University of Cincinnati

Date: 10/26/2023

I, Emily Wang B.S., hereby submit this original work as part of the requirements for the degree of Master of Arts in Psychology.

It is entitled:

When Left means Right: Stimulus-Response Compatibility in a Virtual Reality Puzzle Task

Student's name: **Emily Wang B.S.**

This work and its defense approved by:

Committee chair: Tehran Davis, Ph.D.

Committee chair: Kevin Shockley, Ph.D.

Committee member: John G. Holden, Ph.D.

47845

When Left means Right: Stimulus-Response Compatibility in a Virtual Reality Puzzle Task

A thesis submitted to the

Graduate College

of the University of Cincinnati

in partial fulfillment of the

requirements for the degree of

Master of Arts

in the Department of Psychology

of the College of Arts and Sciences by

Emily Wang

B.S., University of California, Merced,

December 2019

Committee Co-Chair: Kevin Shockley, PhD.

Committee Co-Chair: Tehran Davis, PhD.

Committee Member: John G. Holden, PhD.

Abstract

The ease of interacting with objects typically depends on how the object (the stimulus) fits with the effector (what makes the response). For example, reaching towards a right-handled mug handle may feel more natural with one's right hand than with one's left hand, a phenomenon known as Stimulus-Response Compatibility (SRC) in which a stimulus shows a slower response when it is incompatible with the response. In order to investigate SRC influences on activities involve a series of actions that achieve a broader goal over time (e.g., sports, playing a video game, etc.), in the present study I used a virtual-reality task in which hand-held controllers moved virtual tiles in a sliding-puzzle task where the left-hand controller moved tiles leftward (compatible condition) or rightward (incompatible condition) or vice versa. Participants completed puzzles more slowly in the incompatible condition than in the compatible condition, suggestive of SRC influences on temporally extended tasks.

Acknowledgement

I would like to thank my committee, Kevin Shockley, Tehran Davis, and Jay Holden, for their help and guidance throughout this process and project. I especially want to thank Kevin for his patience and advice throughout the past few years. I also want to thank the support I've received within Cognition, Action, & Perception and the friends I've made in this program. Lastly, I want to thank Maxime, my family, and my cat (Lucy) for their endless and unconditional love and support. I am so very grateful to have them as my support system.

Table of Contents

List of Tables/Figures

Introduction

Stimulus-Response Compatibility

Interactions with some everyday objects can feel intuitive while interactions with other objects may feel awkward, depending on how the object to be acted upon (the stimulus) fits with the effector (what makes the response). For example, reaching towards or grabbing a right-handed mug handle may feel more natural through one's right hand than it would with a left hand. The speed and accuracy in performing this action, such as reaching and grasping, depends on whether the relationship between a stimulus and response is compatible or incompatible, or when the response to the stimuli is intuitive (Proctor & Vu, 2006).[1] This phenomenon is known, generally, as Stimulus-Response Compatibility (SRC) and involves the spatial mapping between sets of stimuli and responses, often demonstrating that incompatible mappings result in longer reaction times (RTs) (see Fitts & Deininger, 1954; Fitts & Seeger, 1953). An example of a compatible scenario in which the right-handed response is assigned to the right-sided stimulus. SRC has been shown in a variety of contexts, such as stimuli presented in various orientations (Tucker & Ellis, 1998), and its influences in human factors and engineering (e.g., Proctor & Reeve, 1989; Proctor & Vu, 2016; Strasser, 2022) has been studied to demonstrate the importance of exhibiting compatibilities in real-world objects such as aviation control displays, automobiles, signage, and machine interfaces when multiple stimuli and responses can be acted upon (Kantowitz et al., 1990). Aviation control displays are a prominent example of how stimulus-response compatibility, or incompatibility, may affect one's ability to pilot an aircraft and thus impact the safety of others. In these display-control environments which deploy instruments and controls each with multiple

[1] Objects that are intuitive to use may be attributed as easy to learn, natural to use, or self-explanatory. Car door handles are examples of good intuitive design. The exterior car door handle has a visible horizontal bar that extends towards the user when pulled, while located across a pocket of space that allows for hand placement.

elements, such as in the airplane cockpit, the navigation panel and buttons on the dashboard must be designed in such way that promotes compatibility, leading to reduced errors and smoother navigation (Yamaguchi & Proctor, 2006). Likewise, compatibility is an important aspect in machine interface and operation. For example, a four-burner stove typically has two back burners located directly behind two front burners and control knobs located across the front of the stove, with each knob controlling a specific burner. Without labels, the relation between a specific burner and knob is indiscernible and may cause user error or injury. However, when staggering the burners from left-to-right so that the knob location corresponds with a burner location, user error significantly decreases (Chapanis & Lindenbaum, 1959).

Simon Effect

A classic paradigm exhibiting Stimulus-Response Compatibility (SRC) influences is observed in the correspondence effect, or the Simon Effect. This effect can be observed when there are differences in task performance between ipsilateral versus contralateral mappings of the stimulus and response, referred to as corresponding and non-corresponding mappings, respectively (Simon, 1990). The nonspatial physical features of the stimulus, such as shape and color, are relevant information that are assigned to left or right directional responses (button press, reach, grasp), while the location of the stimulus itself (left or right of the midline) is irrelevant to the task. Despite the spatial location of the stimulus being task-irrelevant, participants perform faster and more accurately on corresponding mappings versus noncorresponding mappings (Lu & Proctor, 1995; Yamaguchi & Proctor, 2011). The original Simon experiments were conducted using auditory stimuli (e.g., Simon & Rudell, 1967), where tonal or directional commands were presented to the participant's left or right ear in which they responded with a movement or button press using either their left or right hand. The auditory stimuli in these experiments provided relevant information for the response, such as the meaning of the command (left or right), and irrelevant information for the response, such as which ear is being stimulated, which required participants to respond to auditory stimuli presented to the left or right ear. Simon and Rudell (1967) found that participants responded faster when the directional command corresponded and was ipsilateral to the hand. However, to determine which factors attributed to the SRC observed in previous studies, Simon et al. (1970) observed whether it was the correspondence between the ear and hand or the ear and response location. In their study, participants responded to tones presented to either their left or right ear with button presses using uncrossed hands (left key was pressed by left hand) in one condition and crossed hands (left key was pressed by right hand) in the other condition. They found that reaction times were not only faster when the response hand corresponded to the ear stimulated (ipsilateral in uncrossed condition), but also when the ear and responding hand were on the same side of the body (contralateral in crossed condition). Based on their results, SRC was task-dependent and Simon and colleagues suggested that if the stimulus was simple, such as a tone presented to one's ear, then both ear-hand correspondence and ear-response location correspondence contributed to SRC. However, if the stimulus provided more information, such as directional commands as seen in Simon and Rudell's (1967) study, only then ear-response location contributed to SRC. This study further defined the factors that contributed to SRC seen in Simon tasks (i.e., the Simon effect).

Despite the Simon Effect being initially observed using auditory stimuli, this phenomenon extended to visual stimuli as well. Craft and Simon (1970) employed a paradigm in which agents pressed a left or right key in response to the sight of a stimulus, like a colored light indicating a directional command. They found that when subjects pressed the left-hand key for a green light and the right-hand key for a red light, response times were significantly faster when the green light was presented to the left of the body midline and the red light presented to the right, later inferring that the Simon effect was primarily a result of interference when the stimulus and response locations do not correspond. Interference means there is a difference in reaction time (RT) between mappings for which stimulus-response locations do and do not correspond. The Simon studies conclude that the slower reaction time in noncorresponding trials and faster RT in corresponding trials can be explained by a basic natural tendency to respond toward the source of the stimulation.

Beyond the Simon Effect

Early studies of SRC demonstrated that reaching with one's left hand as a response to observing a stimulus that invites a response on (or to) the left instead of a stimulus inviting a response on (or to) the right may produce a shorter reaction time (RT) (e.g., Broadbent & Gregory, 1962). In such earlier studies, the effector location, or hand placement, did not change and were constant (see Craft & Simon, 1970; Simon & Rudell, 1967)—in these instances, hands were placed in front of the participant. Michaels and Schilder (1991) showed that hand locations and hand posture have an influence on reaching reaction time (RT) paradigms. Their experiment revealed the effects of different states of the hand in reaching paradigms that invoke different SRC, indicating that compatibility is influenced by which hand responds and the posture of that hand (fist closed down or palm-side up). Therefore, one's action may affect their perception of the task through different responses, such as small changes in placement or posture, which may invite different compatibilities with the stimulus.

