Reducing control selection errors associated with underground bolting equipment

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A B S T R A C T

Selecting the incorrect control during the operation of underground bolting and drilling equipment causes serious injuries. Shape coding and the layout of dual control banks are two aspects of control design which require further examination. The aims of this research were: (i) to determine whether arbitrary shape coding was effective in reducing selection error rates in a virtual analogy of roof-bolting; and (ii) to determine whether any advantages exist for mirror or place layouts for dual control situations in this situation. Two experiments were conducted to address these questions. No benefits of arbitrary shape coding were evident while control location remained constant. When control location was altered, shape coding did provide a significant reduction in selection error rate. No differences between mirror or place arrangements were detected and this question remains open.

1. Introduction

The introduction of roof and rib bolting to prevent rock falls in underground coal mines was a major safety advance (Mark, 2002). However, additional hazards were introduced in the process. Analyses of narratives describing injuries occurring in both Australia and the United States of America have highlighted the potential of control errors during drilling and bolting to cause serious injuries (Burgess-Limerick and Steiner, 2006; 2007). Examples of typical bolting controls are illustrated in Fig. 1.

Standardising the controls on bolting machines has been suggested many times as a means of reducing the probability of control errors. 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. 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).

A Society of Automotive Engineers (SAE) standard titled “Human factors design guidelines for mobile underground mining equipment” which addressed these issues was defeated at a ballot in 1984 (Gilbert, 1990). A subsequent report (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.

While there are a number of aspects of bolting control design which require consideration, the experiments reported here focus on two topics related to reducing the probability of operating the wrong control, i.e. selection errors. The first issue is shape coding; the second concerns the layout of controls in the situation where multiple banks of controls are provided.

1.1. Shape coding

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 the US Mine Safety and Health Authority (MSHA) to investigate, and a report released (MSHA, 1994) which determined the causes to be the unintentional operation of controls. Amongst other suggestions, a recommendation included in this report was: “Provide industry-wide accepted distinct and consistent knob shapes”.

The MSHA subsequently called for industry comment on an advance notice of proposed rulemaking titled “Safety standards for the use of roof-bolting machines in underground mines” (MSHA, 1997) which suggested that MSHA was developing design criteria for underground bolting machines.

The New South Wales Department of Primary Industries publishes “Mining Design Guidelines” to assist mining companies and

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Fig. 1. Examples of bolting rig controls. The controls illustrated in the top of the figure are on a stand-alone bolting machine; those on the bottom are for bolting rigs located on a continuous mining machine (an integrated bolter-miner).

equipment manufacturers meet their obligations to provide "fit for purpose" equipment. Mining Design Guideline 35.1 (MDG35) "Guideline for bolting and drilling plant in mines, Part 1: Bolting plant for strata support in underground coal mines" (NSW DPI, 2009a) has been published which stipulates a standard set of knob shapes for the primary bolting controls (rotation, feed and timber jack).

While shape coding is very commonly recommended within Human Factors texts, empirical evidence of the effectiveness of shape coding in reducing selection errors is scant. The most frequently quoted example of the effectiveness of shape coding is the instigation in World War II of the use of a wheel shaped knob to correspond to the wheel raising/lowering in an aircraft to reduce the probability of pilots retracting the wheels on landing, rather than the flaps as intended. This evidence remains anecdotal, and as the investigator concerned described the situation, shape coding was not the only control employed viz:

> "I was asked to figure out why pilots and copilots frequently retracted the landing gear instead of the landing flaps after landing… What I found on inspecting the cockpits … was two identical toggle switches side by side, one for the landing gear, the other for the flaps. Given the stress of landing after a combat mission, it is understandable how they could have been easily confused. … The ad hoc remedies proposed at the time (separate the controls and/or shape code them) were substantiated in the human factors literature years later. Another remedy was a more mechanical one – installing a sensor on the landing struts that detected whether they were compressed by the weight of the aircraft. If so, a circuit deactivated the landing gear control in the cockpit" (Chapanis, 1999, p.15–16).

Despite the claim that shape coding was later substantiated, only two published papers exist which address the issue. Both were conceived with aviation applications in mind, and neither provided unequivocal evidence for the benefits of shape coding. This lack of evidence was commented on by Roscoe (1980), who noted:

> "The discriminability of shape-coded switch knobs had been studied vigorously following World War II. … However, further application of shape coding was stalled because no investigator had demonstrated a reliable improvement in any critical switching operation attributable to the application of discriminably shaped switch knobs." (p. 274).

