Performance Consequences of Alternating Directional Control-Response Compatibility: Evidence From a Coal Mine Shuttle Car Simulator

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Objective: To investigate error and reaction time consequences of alternating compatible and incompatible steering arrangements during a simulated obstacle avoidance task. **Background:** Underground coal mine shuttle cars provide an example of a vehicle in which operators are required to alternate between compatible and incompatible steering configurations. **Methods:** This experiment examines the performance of 48 novice participants in a virtual analogy of an underground coal mine shuttle car. Participants were randomly assigned to a compatible condition, an incompatible condition, an alternating condition in which compatibility alternated within and between hands, or an alternating condition in which compatibility alternated between hands. **Results:** Participants made fewer steering direction errors and made correct steering responses more quickly in the compatible condition. Error rate decreased over time in the incompatible condition. A compatibility effect for both errors and reaction time was also found when the control-response relationship alternated; however, performance improvements over time were not consistent. Isolating compatibility to a hand resulted in reduced error rate and faster reaction time than when compatibility alternated within and between hands. **Conclusion:** The consequences of alternating control-response relationships are higher error rates and slower responses, at least in the early stages of learning. **Application:** This research highlights the importance of ensuring consistently compatible human-machine directional control-response relationships.

INTRODUCTION

Driving is a complex perceptual-motor task in which a person controls a vehicle's heading by manipulating a steering wheel in response to internal goals and external stimuli. A driver's performance is influenced by many factors, a critical one being the control-response (C-R) compatibility between the movement direction of the steering control and the response of the vehicle. In most vehicles the steering control is located in front of the driver (facing the direction of travel) and there is a compatible C-R relationship between the movement of the control and the response of the vehicle; that is, clockwise rotations of the steering wheel are compatible with the vehicle heading changing to the operator's right, and counterclockwise rotations result in heading changes to the operator's left. This C-R relationship results in error-free, automatic, and stereotyped steering behaviors (Groeger, 2001).

Research into stimulus-response (S-R) compatibility provides robust and consistent evidence that blocks of compatible S-R trials result in faster and more accurate performance than blocks of incompatible S-R trials (Chua, Weeks, Ricker, & Poon, 2001; Fitts & Seeger, 1953; Proctor & Reeve, 1990). It has been argued that this S-R compatibility effect occurs because compatible S-R ensembles 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,

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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 the discussion continues, there is broad agreement that performance benefits from access to "automatic" or "overlearned" processing when there is a high degree of association or similarity between elements or features of the S-R set. The compatibility effect phenomenon has practical relevance in predicting performance in real-world tasks. For example, when there is a compatible relationship between the movement direction of a control and the subsequent movement direction of the system, better performance is predicted than when this relationship is incompatible.

Another S-R compatibility finding is that performance in consistently incompatible S-R ensembles improves with practice, but even after extensive practice it has not been found to reach that of consistently compatible S-R relationships (Dutta & Proctor, 1992; Fitts & Posner, 1967). For random visuomotor choice reaction tasks in which the compatibility of the trials is not cued before presentation of the stimulus, the reaction time S-R compatibility effect is eliminated, and performance for both compatible and incompatible trials is worse than for pure blocks of incompatible trials (de Jong, 1995; Duncan, 1975; Stoffels, 1996; Van Duren & Sanders, 1988; Vu & Proctor, 2004). The reaction time performance decrements in the compatible trials are generally worse than decrements in the incompatible trials. However, in mixed/random blocks, when the compatibility of the trial is known before the stimulus presentation (precued), a compatibility effect is reinstated between compatible and incompatible trials (de Jong, 1995; Shaffer, 1965; Stoffels, 1996).

Cunningham and Welch (1994) investigated performance in a visuomotor tracking task in which the mapping between the moving target and the stylus-controlled cursor alternated between a "normal" mapping and one in which the mapping was rotated 108° clockwise. Normal and rotated trials were presented in precued alternating blocks of various time periods (ranging from about 2 to 8 min). Results showed that the error rate in trials with normal mapping was much lower than in trials in which the mapping was rotated; however, a large decrease in the error rate occurred in rotated trials over time. The researchers speculated that with more practice, performance in the rotated mapping condition may decrease to that of the baseline levels achieved in the normal mapping condition.

