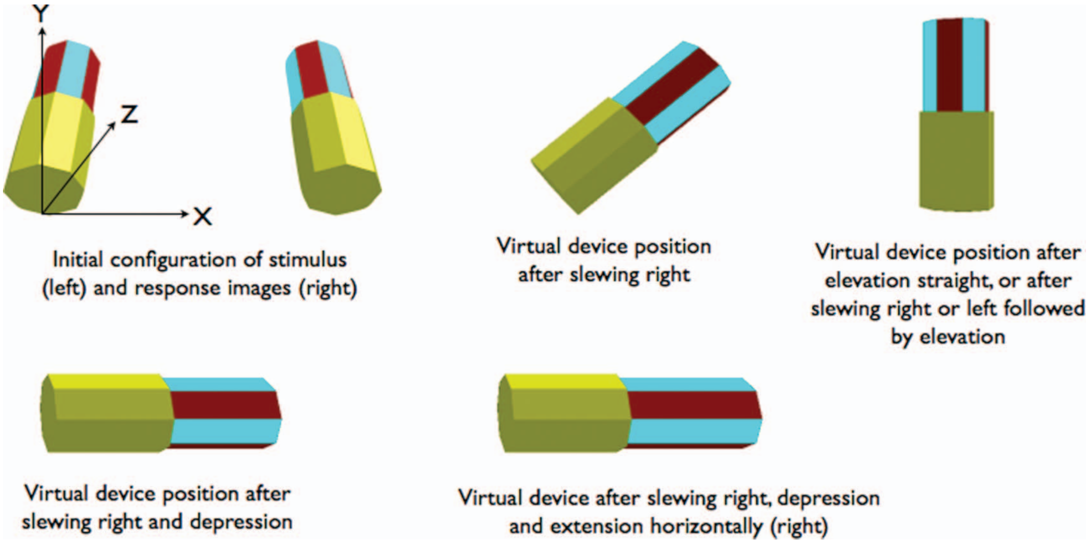

Figure 1. The computer controlled stimulus image (left) prompted participants to manipulate levers to cause the same change in the controlled image (right).

computer-controlled stimulus image. After the required response was indicated to the participant by the computer-controlled stimulus image moving (or changing colour), the participant's task was to move the corresponding lever in the correct direction to cause a matching change in the virtual model. If the correct control was operated in the correct direction, a C major chord was played and the next required movement presented. If an error was made, a descending series of tones was played, the participant-controlled virtual device returned to its prior position and the movement repeated until the correct movement was achieved. The nature of the initial error (selection or direction) was recorded. The order and direction of lever movements varied pseudo-randomly, such that each of 16 different combinations of four required movements appeared in random order during each block of 16 trials (Table 1). This block of 16 trials was presented 10 times to each participant.

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: (i) the colour of the lower portion of the virtual device to change to red; (ii) the virtual device to slew to the right (i.e. rotation about a vertical Y axis illustrated in Figure 1); (iii) the virtual device to elevate (if elevation occurred prior to slew (trials 1–4 and 13–16) then this was a rotation about the horizontal X axis directly towards the participant or, if the elevation was preceded by slew (trials 5– 12), then this movement was a clockwise or anti-clockwise rotation in the plane of the screen about the Z axis illustrated in Figure 1); or (iv) the centre part of the virtual device to lengthen (extend). Extension occurred vertically for those trials where elevation preceded extension/retraction (trials 1–8) and horizontally when extension was preceded by depression (trials 9–16).

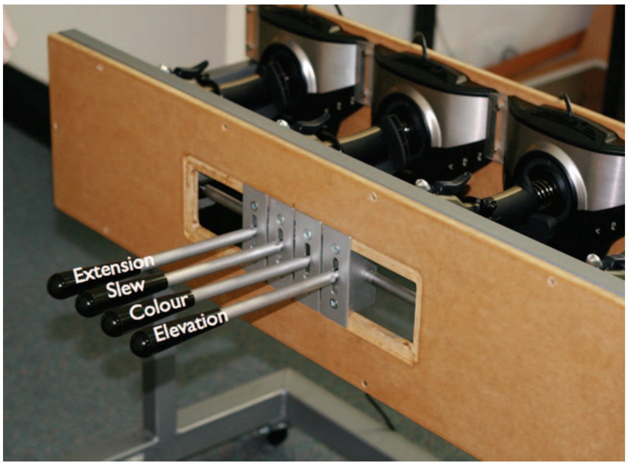

Figure 2. Levers manipulated by participants to cause movement of the virtual device. The lever bank orientation (vertical/horizontal) and position (front, left, right) was adjustable.