Weitz (1947) reported two experiments in which participants operated one of four levers in response to pairs of stimulus lights under varying shape coding conditions. The task was to make as many correct lever movements as possible in a one-minute trial. No differences were found in the number of selection errors between coded and non-coded conditions in situations in which the layout of the controls was unaltered during the experiment. However, fewer selection errors were made by participants assigned to a shape coded condition when the layout (order) of the controls was altered during the experiment.

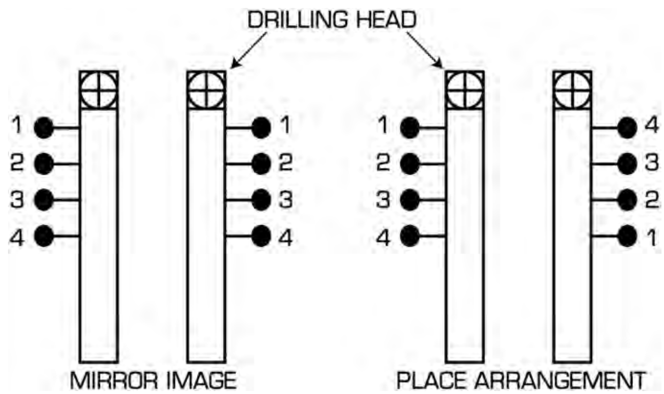

Fig. 2. "Mirror" and "Place" alternatives for situations where dual workstations are provided on different sides of a machine (after Helander et al., 1980).

Slocum et al. (1971) placed participants in a dual task paradigm in which the secondary task was to rotate one of four knobs in response to verbal commands. Three coding conditions were employed: non-shape coded; arbitrary shape coding; and coding which corresponded meaningfully to the commands given. A reduction in selection errors was found for the meaningfully coded knobs for the first block of 48 trials only. No difference was found between arbitrary coded and non-coded knobs during this block, nor were there any differences in error rate between any of the conditions in the second block of trials.

In summary, there is limited evidence that meaningful coding may reduce selection errors, however, arbitrary shape coding has not been demonstrated to reduce selection errors when the location of controls remains constant. The only evidence for a benefit of arbitrary shape coding suggests that a reduction in selection errors may occur following a change in the layout of controls.

1.2. Mirror versus place layouts

Bolting machines, whether stand-alone, or integrated onto continuous miners, typically have dual control stations. The operator will use different hands to operate the controls depending on whether the control bank is to the left or right of the bolting rig. A question then arises regarding the appropriate relationship between the control layouts at the different stations. One alternative is for the control arrangement to be "mirrored", that is, for the controls to be laid out such that controls to be operated by left and right hands are in the same order relative to the drill head, that is the control closest to the drill head on each side corresponds to the same machine function. A non-mirrored arrangement, or "place" arrangement has the controls laid out in the same order left-to-right, that is the left-most control on both sides controls the same function, and so on (Fig. 2).

Helander et al. (1980) noted that the question was controversial, and cited a Masters thesis by Pigg (1954) as the best available evidence. This research involved 64 participants learning a four choice reaction time task in which different colours of a light were paired with four switches placed in a row facing the participant to the left or right of a display containing the light. After six blocks of eight trials, subjects changed hands and repeated the task with the switches either presented in the same left-right sequence, or in a mirrored sequence. The mean time taken to complete eight correct responses (including the time taken for errors) was longer for the first eight trials following the change of hand for those participants in the left–right condition relative to the mirror condition, but this difference was absent in the second and subsequent eight trial series. Fewer errors were also made,

Fig. 3. The computer controlled stimulus image (left) prompted participants to manipulate levers to cause the same change in the controlled image (right).

however no statistical analysis was undertaken of the error data. On the basis of these results, Helander et al. (1980) recommended a mirrored layout, and this recommendation was contained in the proposed SAE standard (Gilbert, 1990).

However, while not citing any evidence, a contrary recommendation was made by Muldoon et al. (1980) "Once an operator learns that rotate is to the left of feed, he should not have to relearn that rotate is to the right of feed on the right boom." … "Since mirror image controls confuse the operator and do not increase efficiency, they should not be used" (p. 41). The proposed "Human Factors Guidelines for Mobile Underground Equipment" provided by Essex Corporation in 1984 (Gilbert, 1990) also recommended against mirror image control configurations for drill stations. Machine Design Guideline 35 (NSW DPI, 2009a) similarly stipulates that controls should be arranged "so that the controls are handed identically, irrespective of the location on the bolting plant e.g., the right hand lever should operate the same function on both sides of the bolting plant".