In real-world tasks it is unlikely that a person would be required to operate a steering control in which the C-R relationship changed randomly between compatible and incompatible. However, there are situations in which the C-R relationship alternates from being consistently compatible for some period of time, perhaps until the completion of a subtask, to consistently incompatible for another period of time. This type of task is evident when driving some underground coal mine shuttle cars.

Shuttle cars are free-steered vehicles commonly used to transport coal from the coal development face to a conveyor. Those shuttle cars that are driven using a steering wheel commonly have it located to one side and between two facing seats, attached to the inside wall of the cab (i.e., the plane of the steering wheel is coplanar with the side of the vehicle and perpendicular to the typical vehicle arrangement). Two facing seats allow the driver to change seats with each change of direction and always face the direction of travel. Because of the position of the steering wheel, drivers can hold the wheel in various ways, such as alternatively using the left or right hand (i.e., isolating compatibility to a particular hand); always using the dominant hand, although in this situation the driver must reach across the body to hold the wheel when driving in one direction; or any combination of these two alternatives. The Visual Field (VF) compatibility principle (Worringham & Beringer, 1998) would predict that when one is driving the shuttle car forward toward the conveyor the C-R relationship is compatible; however, when returning toward the face the relationship is incompatible. Shuttle car drivers thus continually alternate between compatible and incompatible steering configurations with each change of direction.

The fact that miners can drive shuttle cars in this manner is a testament to human adaptability. Cunningham and Welch (1994) provided some information about how performance changes when compatibility is alternated (rather than randomly mixing compatibility); however, more research is needed to investigate real-world tasks in which short temporal blocks of compatible C-R relationships alternate with incompatible C-R relationships. How performance in these situations compares with entirely compatible or entirely incompatible arrangements is also unknown.

The aim of this research project was to use a virtual reality simulation of a situation analogous to the shuttle car to examine steering direction errors and reaction time. A compatible condition and an incompatible condition were carried out to establish what steering performance can be achieved when compatibility does not alternate. Two alternating conditions (compatible trials alternating with incompatible trials) were also investigated: (a) one in which compatibility alternated within and between hands (i.e., a compatible and an incompatible trial were carried out with one hand, and then a compatible and an incompatible trial were carried out using the other hand); and (b) one in which compatibility alternated between hands (a compatible trial was carried out with one hand, followed by an incompatible trial carried out using the other hand).

METHODS

Participants

Forty-eight adults (15 women and 33 men) participated in the experiment (12 participants in each condition). Participant's ages ranged from 19 to 43 years (average 29 years). All held a current driver's license and had normal or corrected-to-normal vision. A cinema voucher was provided to all participants for taking part in the experiment.

Apparatus

The experiment was carried out in a fixed-base driving simulator. The scene was rendered by a Silicon Graphics Onyx 350 equipped with Infinite-Reality II graphics. The scene was projected onto a wall using a BARCO 808S analogue projector. The projected image was 2.33 m high and 3.12 m wide (300 mm from the floor). The image frame rate was 72 Hz, and the update rate of the simulation was 24 Hz. Image resolution was set at 1280 × 1024 pixels. The lateral position, longitudinal position, steering angle, and location of the miner were recorded at 25 Hz.

Two Logitech MOMO Racing Force Feedback Steering Wheels were used as the input steering devices. A spinning knob was attached to the top of each steering wheel. The steering wheels were secured to the side of two tables, with the steering knobs 900 mm from the floor. One steering wheel was located on the left side of the participant, and the other on the right side of the participant, such that the participant could comfortably hold either knob and rotate the steering wheel without constraint. An adjustable chair was placed in front of the screen at a position where the participant's face was approximately 1.5 m from the screen. The chair was adjusted so that the participant's forearm was close to a horizontal position while holding the steering wheel knob. To partially replicate the restricted visibility of a shuttle car, a black partition (1.2 m high, 2.5 m wide) was placed 450 mm from the screen.