Moreover, other studies have explored more nuanced effects of this reaching paradigm, finding that how the stimulus moves or invites a certain type of response influences how SRC effects manifest. While the importance of hand placement for a response has been observed by Michaels and Schilder (1991), the direction and orientation of displayed objects has been shown to invite certain types of responses. Objects with graspable protruding handles, such as a saucepan handle oriented towards the right, will invite compatible responses, like grabbing that object with the right hand. For objects without protruding features, they are most graspable when the axis of the object aligns with a hand on the same axis. Tucker and Ellis (1998) found that when subjects viewed photographs of daily, graspable objects and were asked to make a button-pressing response with either their left or right hand depending on the orientation of the photographed object (inverted or upright), the horizontal orientation of the object determined the subject's response time despite object orientation being irrelevant to the task at hand. They also found that when completing the same task but instead using two fingers from the same hand, there were no significant effects, signifying the emergence of compatibility effects between two different spatially located effectors (left and right hands). Furthermore, changing the way one completes a task, such as reaching to "catch" a stimulus at different positions, invites the SRC to manifest differently. In a study by Michaels (1988), subjects were asked to "catch" or reach towards a stimulus using joysticks from various starting positions. When tasked to focus on the stimulus' actual position, or where the stimulus came from, Michaels found a classic Simon effect in which reaction times were faster when participants reached towards the stimulus that moved from a position ipsilateral to the responding joystick. However, when focusing on the stimulus' destination or the direction it was moving towards, Michaels found that reaction times were faster when participants reached towards the moving stimulus that was either positioned ipsilateral to the responding joystick or contralateral but moving towards the responding joystick, yielding a negative Simon effect. This finding underscored the notion that SRC influences are not just a product of positional compatibilities but rather obtain from functional compatibilities such as if affordances are present (e.g., stimulus is catchable by effector).

Temporally Extended Tasks

Previous studies demonstrating SRC effects have typically been conducted in a single-event tasks such as reaching tasks or finger presses (e.g., Stins & Michaels, 2000) in which there is one discrete act per trial. These single-event responses are called simple-reaction tasks and are presumed to elicit minimal response-selection processes for decision making (Proctor & Van Zandt, 2008). Despite these simple responses, a decision is still made regarding the presence or absence of the stimuli (Rizzolatti et al., 1979). Although single-event tasks are common in experimental settings, it is more common in real-world interactions that our goals involve a series of actions. For example, in order to change a television channel, an actor must locate, reach for, grasp, click the appropriate number of buttons in order to navigate to the desired channel, and then press the button to go to that channel. We often see temporally extended actions in video games in which a player must interact with a dynamic virtual environment using a series of actions in order to complete a task. If a video game tasks a player to traverse through a hazardous environment, a player must identify and press buttons on their controller to attack, jump, or shield themselves from oncoming attacks, all while holding down a direction pad to move their character.

Indeed, research paradigms have used video games to observe the presence of the Simon effect. Action video games, in particular, are often used—their dynamic and fast-paced environments provide effective tests of test hand-eye coordination and reaction time, mirroring response selection in real-life scenarios. Moreover, video game training can lead to improvements in cognitive and visual processing (Green & Bavelier, 2003; Hutchinson & Stocks, 2013; Wu & Spence, 2013), Hutchinson and colleagues investigated whether video game practice led to reduction of the Simon effect (Hutchinson et al., 2015). In this study, participants initially performed a Simon task. Half of the participants were trained on Call of Duty, a first-person shooter (FPS) action video game, on various video game consoles for 10 days while the other participants received no video game training or non-action video game training. After training, participants performed a second Simon task. Consistent with previous findings that action video game practice elicit neuroplasticity in areas associated with attentional control and response selection, Hutchinson and colleagues found that those involved in action video game training exhibited a reduction in the magnitude of observed Simon effects between the first and second tasks, whereas those receiving no training or non-action video game training exhibited no reduced Simon effect. Furthermore, Hutchinson et al. confirmed that video games can be used to reduce reaction times (RTs) on typical laboratory tasks, such as the Flanker test (Dye et al., 2009).

Another study that utilized video games to assess stimulus-response compatibility required players to play Pong, a simple sports video game, to observe how SRC affected their performance in a competitive virtual environment (Brown et al., 1995). In their study, pairs controlled virtual paddles by turning either the left or right knob of a display with their right hand and bounced a virtual ball between each other's court. Akin to the game of table tennis, players intercepted a ball and reflected it to the opposing player's court; if a player does not intercept the ball, the opposing player receives a point. Pairs sat in front of one of the two knobs, either on the left or right side of the display, but always used their right hand to turn it. In one condition the knobs controlled the ipsilateral paddles (paddles on the same side of the corresponding knobs) while in another condition, the knobs controlled contralateral paddles (paddles on the opposite side of the corresponding knobs). Between the ball's intercept location (i.e., the player's court which is either the left or right half of the display) and the player's position (i.e., sitting in front of the left knob or right knob), those who controlled the right knob in the ipsilateral condition and left knob in the contralateral condition demonstrated a right-side advantage where controls used with their right hand steered the right paddle. In contrast, those who controlled the left knob in the ipsilateral condition and right knob in the contralateral condition used their right hand to steer the left paddle. Brown and colleagues, therefore, hypothesized that SRC influences attributed to the right-side advantage and better game performance (meaning because the right-hand always responded, when the right-hand controlled responses on the right side of the screen [regardless of which side the participant was sitting on] participants would win more). As predicted, they found that players seated to the right in the ipsilateral condition and left in the contralateral condition displayed a right-side advantage and won more games against their opponent suggestive of SRC influences. The Brown et al. study, however, did not measure SRC influences directly (e.g., using response times) but did so indirectly via number of wins. Nonetheless, the variety of studies using video games in the study of SRC influences suggests this functional context is a useful tool to observe and evaluate SRC influences. Moreover, the skills required to operate them and learned from practice can transfer and be used in real-world situations (e.g., the skills learned from video game tracking being used for navigating aviation control displays, Bliss et al, 1991). However, despite these successes, studies utilizing video games as a method to explicitly evaluate stimulus-response compatibility (SRC) and the emergence of the Simon effect remain few.

Current Study

While previous studies used video games to evaluate stimulus-response compatibility in single-event tasks, SRC influences affecting performance in competitive virtual environments, and video game training-induced neural plasticity, there is still a lack of understanding how SRC influences affect reaction time performance in dynamic video games that require a series of actions to complete. In the current study I addressed this gap by testing SRC influences in a temporally extended task. To replicate naturalistic type tasks that could be seen in everyday interactions, I used a virtual reality video game. The game involved sliding puzzles, in which a single puzzle tile can be moved at a time in order to achieve a target pattern. SRC was evaluated by using a compatibility manipulation for lateral puzzle tile movements. In the compatible condition the controller held in the left hand produced leftward tile movement when it was clicked on a puzzle tile that could move to the left (i.e., a tile that was not blocked to the left) and a controller held in the right hand produced rightward tile movement when it was clicked on a puzzle tile that could move to the right. In the incompatible condition, the controller in the left hand produced rightward tile movement when it was clicked on a puzzle tile that could move to the right, and the controller in the right hand produced leftward tile movement when it was clicked on a puzzle tile that could move to the left.

I used the number of (tile) movements (required to solve the puzzle) as a proxy for puzzle difficulty and thus as a control for any differences found across puzzles. Other measures included inter-move interval—a measure of all intervals between the end of a given tile movement to the start of the subsequent tile movement for a given puzzle; total task time—the total time it took to complete the puzzle; and number of errors—the number of instances a tile was selected that could not move. If SRC influences obtain in the present temporally extended task, horizontal inter-move intervals (but not vertical inter-move intervals) and total task time should be greater in the incompatible condition than in the compatible condition. I also hypothesized the number of errors should be greater in incompatible conditions than in compatible conditions.