1.3. Objectives

The aims of this research were: (i) to determine whether arbitrary shape coding as proposed within MDG35 is effective in reducing selection error rates in a virtual analogy of operating bolting controls; and (ii) to determine whether any advantages exist for mirror or place layouts for dual control situations. Two experiments were conducted to address these questions.

2. Methods

2.1. Apparatus

A computer generated simulation of a generic device (Fig. 3) 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 ® equipped with InfiniteReality II graphics. The image was projected onto a reflective screen using a BARCO 808S analogue projector 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 on the right to match those of the computer controlled stimulus image on the left. The levers were either identical, or shape coded according to the recommendations of MDG35. These shapes, and the effect of each lever, are described in Fig. 4. A schematic layout of the situation is provided in Fig. 5.

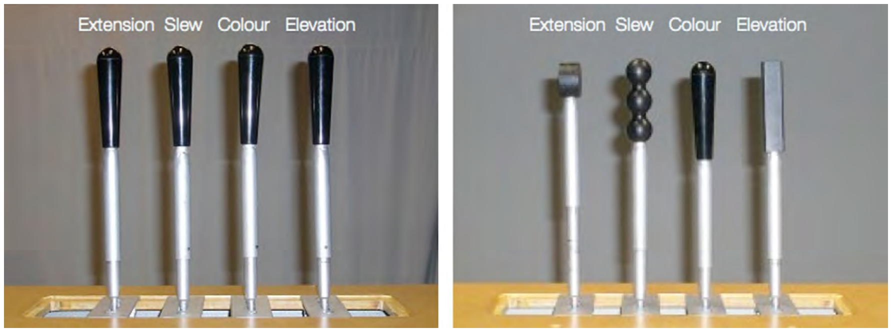

Fig. 4. Levers manipulated by participants in either non-shape coded (left) or shape coded (right) conditions. The shape coded levers utilise the shape provided in MDG35.1 (NSW DPI, 2009a,b).

2.2. Procedure

Each trial required each of the four levers to be operated in varying orders. The required lever and direction of operation was indicated to the participant by the computer controlled image moving (or changing colour). The participant's task was to move the correct lever in the correct direction to cause a matching change in the virtual device controlled by the participant. 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 series of descending tones were 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. For correct responses, the time taken until the lever was operated was recorded (choice reaction time). The order and direction of lever movements varied pseudo-randomly in that each of 16 different combinations of required movements was presented in random order during each block of trials.

In Experiment one, 48 participants were assigned to shape coded or non-coded horizontal controls, with the controls initially placed on the left or right side of the participant. The participants completed five blocks of 16 trials (each trial involving moving each of four levers, prompted via a visual stimuli of a virtual device). Following the initial five trials, the participants changed sides, and performed a second set of five blocks of trials with the levers on the opposite side. For 24 of the participants the order of the levers remained constant from left to right ("place" transfer condition), while for the remaining 24 participants the lever order was reversed ("mirror" transfer condition).

In Experiment two, 36 participants completed 10 blocks of 16 trials, with the location of the levers alternating between left and right with each block. The participants were randomly assigned to (i) the initial side (left or right) and (ii) mirror, place, or random arrangement of levers. The levers were non-shape coded and direction compatibility was constant.

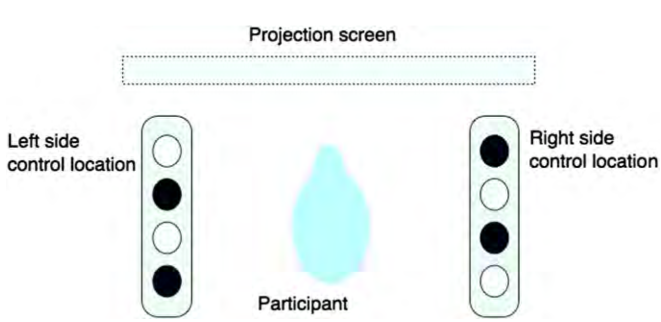

Fig. 5. Schematic of experiment layout (not to scale).

2.3. Analysis

Percent error was calculated for selection error and direction error measures. Error data are bounded by zero, and the distributions are skewed as a consequence. Median and interquartile ranges for these data are presented graphically, and inferential statistical analysis were undertaken on log transformed accuracy (100 − %error) data. Selection error rates and reaction time were examined as a function of coding and block.