Stimuli

The simulated environment consisted of a straight, textured underground mine road, 5 m wide and 3 m high. The virtual shuttle car traveled at a constant speed of 10 km/hr. The simulation included a pair of semicircular illuminated areas that represented the shuttle car's headlights and moved in accordance with the shuttle car's heading. A simulated "miner" randomly appeared six times on each trial, 400 mm to the left or right of the center of the road, to simulate a situation in which an avoidance maneuver is required. The miner was visible for 5.7 s, and the time period between appearances of the miner randomly varied from 9 to 15 s. Figure 1 shows the simulation in progress.

Design and Procedure

The experimental task was a sudden path-deviation driving task involving driving a straight

Figure 1. Photograph of simulation in progress.

path along an underground mine road and avoiding a miner whenever he appeared. Trial duration was approximately 2 min. Participants were randomly assigned to one of four conditions: (a) a condition consisting of 16 compatible trials (compatible condition); (b) a condition consisting of 16 incompatible trials (incompatible condition); (c) an alternating condition in which 8 compatible trials alternated with 8 incompatible trials (total of 16 trials), in which 2 consecutive trials (1 compatible and 1 incompatible) were carried out with one hand, followed by 2 consecutive trials carried out with the other hand (within and between hands condition); or (d) an alternating condition in which 8 compatible trials alternated with 8 incompatible trials (total of 16 trials), in which the compatible trials were carried out by one hand and the incompatible trial by the other hand (between hands condition).

For compatible trials, a clockwise rotation of the steering wheel (while holding the knob) steered the vehicle right and a counterclockwise rotation steered the vehicle left. For incompatible trials, a counterclockwise rotation of the wheel steered the vehicle right and a clockwise wheel rotation steered the vehicle left.

Participants were instructed to steer down the center of the road and maneuver around the miner, who would appear randomly on either side of the road. Information was not provided on how often the miner would appear or the time interval between appearances. Participants were shown how to use the steering wheel in the allocated condition (holding the steering knob with the adjacent hand). Participants in the compatible and incompatible conditions started the trials using their right hand. The starting location and type of trial (either compatible or incompatible) were balanced across participants in the alternating conditions.

Dependent Measures

Steering direction errors. A steering direction error was identified when participants made a steering input of 20° or more that caused the shuttle car to turn toward the miner ≥250 ms after the miner became visible. Recording of errors was conservative – that is, regardless of how many steering errors were actually made between 250 ms and about 2 s after the miner appeared, only one error was recorded.

Reaction time. Reaction time data were calculated when no steering error was made and a marked change in steering wheel angle (≥20°) in the correct direction was evident following the appearance of the miner. Reaction time was defined as the time from the moment the miner first became visible to the moment when the participant started to steer in the correct direction.

RESULTS AND DISCUSSION

Compatible and Incompatible Conditions

The steering direction errors and reaction time data from four consecutive trials were grouped into each of four blocks. Steering direction errors were converted to a percentage of the total possible number of errors (24 per block). Figure 2 shows the mean percentage steering direction errors and mean reaction time for the compatible and incompatible conditions.

Steering direction errors. A two-way ANOVA with one between-subjects factor (compatibility) and one within-subject factor (block) was carried out on the steering direction errors. There was a significant interaction, $F(3, 66) = 7.56, p < .01$, and significant main effects for compatibility, $F(1, 66) = 24.76, p < .01$, and block, $F(3, 66) = 18.44, p < .01$. Participants in the compatible condition made fewer steering direction errors (mean errors 3%) than participants in the incompatible condition (mean errors 16%). A significant linear trend was found in both conditions. Error rate decreased in the compatible condition, $F(1, 11) = 11.23, p < .01$, and the incompatible condition, $F(1, 11) = 39.5, p < .01$.