Method

Participants

Twenty-nine students (15 male, 14 female) from the University of Cincinnati were recruited for this study. Their ages ranged from 18 to 62 years (M = 26.83, SD = 10.85). 17 students were recruited through the UC Psychology Research Participation System (SONA System) and received extra credit. The remaining 12 students were recruited using IRB-approved advertising and received small monetary compensation for their participation. One participant was excluded from this study due to failing to complete the puzzles trials within the allotted time frame. Participants were screened for no history of motion sickness and neurological, neuromuscular, or skeletal disorders. All participants reported normal or corrected-to-normal vision (with contact lenses or eyeglasses), right-handedness, and the ability to stand without assistance. This study is aligned with and covered by the University of Cincinnati Institutional Review Board Protocol #2022-0701.

Apparatus & Materials

The experiment took place in a virtual environment with participants standing, in first-person view, in front of a 3×3 vertically oriented sliding puzzle frame. Eight pieces of each puzzle were pieces present, with the ninth piece missing to allow for sliding, see Figure 1. A series of five puzzle background images (target goals) were placed onto the vertical puzzle frame, one for each of the five trials in different starting configurations, where pieces appear randomly scrambled. Participants were told they would complete a single training puzzle to ensure they understood the task and were familiar with the movement controls in virtual reality, followed by four trial puzzles. The training puzzle, which was unrecorded and had its own configuration, took a minimum of 10 moves to complete whereas the other two configurations randomly assigned to the remaining four test puzzles took a minimum of 15 moves to complete. The minimum number of moves was determined by using an artificial intelligence puzzle solver (Zhao, 2022). The first-person view allowed participants to observe each of their hands, represented by black orbs, as well as where their hand-held controller was pointing, the latter represented by pink lasers stemming from their hands. The virtual reality environment and series of sliding puzzles was created in Unity 2030.3.45f1 (Unity Studios, San Francisco, CA). Participants completed a series of five sliding puzzles in virtual reality wearing the HTC VIVE Pro head mounted display (HMD) and wielding two handheld controllers, one for the left hand and one for the right hand, with the participant's index fingers on the back triggers of both controllers (HTC Corporation, Bellevue, WA). Participants stood between two VIVE base stations located in two opposite corners, which configured the virtual environment to the perimeter of the room (Figure 2).

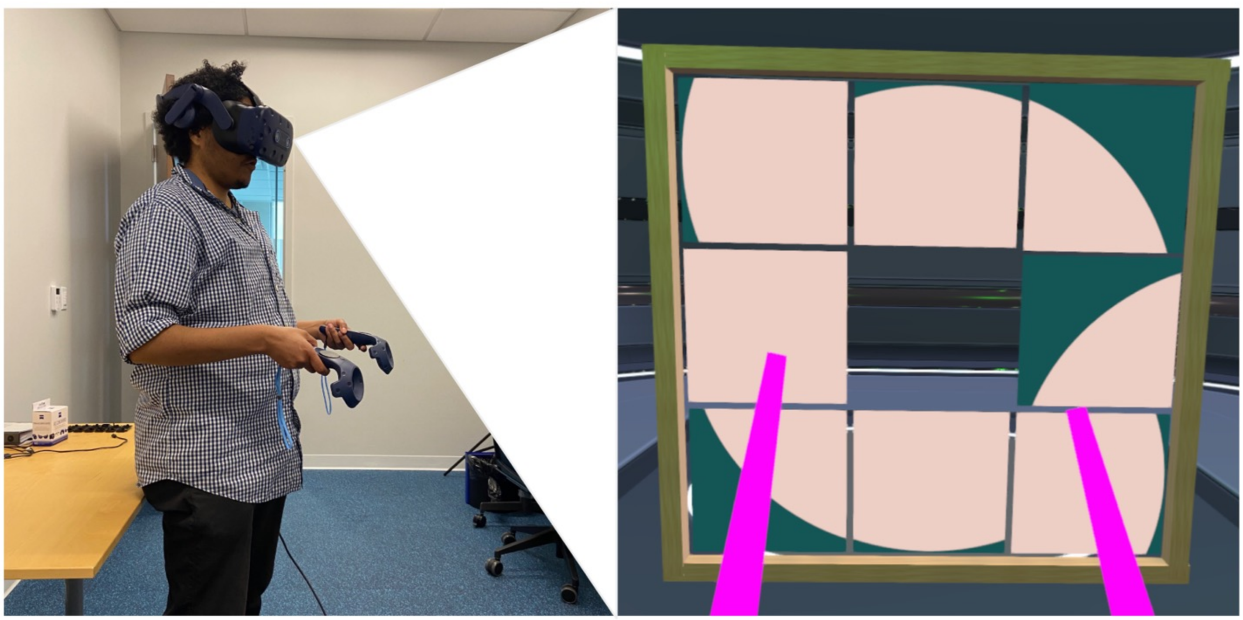

Figure 1. Participant set-up and view of the virtual environment rendered in the HMD. The training puzzle is displayed in its starting configuration with the left controller illustrated by the left-hand laser, and right controller illustrated by the right-hand laser.

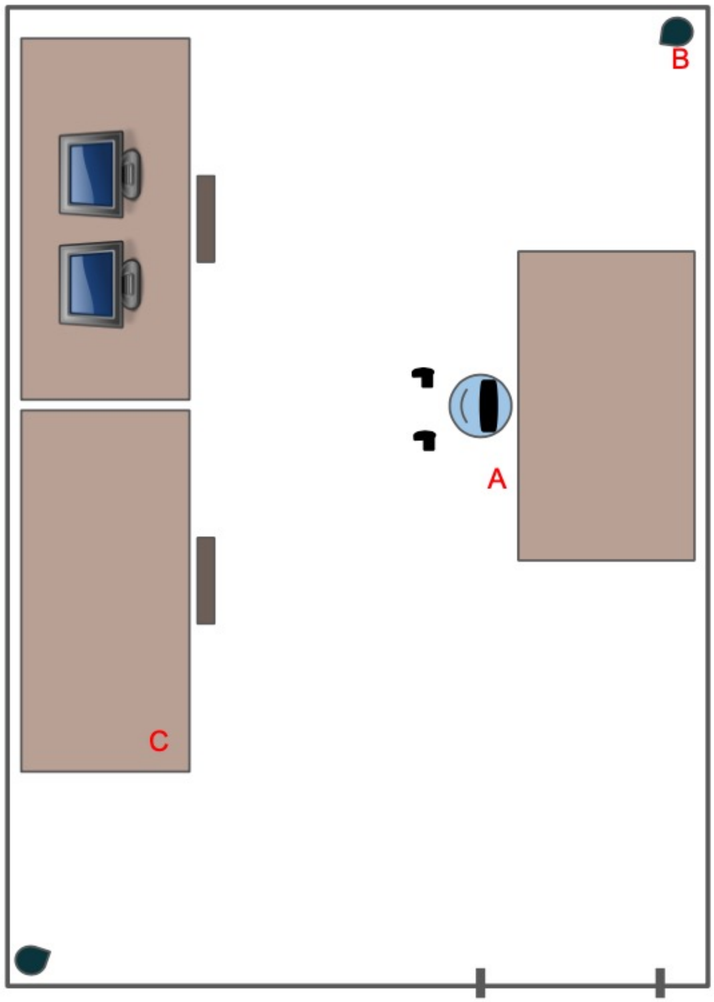

Figure 2. A diagram of the experimental set-up, including the position of the participant and VIVE base stations. (A) The position of the participant, wearing the HTC VIVE Pro head mounted display (HMD) and yielding two handheld controllers. (B) The location of the two VIVE base stations, placed in two opposite corners of the room. (C) The placement of tables and chairs in the room, limiting where the participant can stand.

Participants solved the puzzle by moving one tile at a time to the one open location in the puzzle frame available to them. This was done by highlighting the desired piece with the laser pointer and pressing the trigger on the appropriate controller. The left and right controllers were configured such that they produced different horizontal movements of the selected piece depending on the trial's condition. In the *compatible* condition (see Figure 3A), pressing the left trigger initiated a leftward movement of the puzzle piece (if possible) and the right trigger imitated rightward movement. In the *incompatible* condition (see Figure 3B) the mappings were swapped—the left trigger moved pieces to the right and vice versa. There was no manipulation to the vertical movements so either hand could control vertical movements. Participants were instructed to stand on a marked location for the duration of the study, only being invited for breaks after completing each puzzle.