Conversely, for participants assigned to control-response relationship 2 (CRR2), an upward movement of a horizontal lever, or a movement of a vertical lever away from the participant, caused: (i) the colour to change to blue; (ii) the virtual device to slew to the left; (iii) the virtual device to depress; or (iv) the centre part of the virtual device to shorten (retract).

The participants comprised a convenience sample drawn from the University of Queensland population

Table 1. The 16 combinations of lever movements, which were presented to each participant in pseudo-random order in each block of trials.

Trial no.	Movement 1	Movement 2	Movement 3	Movement 4
1	Red	Up	Extend	Slew right
2	Up	Blue	Retract	Slew right
3	Up	Extend	Red	Slew left
4	Up	Retract	Slew left	Blue
5	Blue	Slew left	Up	Extend
6	Slew left	Red	Up	Retract
7	Slew right	Up	Blue	Extend
8	Slew right	Up	Retract	Red
9	Red	Slew right	Down	Extend
10	Slew right	Blue	Down	Retract
11	Slew left	Down	Red	Extend
12	Slew left	Down	Retract	Blue
13	Blue	Down	Slew right	Extend
14	Down	Red	Slew right	Retract
15	Down	Slew left	Blue	Extend
16	Down	Slew left	Retract	Red

across a range of schools, including the study pool maintained by the School of Psychology. All participants were paid $AUD20 for their participation in the experiment. All participants had normal or corrected to normal vision. No participants had experience in the operation of mining equipment. All participants provided written informed consent prior to testing. Ethical approval was provided by the School of Human Movement Studies Ethical Review Committee (approval HMS07/0103). The function of each lever was explained and demonstrated to each participant as part of a standard instruction script; however, no practice was provided. No person participated in both experiments.

In experiment 1, 48 participants (14 male and 34 female, aged 18 to 33, mean 21.8, SD 3.3 years) completed 10 blocks of 16 trials each, in which the levers were located directly in front of the participants (Figure 3). The levers moved either up and down (when the levers were oriented horizontally), or towards or away from the participant (when oriented vertically) The participants were randomly assigned to: (i) one of two direction compatibility conditions (CRR1 and CRR2); (ii) vertical or horizontal levers; (iii) left or right hand. Four participants self-reported being left handed. No more than one was allocated to any combination of conditions.

In experiment 2, 96 participants (34 male and 62 female, aged 19 to 49, mean 26.8, SD 7.2 years) completed 10 blocks of 16 trials, in which the levers were located to the left or right of the forward-facing participant. The control bank was oriented perpendicularly to the experiment 1 situation (Figure 3). The participants were randomly assigned to: (i) one of two direction compatibility conditions (CRR1 and CRR2); (ii) vertical or

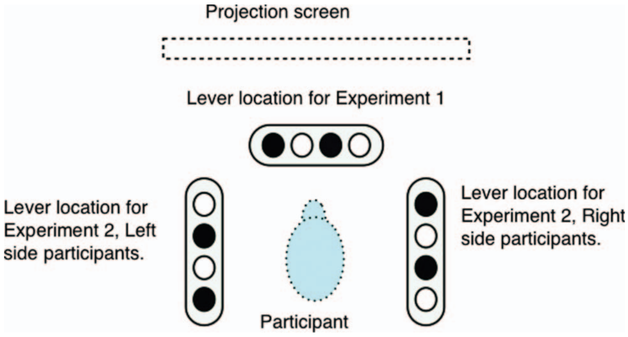

Figure 3. Schematic of experiment layout (not to scale).

horizontal levers; (iii) left or right side. Six participants self-reported being left handed. No more than one was allocated to each combination of conditions.

2.3. Analysis

The dependent variables were percent direction error for: colour change; slew; vertical extension; horizontal extension; elevation straight; elevation laterally movements. Error data are bounded by zero and the distributions are skewed as a consequence. Hence, median and interquartile ranges for these data are presented graphically and inferential statistical analysis (two-way and three-way ANOVA) was undertaken on log transformed accuracy (100%-error) data. Direction error rates were examined as a function of the independent variables of control lever orientation, directional control-response relationship and control side (experiment 2 only). An alpha of 0.01 was chosen to reduce experiment-wise error rate associated with the number of contrasts planned.