Error rates obtained in traditional S-R compatibility experiments are typically very small or omitted from analysis. However, where errors have been analyzed, a performance advantage for compatible S-R sets has consistently been found. When a steering wheel was located in front of the participant, steering direction errors of approximately 2% and 0.49% were found in compatible conditions, as compared with >6% and 0.94% in incompatible conditions (Guiard, 1983, and Proctor, Wang, & Pick, 2004, respectively). A decreasing error rate in the incompatible condition was found (Worringham & Beringer, 1998) in which VF-incompatible reversal errors converged but did not achieve the performance recorded in the VF-compatible condition.

As expected, in the current experiment a performance advantage was evident for the compatible condition as compared with the incompatible

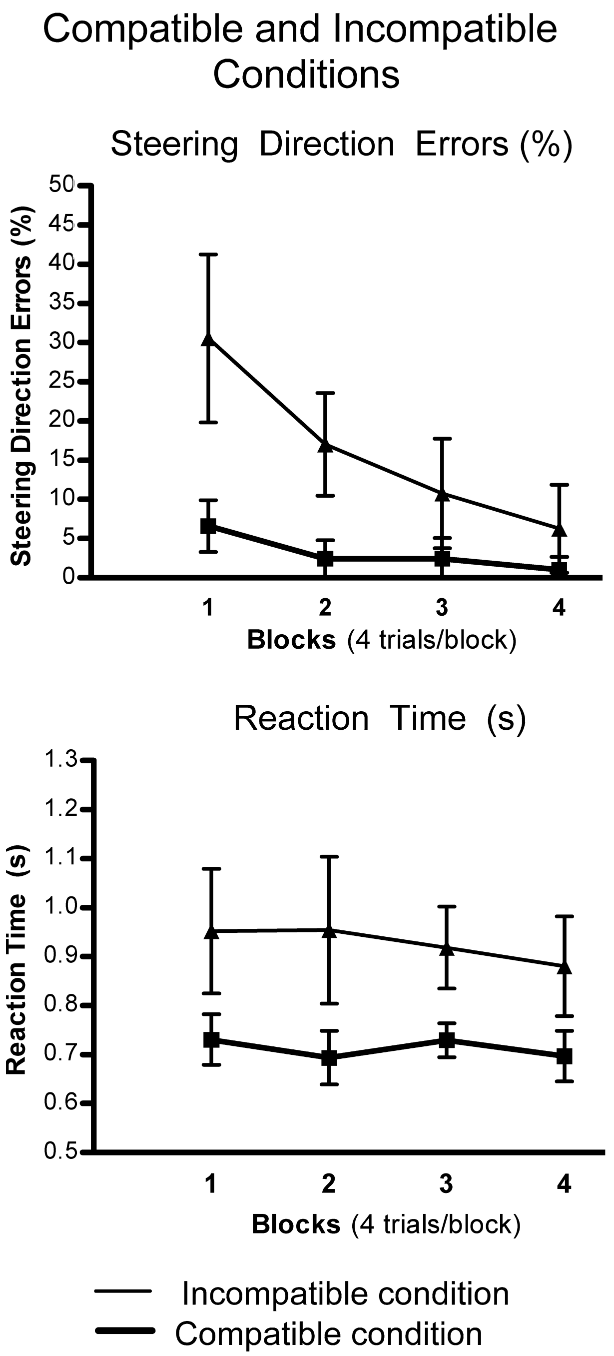

Figure 2. Mean percentage steering direction errors and mean reaction time for the compatible and incompatible conditions (error bars = 95% confidence intervals).

condition. The experiment involved participants driving for approximately 30 min, and although error rate decreased over time in both conditions and the difference between conditions was no longer significant by Block 4, it is not possible to determine from these results whether extended practice would result in extinction of the compatibility effect.

Reaction time. To analyze the reaction time data for the compatible and incompatible conditions, a two-way ANOVA with one between-subjects factor (compatibility) and one within-subject factor (block), was carried out. There was a significant main effect for compatibility, $F(1, 66) = 25.67$, $p < .01$. There was no significant interaction, $F(3, 66) = .9$, $p = .44$, or main effect for block, $F(3, 66) = 2.69$, $p = .053$. When no steering direction errors were made, participants in the compatible condition responded more quickly (mean reaction time 713 ms) than participants in the incompatible condition (mean reaction time 910 ms).