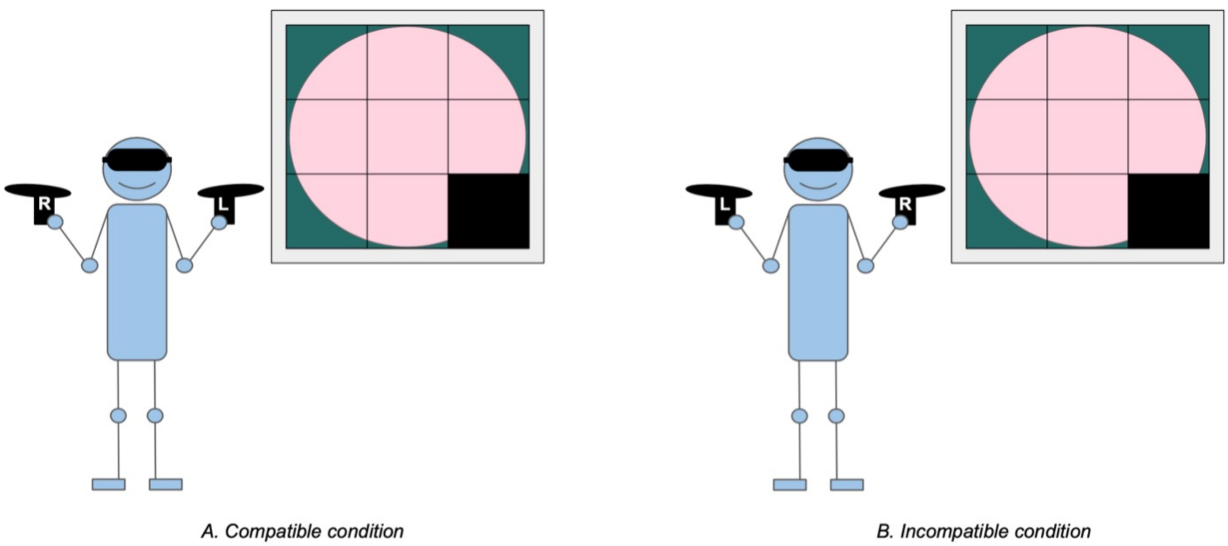

Figure 3. Experimental conditions. (A) Compatible condition, where the left controller is in the left hand. (B) Incompatible condition, where the left controller is in the right hand.

Procedure

Before the start of the experiment, participants were informed that their task was to complete five sliding puzzles within a 45-minute session. Participants were screened for right-handedness, motion sickness, and the ability to stand without assistance. After participants provided informed consent, their demographic information was recorded: sex, age, and height. They were given a brief introduction to the equipment (VIVE Pro head mounted display [HMD] and two handheld controllers) and had the HMD fitted to their head. They then grasped the two controllers, one held by each hand, and placed their index fingers on the back trigger of the controllers. After donning the equipment, participants entered the virtual reality environment and stood in front of a 3×3 vertical sliding puzzle. They were instructed that in order to move a puzzle tile, they needed to hover their laser hand over a tile that was adjacent to an open space and press the back trigger on the controller. Pressing the back trigger of a controller permitted a puzzle tile to move if it was adjacent to an open space; selecting a puzzle tile not adjacent to an open space yielded no movement but instead logged an error. The direction in which one could move a puzzle tile was dependent on which controller was used and what movement compatibility was activated relative to whether there was an open space adjacent to that tile.

The study started with a training puzzle to familiarize participants with the task and puzzle mechanics. Participants were given 10 minutes to solve the training puzzle (See Figure 3). This was to ensure that participants understood the movement mechanics and had practice with a sliding puzzle before starting the experiment proper. The four test puzzles, whose tile moves and times were recorded, were presented in a randomized order with two of each starting configuration (see Figure 4). Participants who did not complete all five puzzles were dropped from this study.

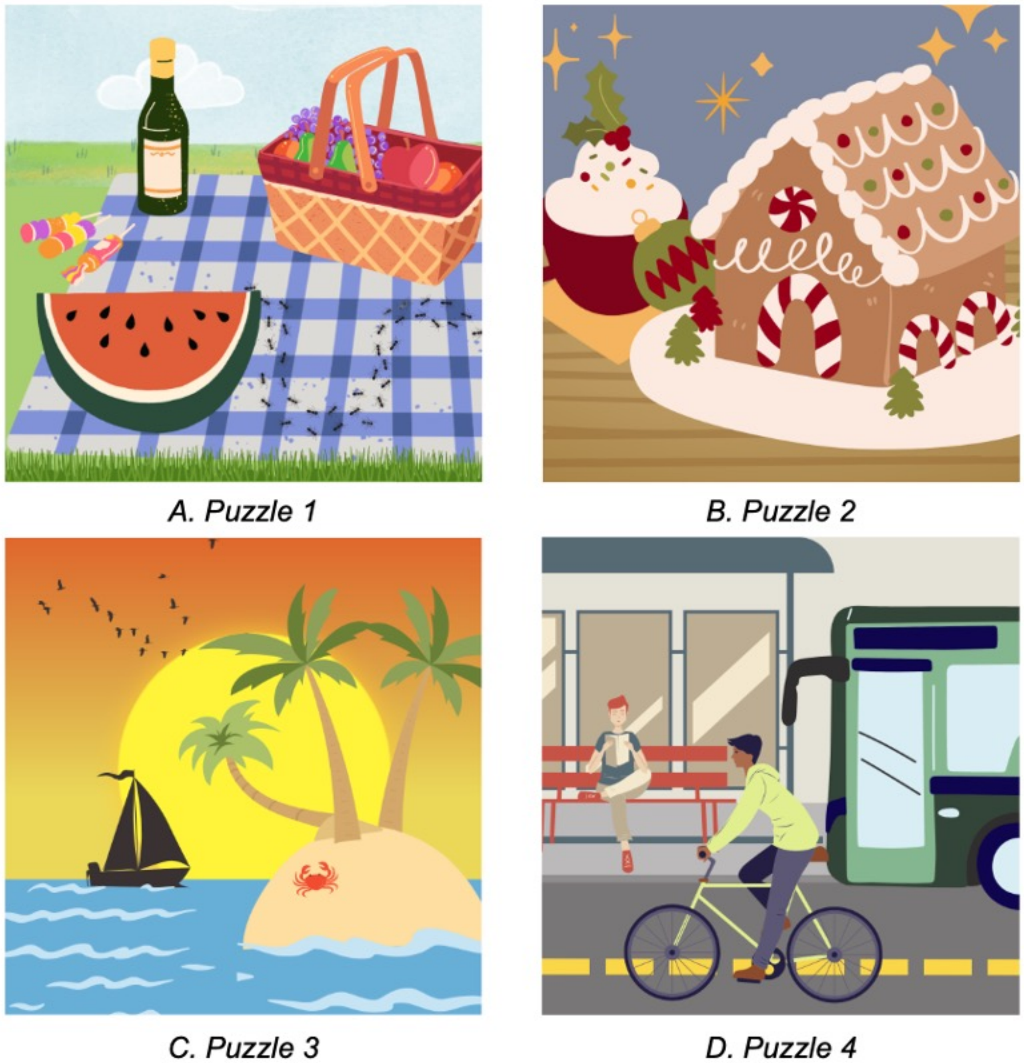

Figure 4. The four test puzzles used in the experiment.

Measures included number of moves (the total number of moves used to successfully complete each puzzle), total task time (the total time to successfully solve a puzzle from start to finish), the number of errors (the number of instances where a tile was selected to be moved but that could not be moved in the available direction [e.g., if a tile could be moved left but the participant selected that tile using the left hand in the incompatibility condition]). In addition, for each trial I created a time series of inter-move intervals (IMI). IMI was defined as the duration between the conclusion of one tile movement trial and the start of the subsequent movement. IMIs were categorized based on the direction of the subsequent tile movement: Horizontal IMI represents the average duration when the subsequent tile movement was horizontal, while Vertical IMI denotes the average time for instances where the following tile movement was vertical. The average Horizonal IMI and Vertical IMI were submitted to further analysis.