3. Results

3.1. Experiment 1: Effect of directional control-response relationship for front-on controls

Two-way ANOVA (lever orientation × control-response relationship) for direction errors are provided in Table 2.

3.1.1. Colour

No significant effects of lever orientation or directional control-response relationship were observed for direction error for the colour lever. The median direction error across all conditions was 0.63%.

3.1.2. Slew

No significant effects of lever orientation or directional control-response relationship were observed for

Table 2. Experiment 1 – Two-way ANOVA results for direction errors for each lever.

	Direction errors					
	Orientation		CRR		Interaction	
Lever	F	*p*	F	*p*	F	*p*
Colour	0.04	0.851	0.19	0.666	1.98	0.166
Slew	1.29	0.261	0.12	0.728	0.66	0.421
Vertical extension	0.68	0.413	22.6	<0.001	1.65	0.206
Horizontal extension	0.25	0.508	11.8	0.001	0.45	0.51
Elevation straight	1.68	0.201	0.05	0.838	7.57	0.009
Elevation laterally	4.97	0.03	5.84	0.02	0.05	0.820

CRR = control-response relationship.
Note: all degrees of freedom 1,44. ANOVA for direction errors calculated from log transformed data.

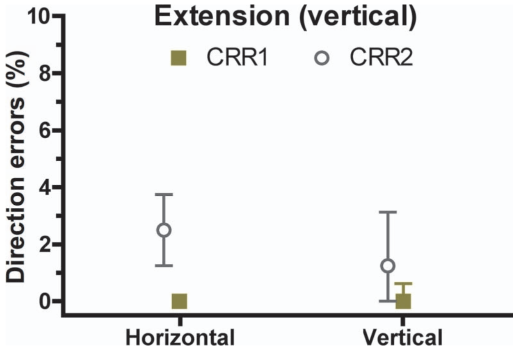

Figure 4. Experiment 1 – Median (interquartile range) direction errors for the 12 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the extension lever in those trials where extension or retraction occurred vertically (i.e. elevation of the device occurred prior to extension/retraction).

direction error for the slew lever. The median direction error across all conditions was 3.1%.

3.1.3. *Vertical extension*

The median rate of direction errors when extension or retraction of the virtual device in a vertical direction was required was significantly lower in the CRR1 condition regardless of the control orientation (Figure 4). An upward movement of a horizontal lever to extend a device vertically upwards was associated with more accurate performance in this experiment (front-on controls). Similarly, movement of a vertical control lever away from the forward-facing operator is compatible with the controlled device extending (lengthening) vertically upwards.

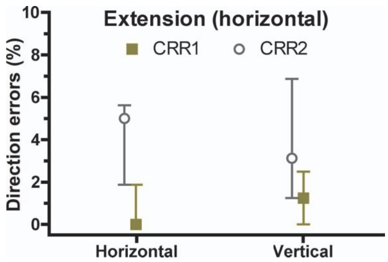

Figure 5. Experiment 1 – Median (interquartile range) direction errors for the 12 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the extension lever in those trials where extension or retraction occurred horizontally (i.e. depression of the device occurred prior to extension/retraction).

3.1.4. *Horizontal extension*

Significantly fewer errors were also observed for extension in the horizontal direction for participants assigned to the CRR1 condition (Figure 5). No significant effect of orientation was observed, nor were there any significant interactions between orientation and directional control-response relationships. Requiring an upward movement of a horizontal lever, or an away movement of a vertical lever, was compatible with a horizontal extension of the controlled device.

3.1.5. *Elevation straight*

A significant interaction between directional control-response relationship and lever orientation was noted for direction error (Figure 6). Participants assigned to the horizontal control lever condition made significantly fewer errors in the CRR1 condition. The reverse was true for those performing the task with vertical controls. To rotate a controlled device vertically backwards towards an operator facing the controls, fewer errors occurred if a horizontal lever was moved upwards, or a vertical lever was moved towards the operator.

3.1.6. *Elevation laterally*

No significant effects of control orientation or directional control-response relationship were observed when the elevation or depression occurred laterally, that is, in the plane of the screen, although the median direction error rate was zero for participants assigned to the CRR1 with horizontal

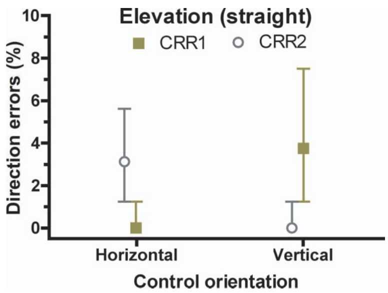

Figure 6. Experiment 1 – Median (interquartile range) direction errors for the 12 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the elevation lever in those trials where elevation or depression occurred directly towards or away from the participant (i.e. elevation or depression of the device occurred prior to slew).

lever orientation. The overall median direction error rate was 1.25%.