3. Results

3.1. Experiment one

Fig. 6 illustrates the median selection error rates and reaction time for each group for the 10 blocks of trials. Median error rates were very low following the first block of trials and, apart from a main effect of block (F [9396] = 24.7, $p < 0.001$), there were no significant effects of group, nor were there any significant two-way or three-way interactions. Similarly, apart from a main effect of block on reaction time (F [9396] = 77.9, $p < 0.001$), there were no significant effects of group, nor were there any significant interactions for reaction time.

Following five blocks of trials, the side on which the levers were placed changed from right to left, or vice versa. The error and reaction time data for the block of trials immediately following the change of sides (block six) was extracted for further analysis. A Two-way ANOVA on the log transformed data revealed a significant effect of coding (F [1,44] = 7.54, $p = 0.009$), but no significant effect of lever layout (mirror or place) (F [1,44] = 0.005, $p = 0.947$), nor any interaction (F [1,44] = 0.19, $p = 0.665$). No significant differences were found for reaction time during this block of trials. (Effect of coding F [1,44] = 2.422, $p = 0.127$; Effect of group F [1,44] = 0.033, $p = 0.858$; Interaction F [1,44] = 0.128, $p = 0.723$).

3.2. Experiment two

Fig. 7 provides median selection error rates and mean reaction time for the three groups of participants across ten blocks of trials. A Two-way ANOVA performed using log transformed accuracy data revealed a main effect of block (F [9297] = 6.37, $p < 0.001$) but no significant effect of group (F [2297] = 0.63, $p = 0.537$), nor any interaction (F [18,297] = 0.74, $p = 0.773$).

A Two-way ANOVA conducted on the reaction time for correct responses revealed that while the main effect of group was not significant (F [2297] = 0.64, $p = 0.534$); there was a significant effect of block on reaction time (F [9297] = 63, $p < 0.001$) and a significant interaction between block and group (F [18,297] = 2.014, $p = 0.0091$) indicating that longer time was taken to operate the levers by participants in the random lever arrangement during some blocks

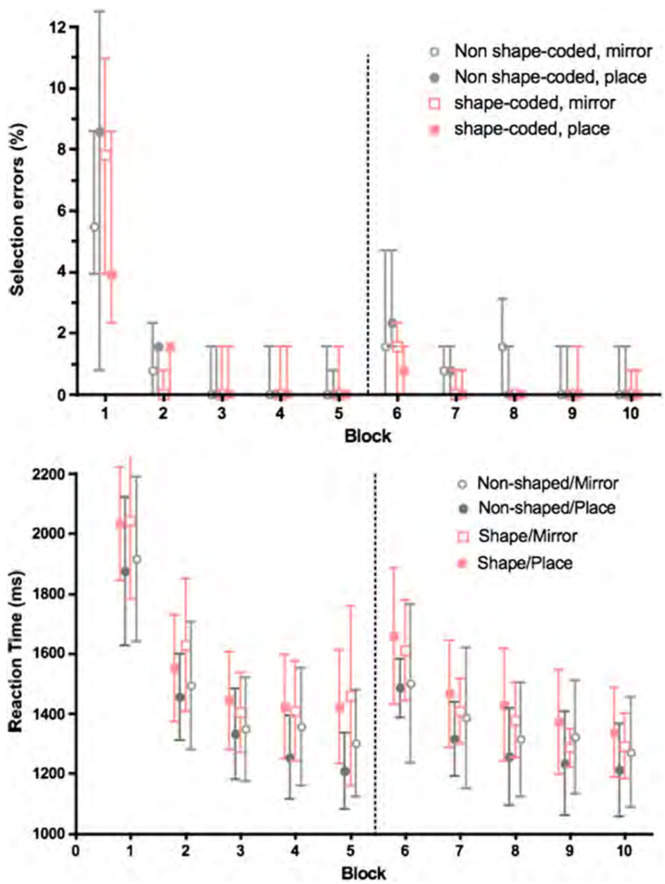

Fig. 6. Median (interquartile range) selection errors and mean (95% confidence interval) reaction time as a function of group and block for Experiment 1.