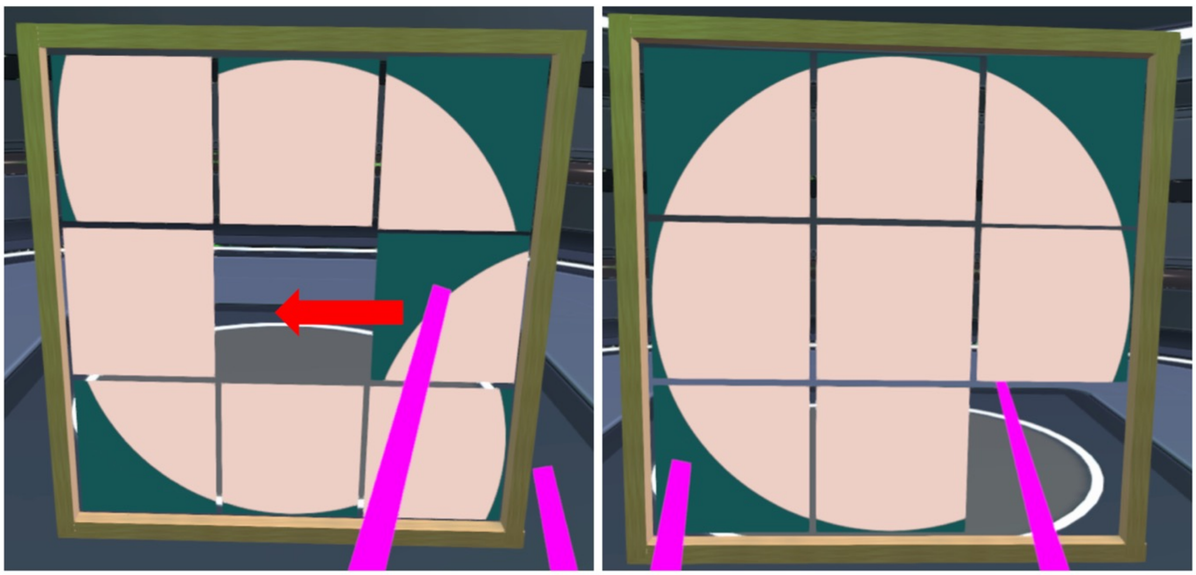
A. Puzzle with jumbled pieces and arrow showing where a tile can move
B. Puzzle solved

Figure 5. Practice puzzle in virtual reality. (A) Puzzle with jumbled tiles in the starting configuration, with red arrow indicating a tile's allowed movement. (B) Puzzle solved in its finished configuration, with one piece missing in the bottom right corner.

Results

Data processing and preparation

Prior to testing my hypotheses, I performed a test of whether the number of Moves predictor was influenced by the Mapping manipulation. This test was performed to investigate for any potential confounds or considerations with using number of moves as a predictor in subsequent modelling (e.g., did trials involving Incompatible SRC mappings require more moves to complete than trials with Compatible SRC mappings, or *vice versa)*. I tested for this possibility using a linear mixed effects model predicting number of Moves as a function of Mapping condition (including random intercepts for each participant). Analysis of variance of the resulting model did not show statistically significant differences in the number of Moves between Mapping conditions, $F\,(1, 83) = 2.82$, $p > .05$ (degrees of freedom were calculated using Satterthwaite's method).

Next, outliers for each of the dependent measures were identified using Rosner's (1983) generalized extreme Studentized test. Measures of total time, horizontal IMI, and vertical IMI were log transformed to address violations of normally distributed model residuals. Total error data was left untransformed. Each outcome measure was submitted to an independent linear mixed effects model with Mapping (compatible versus incompatible) and (number of) Moves as fixed effects, and accounting for individual differences by including random intercepts for each participant. To test for significance, the models' degrees of freedom were calculated using Satterthwaite's method. The coefficients and significance tests for each model can be found in Table 1. Additionally, when necessary, I evaluated interactions between Mapping (categorical predictor) and the number of Moves (continuous predictor) by performing pairwise comparisons of Mapping at three different levels within the Moves distribution: the 25th, 50th, and 75th percentiles. This approach provided a more explicit understanding of how the influence of Mapping on horizontal inter-move intervals shifted with the total number of moves for low difficulty (25th percentile), moderate difficulty (50th percentile) and high difficulty (75th percentile) trials.

Table 1

Summary Model of Horizontal Inter-Move Interval

	Estimate	Std. Error	*t*	*df*	*p*-value
(Intercept)	1.95E-01	5.37E-02	3.64	33.16	< .01
Mapping	-6.62E-02	6.16E-02	-1.07	38.97	.29
Move Total	-2.73E-04	5.06E-05	-5.41	4345.74	< .01
Mapping * Move Total	3.23E-04	9.33E-05	3.46	2479.86	< .01

Summary Model of Vertical Inter-Move Interval

	Estimate	Std. Error	*t*	*df*	*p*-value
(Intercept)	-1.56E-01	5.26E-02	-2.97	33.46	.01
Mapping	7.23E-02	4.32E-02	1.67	63.56	.10
Move Total	-1.47E-04	4.97E-05	-2.87	1223.52	< .01
Mapping * Move Total	3.99E-05	8.84E-05	0.45	700.55	.65

Summary Model of Total Time

	Estimate	Std. Error	*t*	*df*	*p*-value
(Intercept)	6.09E+01	2.24E+01	2.72	74.8	.01
Mapping	-6.81E+01	2.52E+01	-2.7	84.14	.01
Move Total	1.16E+00	6.16E-02	18.84	95.97	< .01
Mapping * Move Total	4.83E-01	1.02E-01	4.75	90.64	< .01

Summary Model of Total Errors

	Estimate	Std. Error	*t*	*df*	*p*-value
(Intercept)	17.34	4.94	3.51	103	< .01
Mapping	-12.33	6.87	-1.79	103	.08
Move Total	0.14	0.02	8.95	103	< .01
Mapping * Move Total	0.12	0.03	4.59	103	< .01

Table 1. Four linear mixed effects model summaries for Horizontal Inter-Move Interval, Vertical Inter-Move Interval, Total Time, and Total Errors.

Horizontal inter-move interval

For horizontal inter-move interval, the results revealed a significant effect for Moves (*Estimate* = -2.73×10^{-4}, *SE* = 5.06×10^{-5}, $p < .001$) and an interaction between Mapping and Moves (*Estimate* = 3.23×10^{-4}, *SE* = 9.33×10^{-5}, $p < .001$). Given the significant interaction observed between Mapping and Moves, I explored this relationship further through post-hoc analyses. The post-hoc analyses revealed that for higher difficulty trials (the 75th percentile of Moves), horizontal inter-move intervals were significantly lower in the compatible condition compared to the incompatible condition (p = .03) which was consistent with my hypothesis. However, at the low and moderate difficulties, the influence of Mapping on horizontal inter-move intervals was not statistically significant (ps > .05) which was unexpected. In other words, and as illustrated in Figure 5, for trials with a low number of moves, there was no difference between the Mapping conditions. However, as the total number of Moves increased, trials in the incompatible condition showed greater average inter-move-intervals than trials in the compatible condition. This was largely due to a significantly negative relationship between average inter-move-intervals and number of trials in the Compatible condition, $b = -2.73 \times 10^{-4}$, $p < .001$. In contrast inter-move-intervals for trials in the Incompatible condition were largely unchanged with total number of moves, $b = 4.96 \times 10^{-5}$, $p = .53$.