3.2. *Experiment 2: Effect of directional control-response relationships for side-on controls*

Three-way ANOVA (side × orientation × control-response relationship) results for direction error are provided in Table 3.

3.2.1. *Colour*

No significant main effects or interactions were found for the colour lever. The median rate of direction error was 1.25%.

3.2.2. *Slew*

A significant two-way interaction between lever side and the direction control-response relationship was observed (Figure 7). Direction errors were made less frequently when a horizontal lever on a participant's right side was raised to cause a right slew movement (CRR1), a vertical lever on a participant's right side was pushed away to cause a right slew movement (CRR1), a horizontal lever on a participant's left side was raised to cause a left slew (CRR2) a vertical lever on a participant's left side was pushed away to cause a left slew (CRR2). The lowest direction error rates were exhibited by participants assigned to the right CRR1 vertical and left CRR2 vertical conditions.

3.2.3. *Vertical extension*

A significant main effect of the directional control-response relationship was evident for directional error when operating the extension lever to lengthen or

Table 3. Experiment 2 – Three-way ANOVA results for direction errors.

	Side		Orientation		CRR		Side × orientation		Side × CRR		Orientation × CRR		Side × orientation × CRR	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
Colour	0.46	0.50	1.66	0.20	3.38	0.07	0.44	0.51	1.68	0.20	1.12	0.29	4.01	0.048
Slew	0.94	0.33	2.76	0.10	1.20	0.28	0.15	0.70	14.4	<0.001	0.172	0.68	6.12	0.015
Extend up	0.001	0.981	0.04	0.84	21.2	<0.001	0.03	0.86	0.02	0.88	0.21	0.65	2.42	0.123
Extend right	5.02	0.028	2.39	0.126	11.9	0.001	0.52	0.472	0.575	0.45	0.641	0.426	1.24	0.269
Extend Left	0.242	0.624	1.17	0.282	9.49	0.003	0.74	0.39	2.62	0.11	1.81	0.18	0.185	0.668
Elevate straight	0.244	0.622	10.2	0.002	2.38	0.13	0.473	0.49	0.008	0.928	27.79	<0.001	0.07	0.79
Elevate clockwise	2.20	0.14	0.42	0.52	2.58	0.11	1.14	0.29	0.01	0.93	8.89	0.004	12.8	0.001
Elevate anti-clockwise	2.72	0.10	17.1	<0.001	2.61	0.11	3.31	0.07	9.1	0.003	0.151	0.70	4.07	0.047

CRR = control-response relationship.
Note: all degrees of freedom 1,88. ANOVA for direction errors calculated from log transformed data.

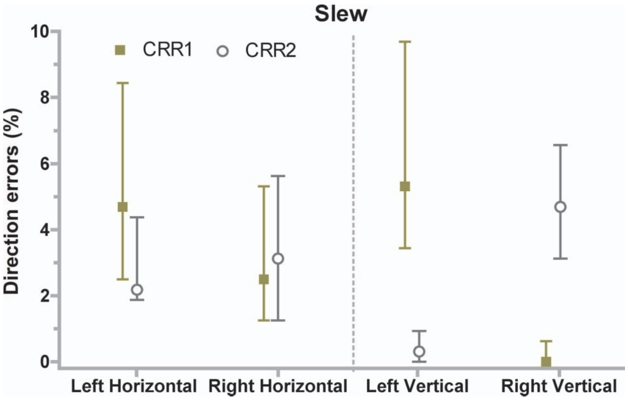

Figure 7. Experiment 2 – Median (interquartile range) direction errors for the 24 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the slew lever.

shorten the virtual device vertically (Figure 8). Regardless of the side or lever orientation, the lowest direction error rate occurred when a horizontal lever was raised, or a vertical lever was pushed away, to cause extension upwards.

3.2.4. *Horizontal extension*

Similarly, for both left and right horizontal extension, a significant main effect of directional control-response relationship was found. Regardless of side or lever orientation, fewer directional errors were consistently made in the CRR1 condition, that is, when raising a horizontal lever, or pushing a vertical lever away, caused horizontal extension (Figure 9).