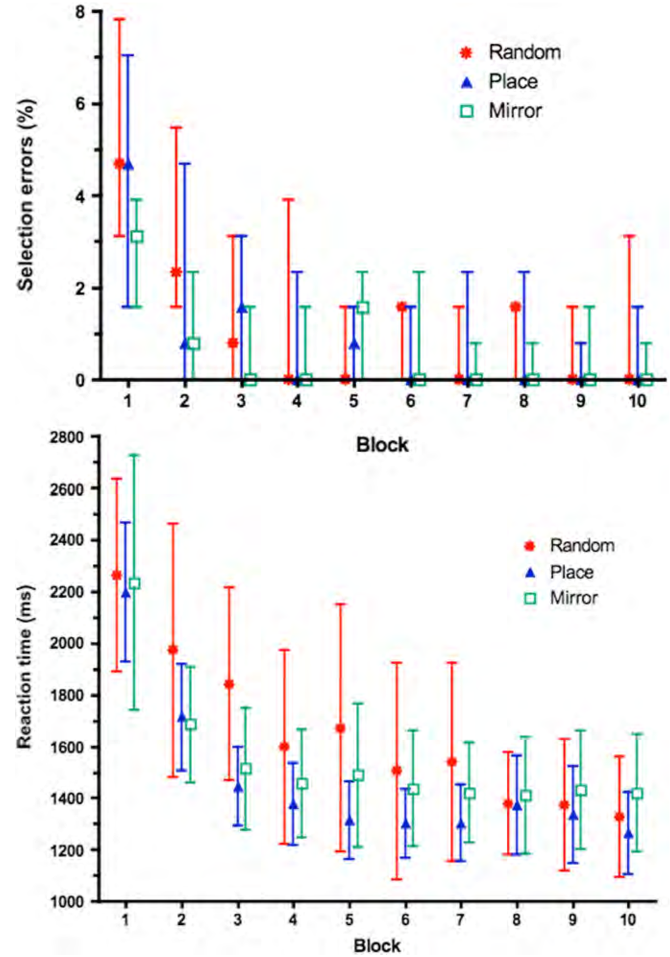

Fig. 7. Median (interquartile range) selection errors and mean (95% confidence interval) reaction time as a function of group and block for Experiment 2.

(two to five). No significant differences between place and mirror arrangements were present.

4. Discussion

The results of Experiment one do not provide any evidence that arbitrary shape coding was effective in reducing the probability of selection errors during the performance of a task requiring the manipulation of one of four levers, when the layout of the controls remained constant. However, for the block of trials immediately following the change of side, a significantly lower selection error rate was found for participants assigned to the shape coded conditions.

The frequency of selection errors was very low after the initial block of 16 trials (64 correct lever movements) suggesting that although the duration of the experiment was relatively brief, the task was quickly learned, and increasing the duration of the experiment would be unlikely to lead to differing conclusions. However, the task characteristics, particularly the relatively small number of levers, may have created a situation in which selection errors were unlikely to occur once the task was learned. It may be that a larger number of levers may have lead to an observable advantage of shape coding whilst control location remained constant.

The virtual environment paradigm suffers from a lack of ecological validity, particularly in absence of significant cognitive demands or competing attentional demands. A more realistic scenario in which the operator's attention was divided, may have yielded a greater number of selection errors, and hence greater opportunity for the potential benefits of shape coding to be realised. The experimental participants consisted of a convenience sample drawn from university staff and students, and none had experience operating underground bolting machines. It is possible that experienced operators may have utilised the shape coding cues more effectively (although few operators have experience of shape coded controls). Additional investigations are underway at NIOSH Pittsburgh Research Laboratory to explore these issues further using physical models of bolting machines.

The previous literature examining shape coding provides consistent evidence, however. Slocum et al. (1971) utilised a dual task paradigm, and similarly, found no evidence of a benefit of arbitrary shape coding. The second experiment reported by Weitz (1947) required participants to select between seven levers, also leading to consistent results. This experiment is worthy of closer examination. Fig. 8 is redrawn from Weitz (1947) and presents the average number of selection errors for four groups of 25 participants who performed 16 one-minute trials in which four of seven controls were manipulated in response to four pairs of stimulus lights. The levers were either shape-coded (groups I and II) or identical (groups III and IV), and for two groups (I and III) the lever locations were changed after eight trials; while the lever locations remained constant for the remaining groups (II and IV).