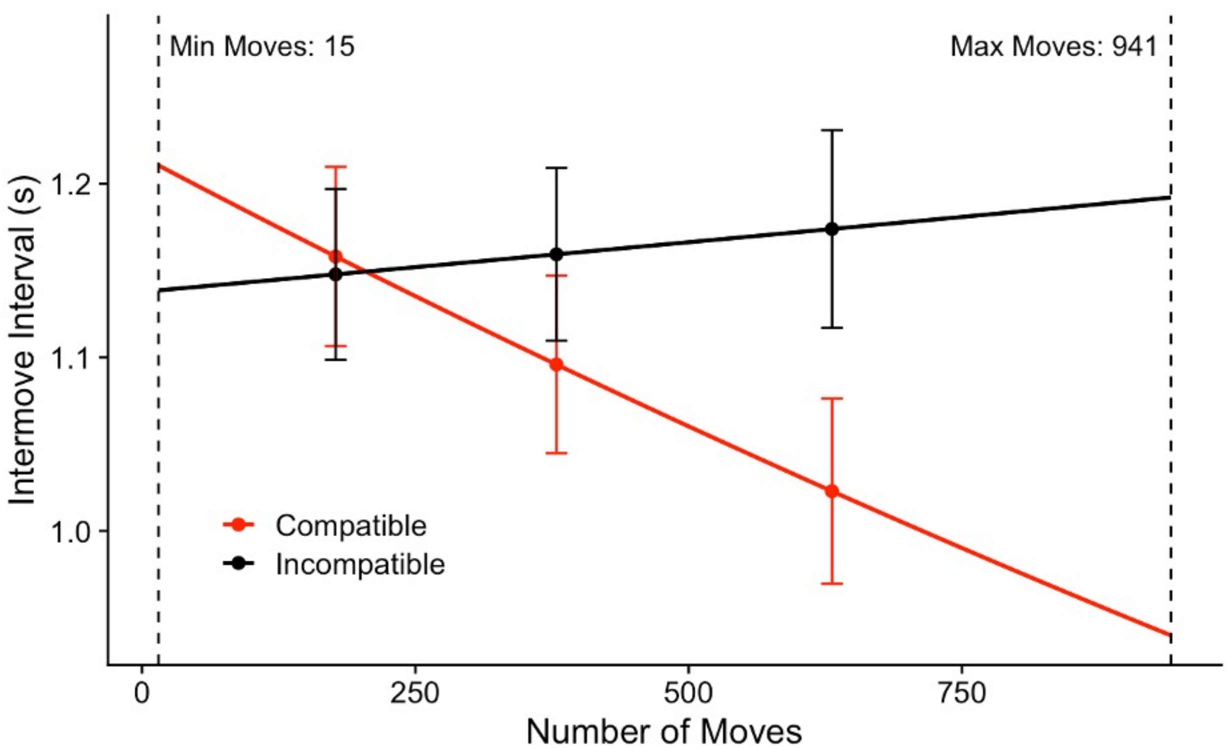

Figure 6. Horizontal inter-move interval by number of moves. Error bars represent standard error and are placed at the 25th, 50th, and 75th percentiles of number of moves.

Vertical inter-move interval

For vertical inter-move interval, there was no distinction between Mapping conditions ($p > .05$) and only a significant effect for (number of) Moves (*Estimate* = -1.47×10^{-4}, $SE = 4.97 \times 10^{-5}$, $p < .001$), which is represented by a decrease in inter-move interval as the number of moves increases (see Figure 6). This suggests that the Mapping effect had no influence on vertical movements, as predicted, but that trials with greater number of moves tended to have lower vertical inter-move-intervals.

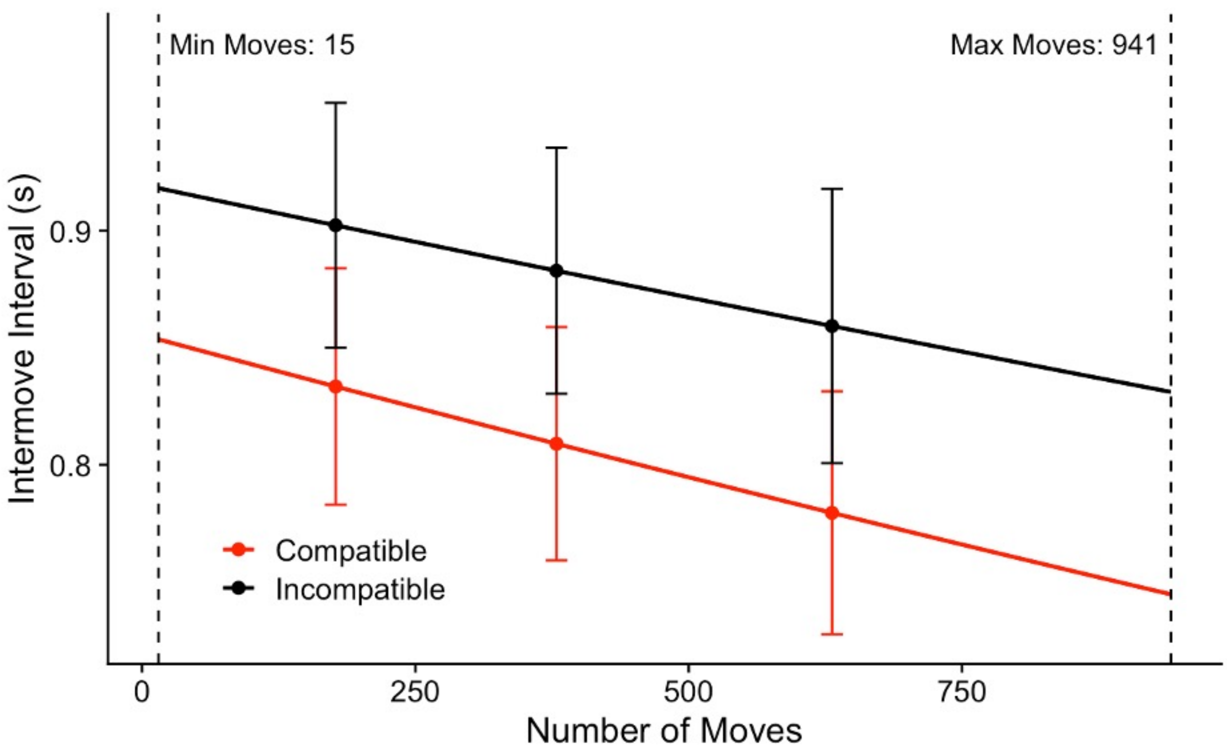

Figure 7. Vertical inter-move interval by number of moves. Error bars represent standard error and are placed at the 25th, 50th, and 75th percentiles of number of moves.

Total task time

With respect to total task time, the analysis revealed significant effects for both Mapping (*Estimate* = -68.11, *SE* = 25.20, p = .01) and number of Moves (*Estimate* = 1.16, *SE* = 0.06, p < .001), as well as an interaction (*Estimate* = 0.48, *SE* = 0.10, p < .001). Given the significant interaction between Mapping and Moves, I ran post-hoc analyses as seen in Figure 7, the magnitude of the Mapping effect grew with total number of moves. Detailed post-hoc analysis revealed that task times at moderate difficulty (p = .001) and higher difficulty (p < .001) trials, were significantly lower in the compatible condition compared to the incompatible condition. However, at lower difficulties, the effect of Mapping on total time was not statistically significant (p >.05). The interaction suggests that the difference in completion time of the task between compatible versus incompatible mapping grows with increased difficulty, represented by number of moves. As seen in Figure 8, the total task time significantly increased as the number of moves increased for both compatible and incompatible conditions.

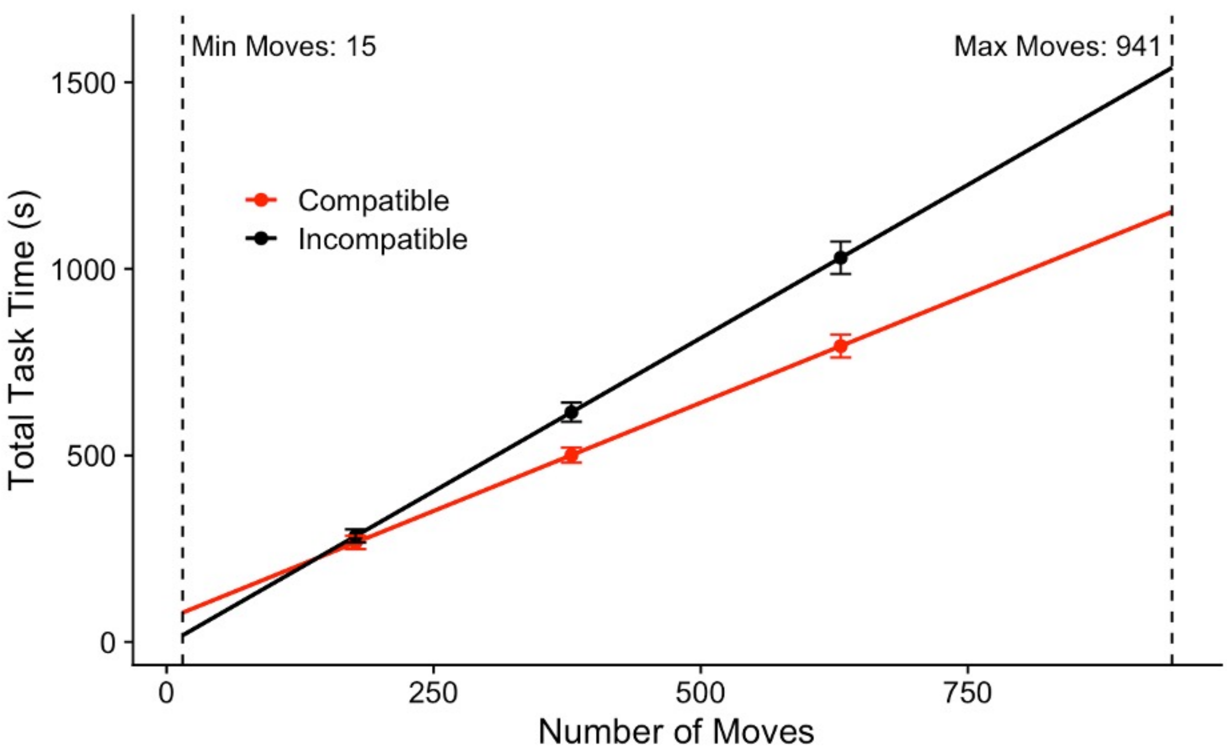

Figure 8. Total time by number of moves. Error bars represent standard error and are placed at the 25th, 50th, and 75th percentiles of number of moves.