3.2.5. *Elevation straight*

A significant interaction between directional control-response relationship and lever orientation was noted (Figure 10). For horizontal controls, participants assigned to the CRR1 condition made significantly fewer errors than those assigned to the CRR2 condition; whereas for vertical controls, the participants in the CRR2 condition made fewer errors. To rotate a controlled device vertically backwards towards an operator facing the controls, fewer errors occurred if a horizontal lever was moved upwards, or a vertical lever was moved towards the operator. The lowest error rates occurred in the horizontal lever, CRR1 condition and this difference resulted in a significant main effect of lever orientation.

3.2.6. *Elevation laterally*

When the controlled device was initially oriented 45° to the left or right, and elevated or depressed clockwise or

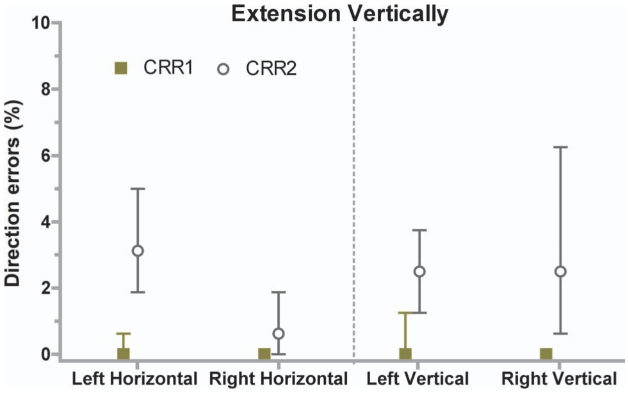

Figure 8. Experiment 2 – Median (interquartile range) direction errors for the 24 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the extension lever in those trials where extension or retraction occurred vertically (i.e. elevation of the device occurred prior to extension/retraction).

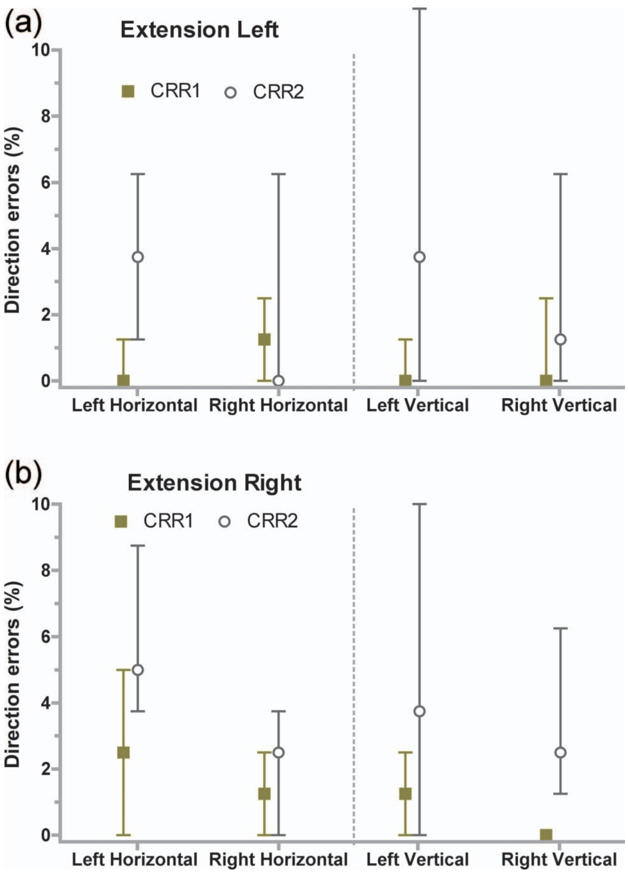

Figure 9. Experiment 2 – Median (interquartile range) direction errors for the 24 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the extension lever in those trials where extension or retraction occurred horizontally left (a) or right (b) (i.e. depression of the device occurred prior to extension/retraction).