The prediction of a reaction time compatibility effect between blocked compatible and incompatible trials was supported in the current experiment; however, the expected improvement over time for blocked incompatible trials was not. Research into drivers' steering behavior (Reid & Solowka, 1981) found that in short-preview obstacle-avoidance maneuvers, 400 to 600 ms was a typical response time from observation of the potential obstacle to initiating evasive steering (although it can be up to 1.25 s because of inattention or deliberate driving technique). It has been suggested that this steering response latency is typically a stereotypic response (Summala, 2000). Reaction times of 374 to 390 ms and 439 ms were obtained in compatible steering tasks (Guiard, 1983, and Proctor et al., 2004, respectively).

In the current experiment, to successfully maneuver around the miner, participants needed to respond quickly but not necessarily immediately upon presentation of the miner. It may be that this allowable time period for a response (5.7 s from the first appearance of the miner to passing the miner) and, possibly, the difficulty of the task were contributing factors for the lack of improvement in response times in the incompatible condition.

Alternating Conditions

The steering direction errors and reaction time data from two consecutive compatible or incompatible trials were grouped into each of four blocks. Steering direction errors were converted to a percentage of the total possible number of errors (12 per block). Figure 3 shows the mean percentage steering direction errors and mean reaction time for the alternating within and between hands condition and the alternating between hands condition.

Steering direction errors. For the alternating within and between hands condition (Figure 3a), a two-way ANOVA with two within-subject factors (compatibility and block) found significant effects