Errors

For errors, the analysis revealed significant effects for Moves (*Estimate* = 0.14, *SE* = 0.02, $p < .001$) as well as Mapping × Moves interaction (*Estimate* = 0.12, *SE* = 0.03, $p < .001$). Post-hoc analyses revealed that the magnitude of the Mapping effect increased with trial difficulty. For lower difficulty trials (25th percentile) there was no statistically significant difference in the number of errors between Mapping conditions ($p > .05$). However, the number of errors was significantly greater in the Incompatible condition for moderate and higher difficulty trials (50th and 75th percentile) (*p*s < .001). As seen in Figure 9, the number of errors significantly increased as the number of moves increased for both compatible and incompatible conditions.

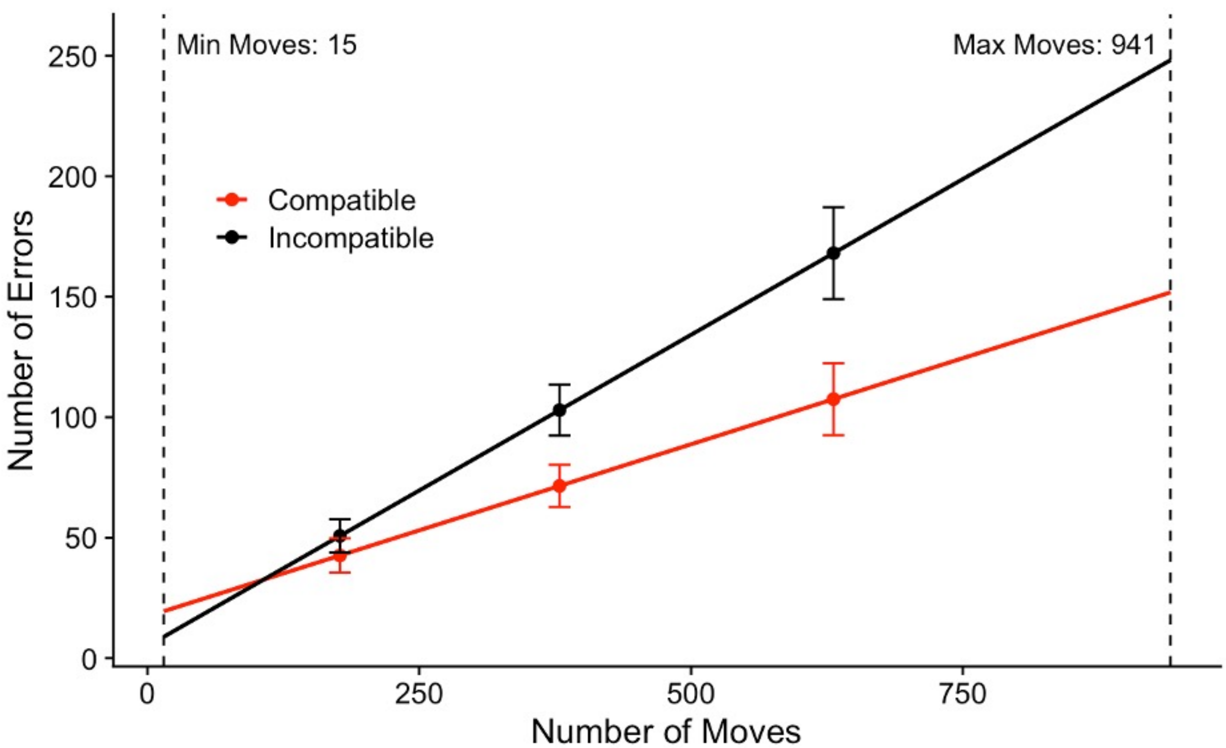

Figure 9. Errors by number of moves. Error bars represent standard error and are placed at the 25th, 50th, and 75th percentiles of number of moves.

Discussion

The purpose of this study was to investigate whether classic stimulus-response compatibility (SRC) influenced performance in a spatiotemporally extended task. Total task time, horizontal and vertical inter-move intervals, and the number of errors made by participants were assessed. Using a virtual reality sliding puzzle game, I hypothesized that those completing a puzzle with compatible horizontal movements (e.g., left hand controls leftward movement) would yield shorter task times, shorter horizontal inter-move intervals, and would make fewer errors than those in the incompatible movement condition (contralateral controls e.g., left hand controls rightward movement). In general, the results supported these hypotheses. Moreover, results from each of our measures suggest that the effects of SRC were influenced by the number of moves, or difficulty, associated with each trial. For example, all inter-move intervals (the intervals between the end of a given directional tile movement to the start of the subsequent directional tile movement) except for incompatible horizontal movements exhibited a negative relationship with number of moves, where inter-move intervals generally were shorter for trials with greater number of moves. One possibility is that this pattern of effects may reflect a general response strategy when faced with more difficult trials. Another possibility is that prolonged and repeated gameplay resulted in the reduction of the Simon effect, as seen in Hutchinson et al. (2015). The latter interpretation, however, must be tempered by the finding that errors also increased with number of moves. That is, the decrease in response time with increasing number of moves could also reflect a more reckless approach as the task takes longer (see discussion of errors below). For the purposes of this thesis (and my original hypotheses) I did not directly test the possibility of within-trial effects, but examining within-trial (learning) effects warrants future investigation.

Irrespective of the underlying causes for the decrease in response times with an increasing number of moves, we found that trials requiring more moves to complete were more likely to exhibit the impact of our mapping manipulations. As hypothesized, trials in which participants had incompatible horizontal movements had longer inter-move intervals compared to those with compatible horizontal movements, most noticeably when the number of moves increased. For vertical movements, however, inter-move interval was not influenced by the mapping manipulation. These results are consistent with the hypothesis that only horizontal movements were influenced by the horizontal mapping manipulation and confirm the presence of SRC influences in the present task. This finding is particularly intriguing because it contrasts with traditional tasks where responses are isolated from each other. Prior research typically shows statistical evidence for stimulus-response compatibility (SRC) effects even with a relatively small number of trials (Craft & Simon, 1970; Fitts & Deininger, 1954; Simon & Rudell, 1967). However, in the context of puzzle-solving, SRC effects become noticeable only in trials that exceed a certain threshold of moves—typically more than 250. This discrepancy implies that SRC effects might not be fixed but rather subject to the nuances of the task context, potentially swayed by overarching goals and their inherent task demands rather than by the simple pairing of stimuli and responses. For example, in a goal-directed task like solving a sliding puzzle, observed differences could result from the complexity of the task, the cognitive demands, learning effects, and perceptual exploration. In the case of the latter, for example participants likely needed to assess not only the target tile, but the entire puzzle when determining the next move. To frame this in terms of stimulus-response compatibility, it can be said that each move effectively changed the global stimulus context without changing the immediate stimulus-response mapping that was being acted upon. Such exploration when deciding to move a tile likely added considerable variation to IMI from move to move. In sum, while most SRC experiments have used discrete, non-sequentially dependent tasks, where participants perform a single action response to a single stimulus, repeatedly, trial after trial, the present study has shown that not only is the SRC effect is also present in spatiotemporally extended tasks where participants must perform a series of actions, but also that the presence and magnitude of the SRC effect was context dependent. Exploring the relationship between these higher order influences and SRC warrants future examination.