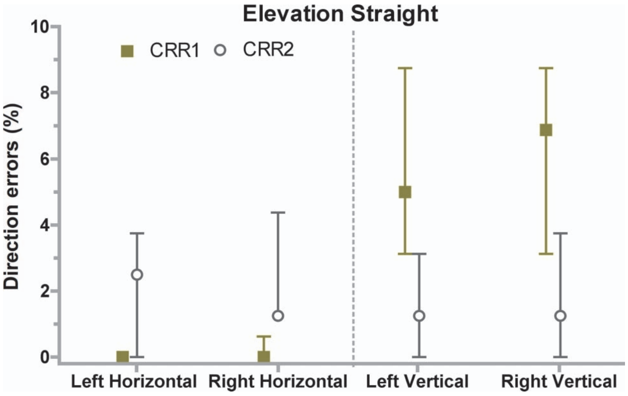

Figure 10. Experiment 2 – Median (interquartile range) direction errors for the 24 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the elevation lever in those trials where elevation or depression occurred directly towards or away from the participant (i.e. elevation or depression of the device occurred prior to slew).

anti-clockwise, the pattern of statistical results was complex. A combination of three-way interaction (for clockwise elevation) and two two-way interactions (orientation × control-response relationship for clockwise elevation and side × control-response relationship for anti-clockwise elevation) were observed, as well as a main effect of orientation for elevation anti-clockwise. Inspection of the median values (Figure 11) indicates that, in both cases, very low direction error rates were exhibited by participants assigned to the horizontal lever and CRR1 condition. Higher direction error rates occurred for participants assigned to the horizontal lever CRR2 condition, indicating that regardless of the side on which the lever was located, raising a horizontal lever was compatible with clockwise or anti-clockwise elevation. For vertical levers, it was evident that an interaction between side and directional control-response condition occurred, in that the fewest errors occurred when the direction of movement of the vertical lever was consistent with the direction of the response. For example, fewer errors occurred for a vertical lever placed to a participant's right when pushing the lever away caused clockwise elevation; whereas for a vertical lever placed to a participant's left, pulling the lever towards to cause a clockwise elevation caused fewer errors.

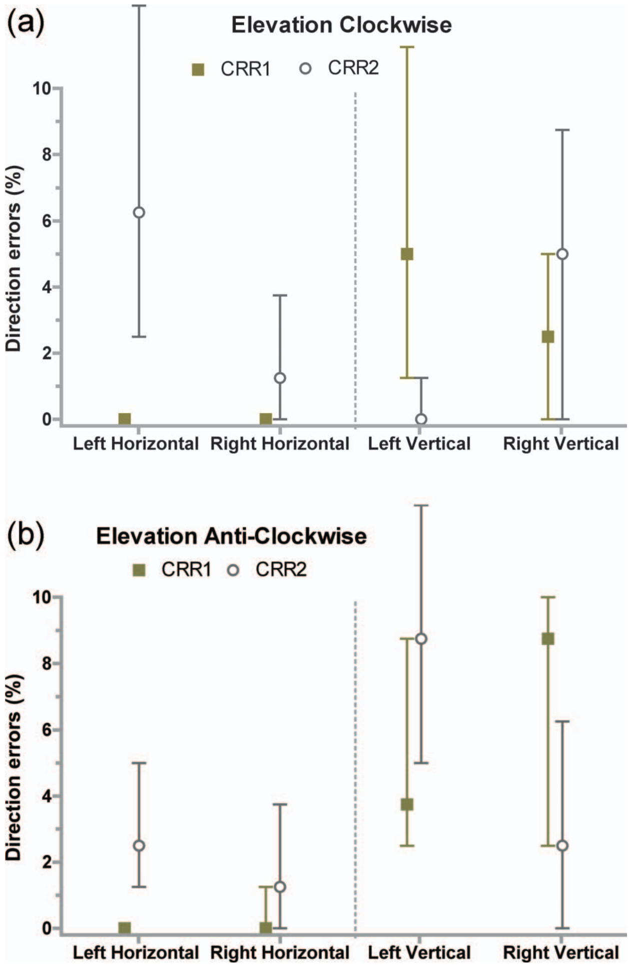

Figure 11. Experiment 2 – Median (interquartile range) direction errors for the 24 participants assigned to each combination of lever orientation and directional control-response relationship (CRR) for the elevation lever in those trials where elevation or depression occurred clockwise (a) or anti-clockwise (b) in the plane of the display (i.e. slew occurred prior to elevation or depression).