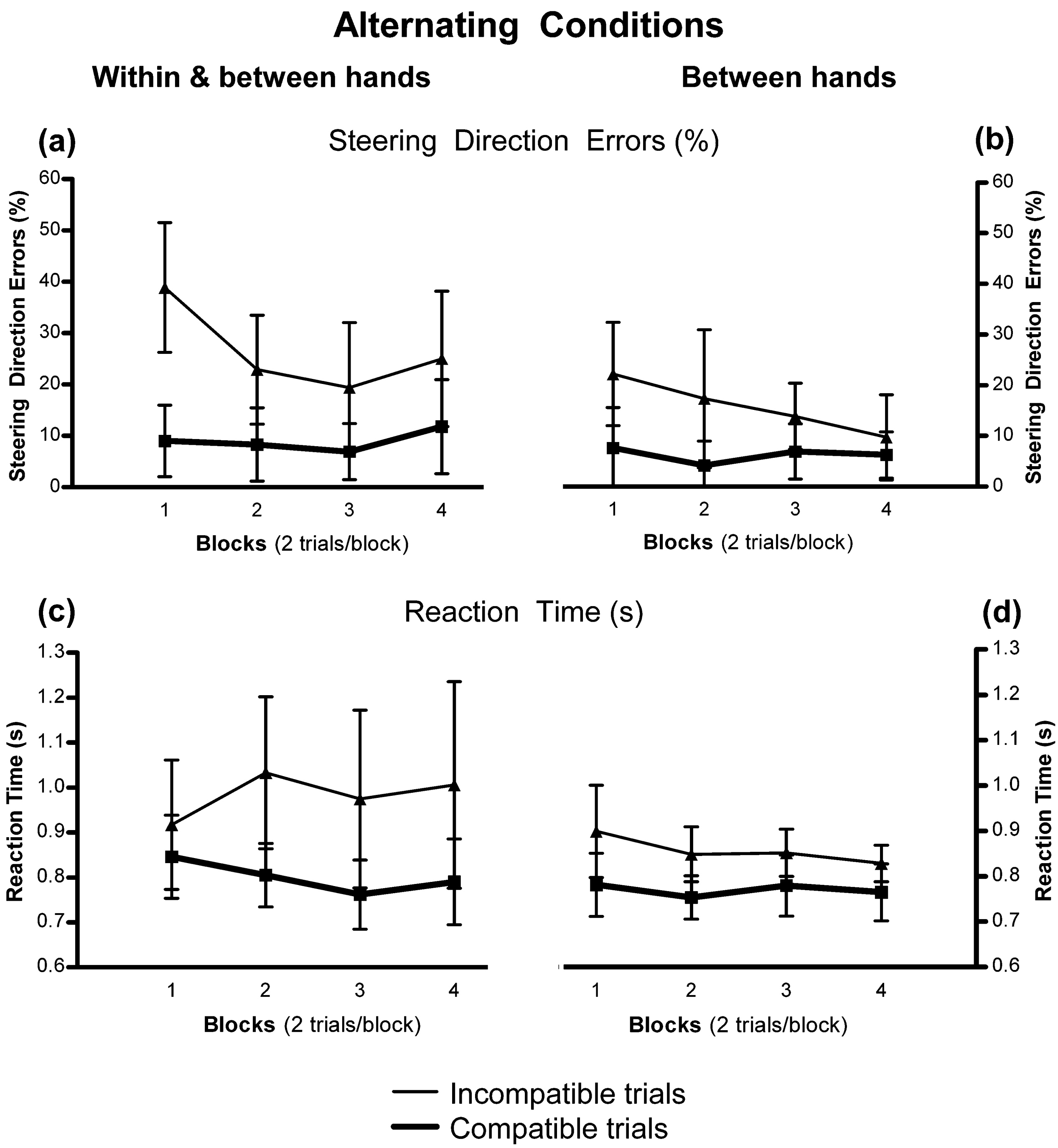

Figure 3. Mean percentage steering direction errors and mean reaction time for the two alternating conditions (error bars = 95% confidence intervals).

of compatibility, $F(1, 11) = 12.161$, $p < .01$, and block, $F(3, 33) = 4.144$, $p < .02$, and the interaction approached significance, $F(3, 33) = 2.804$, $p = .055$. A significant quadratic trend was found in the incompatible trials, $F(1, 11) = 14$, $p < .01$, indicating that an error rate decrease was followed by an error rate increase.

For the alternating between hands condition (Figure 3b), a two-way ANOVA with two within-subject factors (compatibility and block) found a significant effect of compatibility, $F(1, 11) = 14.524$, $p < .01$; however, neither the interaction, $F(3, 33) = 1.7$, $p = .19$, nor the main effect of block, $F(3, 33) = 1.5$, $p = .23$, was significant.

An error rate performance advantage of precued compatible trials over precued incompatible trials has been found in situations in which compatibility alternates at regular intervals, and performances in incompatible trials were shown to improve over time (Cunningham & Welch, 1994).

As detailed previously, a compatibility effect was also evident in both alternating conditions of the current experiment; however, a consistent or significant performance improvement from Blocks 1 to 4 was not evident in either condition. The increased error rate in the last block of the within and between hands condition may indicate that participants become fatigued because of the higher degree of concentration required for this task. This pattern of performance was not evident in the between hands condition.

An investigation of the performance differences between the two alternating conditions was carried out. A two-way ANOVA with one within-subject factor (compatibility) and one between-subjects factor (group) found a significant effect of compatibility, $F(1, 44) = 18.88$, $p < .01$, and group, $F(1, 44) = 4.72$, $p < .05$, but no interaction, $F(1, 44) = 1.64$, $p = .21$. Participants in the alternating within and between hands group had a greater error rate than participants in the between hands group.

Reaction time. For the alternating within and between hands condition (Figure 3c), a two-way ANOVA with two within-subject factors (compatibility and block) found a significant interaction, $F(3, 33) = 4.104$, $p < .02$, and a significant effect of compatibility, $F(1, 11) = 8.614$, $p < .02$, but not block, $F(3, 33) = 0.82$, $p = .49$.

For the alternating between hands condition (Figure 3d), a two-way ANOVA with two within-subject factors (compatibility and block) found significant effects of compatibility, $F(1, 11) = 11.6$, $p < .01$, but no interaction, $F(3, 33) = 0.65$, $p = .59$, or block effect, $F(3, 33) = 1.7$, $p = .19$.