The average error data for groups II and IV demonstrates no evidence of an advantage of shape coding when the location of the levers remained constant. However, a comparison of the data from

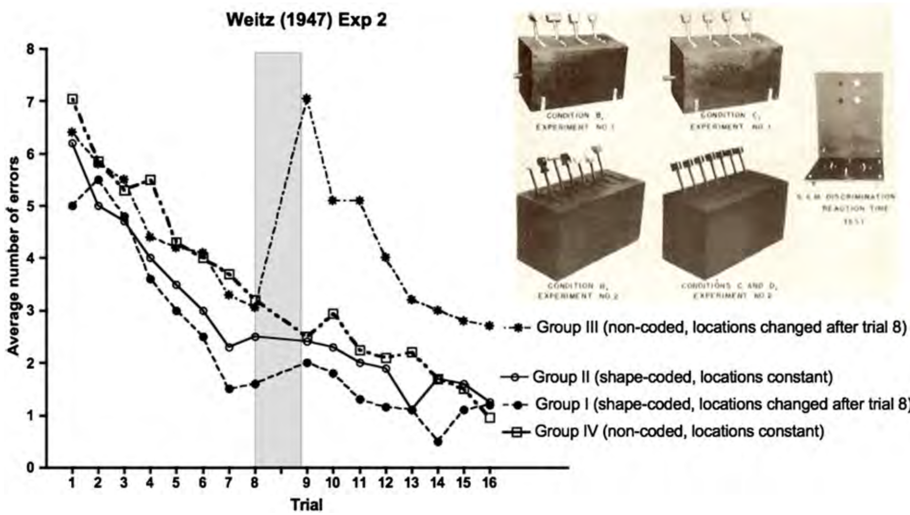

Fig. 8. Average selection errors for four groups of participants manipulating four of seven levers in response to pairs of lights. For groups I and III the order of the levers was changed after eight trials, while the order remained constant for groups II and IV. The levers were shape coded as illustrated (labelled "Condition B") for groups I and II, and non-coded for groups III and IV. (Figure redrawn from Weitz, 1947).

groups I and III demonstrates a reduction in error rates achieved by shape coding in the situation in which the location of levers is altered. These data, in conjunction with the data provided by Experiment one here, justify a recommendation that shape coding should be employed for bolting control levers. However, for maximum benefit, and perhaps for any benefit, to be realised, the shapes must have a consistent relationship to lever function between different bolting equipment, as well as within the same piece of equipment. Consequently, the shapes proposed for bolting equipment in MDG35 should be employed universally for all underground drilling and bolting equipment.

Further, the provision of shape coding creates an additional risk that selection errors may be provoked if the shapes were inadvertently swapped during equipment maintenance. This risk was highlighted by the investigation of a serious injury (NSW DPI, 2009b) in which it was noted that:

> "The bolter rotation and bolter raise control handles are located beside each other at the same height but are differing shaped handles. The handle shape was not consistently applied to all control stations on the machine".

Consequently, it is recommended that standards which specify shape coding should also include a provision stipulating that the design of the controls must incorporate a means of ensuring that the shaped handles cannot be inadvertently fitted to the incorrect lever. This recommendation is consistent with clause 5.4.1.4.4.e of MIL-STD-1472f (DOD, 1999) which states "Shape-coded knobs and handles shall be positively and non-reversibly attached to their shafts to preclude incorrect attachment when replacement is required".

Neither experiment was able to demonstrate a difference between mirror or place layouts for situations in which dual control workstations are provided. Limited evidence was available to suggest that both mirror and place layouts had an advantage over a random arrangement, at least in the absence of shape coding. It may be that either place or mirror arrangements are satisfactory, although there may be advantages in standardising on one or the other. The only previous examination of the topic (Pigg, 1954) provided evidence only of a very short-lived temporal advantage of a mirror arrangement (although in this case the orientation of the controls was constant, with the only change being the hand used). Again, the limited ecological validity of the paradigm means that the results must be interpreted with caution. However, the question of whether control layouts for dual control situations should be mirrored or place remains open and should be the subject of further investigation, ideally using a paradigm which more closely resembles the real task.

5. Conclusion

Evidence exists to suggest that beneficial consequences of arbitrary shape coding exist in situations in which the relationship between shape and function is constant, but the location of the controls is altered: either by changing to a different workstation; or a different machine. Consequently it is important to ensure that the relationship between shape and function is standardised, and that a means is provided to prevent shaped handles being placed on the incorrect lever. Whether arbitrary shape coding has benefits when control layout remains constant is unknown. Further research is required to determine whether mirror or place arrangements should be used where dual controls banks are provided for operation by left and right hands. To overcome the limited ecological validity of the current paradigm, future research should be undertaken using a paradigm which more closely resembles the real task.

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