4. Discussion

The experimental paradigm was effective in discriminating differences in directional error rates between directional control-response relationships, and the results from both experiments were largely consistent. The task was relatively quickly learned and the majority of errors were made in the initial blocks of trials. With few exceptions, the results confirmed the general applicability of the principles of consistent direction, and visual field compatibility principle (Worringham and Beringer 1998). In particular, the finding that directional error rates were minimised 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 raises the possibility that self-reported directional expectations are not necessarily predictive of behaviour or of the ease of learning different directional control-response relationships. Hoffmann (1997) and Chan and Chan (2003) have similarly reported discrepancies between reported directional expectations and actual behaviour.

The control of slew was associated with a relatively high probability of control errors (median error rates above 2%) in most of the situations examined. The exceptions were situations in which a vertical lever was located to a participant's right or left with a directional control-response relationship such that moving the lever away caused the device to slew in the same direction. That is, a vertical lever located to a participant's right paired with a directional relationship, such that pushing the lever away caused a slew to the right, was associated with very few direction errors. Similarly, very few direction errors occurred when a vertical lever located to the participant's left was paired with a directional relationship such that pushing the lever away caused slew to the left. Only six of the participants in experiment 2 self-reported being left-handed. Random assignment resulted in no more than one left-handed participant being assigned to any combination of conditions, making handedness an unreasonable explanation for effects observed. The effects are consistent with the principle of consistent direction. Directional error rates were higher when the direction of movement of the slew (left or right) was perpendicular to that of the control (i.e. all front on situations examined and all horizontal lever orientations), regardless of the directional control-response relationship. These situations should, therefore, be avoided.

In contrast, the optimal directional control-response relationship for extension/retraction was not always consistent with the principle of consistent direction. Whether the controls were located in front or to either side of the participants, and regardless of whether the extension/retraction occurred when the virtual device was vertical or horizontal, directional error rates were significantly lower in the control-response conditions in which raising a horizontal control, or pushing a vertical control away, caused extension of the virtual device. This finding suggests that a compatibility relationship between 'lengthening/shortening' or 'extension/retraction' exists in addition to the directional movement relationship.

That said, the lowest error rates occurred when these movements were also consistent with the principle of consistent direction (for example, when a pushing a vertical lever located on a participant's right caused horizontal extension to the right), suggesting that the effects are additive.

The compatibility of the directional control-response relationship for the situation in which the controlled device was elevating or depressing (via rotation either towards or away from the participant or via clockwise or anti-clockwise rotation) depends on the orientation of the control. When the control was oriented vertically on the left or the right, the principle of consistent direction holds, in that very few directional errors occurred for a vertical control in front of the participant, when pulling the lever back caused the controlled device to rotate in the same direction (CRR2). Similarly, fewer direction errors occurred for clockwise and anti-clockwise device movement when the corresponding movements of vertical controls located to a participant's left or right were in the same direction.

In the situation where a vertical control to the left or right was used to elevate or depress the device directly towards or away from the operator, a directional control response, in which pulling the lever towards the operator caused elevation, resulted in fewer errors. This relationship is consistent with the results reported by Humphries (1958) and Worringham and Beringer's (1998) principle of visual field compatibility.

When a vertical control in front of the participant, moving towards or away from the participant, was used to control clockwise or anti-clockwise elevation and depression in the frontal plane, there was no advantage of either directional control-response relationship, and the rate of direction error was always relatively high. In this situation, neither directional relationship was compatible, and this situation should be avoided. Where horizontal controls were used to cause elevation, either towards the participant or in a perpendicular plane, fewer direction errors occurred in situations in which an upward movement of the lever caused elevation.

5. Conclusion

The principle of consistent direction and the visual field compatibility principle were predictive of the results obtained in the majority of combinations of control placement, orientation and device response examined here. The exception is the strong compatibility between an upward movement of a horizontal lever, and the away movement of a vertical lever, to cause extension (lengthening) of the controlled device, regardless of whether the direction of movement of the control is consistent with the direction in which the extension occurs. This finding suggests that another dimension of 'lengthening/shortening' or 'extension/retraction' directional compatibility exists in addition to movement directional compatibility. This finding is particularly important in the context of some mining equipment, where extension both vertically and horizontally occurs. The controls for such devices should be standardised to comply with this principle.

The effects of the different dimensions are likely to be additive, in that error rates were lowest when the upward or away movement of the control was also congruent with the direction of the extension.

The results also indicate that the control of left/right slew by horizontally oriented control levers and the control of clockwise/anti-clockwise elevation in a frontal plane with vertically oriented control levers were associated with relatively high rates of directional errors. These findings are of relevance for the design of other widely used equipment such as cranes (e.g. Sen and Das 2000).

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