S-R compatibility research has consistently found that when compatible and incompatible trials are precued, a reaction time compatibility effect results. Compatibility effects were also found in this experiment where alternating compatible and incompatible trials were precued. However, the expected improvement in performance in incompatible trials was not found.

A comparison was made between reaction time performances of the alternating within and between hands group and the alternating between hands group. A two-way ANOVA with one within-subject factor (compatibility) and one between-subjects factor (group) found a significant effect of compatibility, $F(1, 44) = 9.02$, $p < .01$, but no interaction, $F(1, 44) = .88$, $p = .35$, or effect of group, $F(1, 44) = 3.12$, $p = .08$. Reaction times were greater in incompatible trials than in compatible trials in each group, but there was no significant difference between the groups.

An examination of steering direction errors and reaction time for incompatible trials in the alternating within and between hands condition (Blocks 1 to 2) revealed that a marked decrease in error rate, $t(11) = 3.627$, $p < .01$, two-tailed, occurred simultaneously with a marked increase in reaction time, $t(11) = 2.608$, $p < .05$, two-tailed. This pattern of results indicates that participants in the alternating within and between hands condition traded off speed for accuracy in response to their high error rate in the first block of incompatible trials. A speed-accuracy trade-off was not evident in the alternating between hands condition.

To enable overall error rate and reaction time performance comparisons to be made between consistent conditions and alternating conditions, compatible and incompatible trials in the alternating conditions were averaged. Percentage errors and reaction time means and standard deviations for the compatible, incompatible, and alternating conditions are shown in Table 1. One-way ANOVAs were conducted on error rate, $F(3, 44) = 9.747$, $p < .01$, and reaction time data, $F(3, 44) = 7.197$, $p < .01$, and significant effects of condition were found. Bonferroni post hoc tests revealed a significant error rate and reaction time performance advantage for the compatible condition as

TABLE 1: Steering Direction Errors and Reaction Times for the Four Conditions

	Compatible		Incompatible		Alternating Within and Between Hands		Alternating Between Hands	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Steering direction errors (%)	3.1	2.43	16.1	8.36	17.8	8.73	11	7.9
Reaction time (s)	0.71	0.05	0.91	0.12	0.89	0.18	0.81	0.07

compared with the incompatible condition and for the alternating within and between hands condition.

In summary, error rate and reaction time performance advantages of consistently compatible C-R relationships were evident in this virtual reality simulation of an underground coal shuttle car. The participants made fewer steering direction errors and faster responses when the C-R relationship was consistently compatible rather than consistently incompatible or presented in alternating short blocks of compatible and incompatible trials (analogous to the situation encountered in the real situation).

Although compatibility effects were found in the alternating conditions, alternating within and between hands resulted in the highest error rate, even though half the trials were compatible. It is speculated that greater concentration is required for this task and that increases in error rate toward the end of the experiment may have been attributable to participants' fatigue. Isolating compatibility to one hand (the alternating between hands condition) resulted in better performance than when compatibility alternated within and between hands. Performance improvements were mainly evident in error rates of consistently incompatible trials. The expected similar pattern of improvement over time for reaction time was not as obvious in the results, possibly because the presentation of the obstacle (the miner) did not require participants to respond immediately.

A change in the design of these vehicles, and other machines in which C-R relationships alternate, may be justified. This experiment's results suggest that reengineering a shuttle car's steering wheel configuration so that it is compatible in both directions, consistent with the VF compatibility principle (Worringham & Beringer, 1998), would result in lower steering direction error rates and faster responses. However, it is not known what the consequences would be for experienced operators changing to such an arrangement. A possible alternative solution for operators highly familiar with the steering wheel configuration may be to provide a joystick that operates as the steering device and to mount it on a rotating seat (as proposed by one shuttle car manufacturer). However, whatever steering device is used, an investigation of the issue of C-R compatibility needs to be central in the design process.

This experiment illustrates potential performance in the early stages of learning in various C-R compatibility situations; however, whether the performance differences persist after extensive practice, and what the consequences of a change in underground coal mine shuttle car design would be for existing miners, remain to be determined.

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