In contrast to the finding that inter-move intervals, generally, decreased with number of moves, total task time increased with number of moves. This is unsurprising in the sense that the more moves, the longer the total task time will be. At the same time, the observed Mapping by Moves interaction suggests total move time was also influenced by the mapping. This pattern of effects was largely as anticipated in that total trial times tended to take longer when the SRC mapping was incompatible. That this effect increased as trials took longer to complete again supports the suggestion that SRC effects were largely amplified by trial difficulty. That there was no statically significant difference in the number of moves (i.e., task difficulty) between Mapping conditions suggests that these effects are not simply a product of Incompatible trials taking a higher number of moves to complete. Taken together these results suggest that the increases in total trial time was largely due to increase in the time to initiate movements in the Incompatible condition, and not due to one condition simply requiring more moves than the other. It seems likely that compatibility did not serve to change the task difficulty directly, but rather that participants were more likely to inadvertently select an unintended tile or take longer to initiate trials in the incompatible condition due to confusion resulting from the mapping manipulation. This interpretation is consistent with the pattern of results for errors.

The number of errors not only increased with the number of moves (i.e., more opportunities to make an error) but were also inflated by the presence of an incompatible SRC mapping, again suggesting that participants were more likely to select an unintended tile in the incompatible condition due to confusion from the mapping manipulation. At the same time, it is very possible that the task constraints (or more precisely, the lack thereof) may have influenced these results. Participants were not directed to, nor incentivized to, make the fewest errors possible, nor were they penalized if they made an error. Because there was no task imperative to minimize errors, it is fair to say that errors were "cheap" (i.e., inconsequential). This may have resulted in some participants indiscriminately selecting and moving tiles, regardless of whether the movement was advantageous, either as a strategy (i.e., to see if a move helped them see a pathway to success) or simply out of frustration. If error minimization was incentivized, participants would likely have adopted a more careful strategy leading to fewer errors. This lack of incentivization could also explain why there is a positive relationship between number of moves and errors (i.e., the more moves solving the task entailed, participants likely became increasingly frustrated or felt the need to adopt a more reckless strategy). These issues will require additional studies to better understand the nature of what was observed for errors.

Summary and Conclusions

To the best of my knowledge, this is the first empirical study to provide direct evidence of stimulus-response compatibility influences across a series of responses that were spatiotemporally dependent upon one another to achieve the goal of the task and, in addition, also found that the presence and magnitude of SRC influences were context dependent. In all measures except for vertical inter-move interval, SRC influences were weak when number of moves required to solve the puzzle were low but became more apparent as number of moves required to solve the puzzle increased. These findings suggest the nature of temporally extended tasks, affect how SRC influences are presented. Temporally extended tasks are common in everyday activities such as typing, organizing objects, sports and video games. For instance, in video games, players often need to press a combination of buttons to perform a sequence of actions. An example includes chaining together basic attacks to execute more complex actions and maneuvers in the game "Mortal Kombat" (NetherRealm Studios, 2023). Similarly, in "Fall Guys" (Mediatonic Limited, 2021), players must time and select a sequence of moves to navigate through different in-game obstacles successfully. Although there are prior studies that have used video games to observe stimulus-response compatibility or computer tasks to observe the Simon effect, most have not used sequentially dependent actions and the one study that has (Brown et al., 1995) did not measure SRC influences directly (at the level of individual actions) but rather studied the influence of compatibility on number of wins. Moreover, this is the first instance to my knowledge of SRC being observed in a virtual reality-based video game. Given the growing accessibility of virtual reality to the public and the usage of virtual reality as a tool in fields like education, healthcare, and gaming (Ball et al., 2021; Campos et al., 2022; Hamad & Jia, 2022), it is important to understand the nature of interactions in virtual environments and consider SRC latency influences when designing tasks in VR, especially for time-sensitive tasks.

Future Directions

Although stimulus-response compatibility influences were observed in the present study, the lack of control for errors may have attenuated or exaggerated these influences. Errors should be minimized in future studies in order to more easily interpret the other measures of performance. This can be done by emphasizing to participants to complete the study as best and as accurately as they can. Penalties that do not affect gameplay, such as vibrating controllers or color-changing borders, may also deter and minimize errors. Future research should also explore whether SRC influences are found in dyadic task using virtual reality. Previous studies have demonstrated SRC influences across participants when dyads completed a task together. For example, Sebanz et al. (2003) demonstrated what is known as the *joint simon effect* when dyads completed a Simon task jointly. They found responses to be slower when the stimulus was incompatible with the response effector (e.g., when a color-coded stimulus pointed away must be responded to by the participant assigned to that color) than when the stimulus was compatible with the response effector (e.g., when a color-coded stimulus is pointed towards the participant assigned to respond to that color) (see also Dolk et al., 2014; Yamaguchi et al., 2018). Given that the current study showed SRC influences over a spatiotemporally extended task, this suggests that if dyads performed the present task jointly (such that one person controlled leftward-movement of tiles and their partner controlled rightward-movement of tiles) we should see a similar pattern of results as observed for individuals in the present experiment. This would suggest that collaborative video games are just as susceptible to SRC influences and that these must be considered in the interface design of such games.

References

Ball, C., Huang, K.T., & Francis, J. (2021). Virtual reality adoption during the COVID-19 pandemic: A uses and gratification perspective. *Telematics and Informatics*, 65, 1-13. https://doi.org/10.1016/j.tele.2021.101728

Bliss, J., Turnage, J. J., Kennedy, R. S., & Dunlap, W. P. (1991). Communality of Videogame Performances with Tracking Tasks. *Perceptual and Motor Skills*, *73*(1), 23–30. https://doi.org/10.2466/pms.1991.73.1.23

Broadbent, D.E., & Gregory, M. (1962). Donders' B- and C-reactions and S-R compatibility. *Journal of Experimental Psychology*, *63*, 575-578. https://doi.org/10.1037/h0044674.

Brown, R. M., Brown, N. L., DeLong, D., & Reid, K. (1995). Stimulus-response compatibility and videogame performance. *Perceptual and Motor Skills*, *80*(2), 691–698. https://doi.org/10.2466/pms.1995.80.2.691

Campos, E., Hildrogo, I., & Zavala, G. (2022). Impact of virtual reality use on the teaching and learning vectors. *Frontiers in Education*, 7, 1-15. https://doi.org/10.3389/feduc.2022.965640

Chapanis, A., & Lindenbaum, L. E. (1959). A Reaction Time Study of Four Control-Display Linkages. *Human Factors*, *1*(4), 1–7. https://doi.org/10.1177/001872085900100401

Craft, J. L., & Simon, J. R. (1970). Processing symbolic information from a visual display: Interference from an irrelevant directional cue. *Journal of Experimental Psychology, 83*(3), 415–420. https://doi.org/10.1037/h0028843

Dolk, T., Hommel, B., Colzato, L.S., Schutz-Bosbach, S., Prinz, W., & Liepelt, R. (2014). The joint Simon effect: a review and theoretical integration. *Frontiers in Psychology*, 5, 1-10. https://doi.org/10.3389/fpsyg.2014.00974

Dye, M.W.G., Green, C.S., & Bavelier, D. (2009). The development of attention skills in action video game players. Neuropsychologia, *47*(8-9), 1780-1789. https://doi.org/10.1016/j.neuropsychologia.2009.02.002

Fitts, P.M., & Deininger, R.L. (1954). S-R Compatibility: Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology*, *48*(6), 483-492. https://doi.org/10.1037/h0054967

Fitts, P.M., & Seeger, C.M. (1953). S-R Compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*(3), 199-210. https://doi.org/10.1037/h0062827

Green, C.S, & Bavelier, D. (2003). Action video game modifies visual selective attention. Nature, 423, 534-537. https://doi.org/10.1038/nature01647

Hamad, J., & Jia, B. (2022). How Virtual Reality Technology Has Changed Our Lives: An Overview of the Current and Potential Applications and Limitations. International Journal of Environmental Research and Public Health, 19(18), 1-14. http://doi.org/10.3390/ijerph191811278

Hutchinson, C.V., & Stocks, R. (2013). Selectively Enhanced Motion Perception in Core Video Gamers. *Perception*, *42*(6), 675-677. https://doi.org/10.1068/p7411

Hutchinson, C.V., Barrett, D.J.K., Nitka, A., & Raynes, K. (2015). Action video game training reduces the Simon Effect. *Psychonomic Bulletin & Review, 23*, 587–592. https://doi.org/10.3758/s13423-015-0912-6

Kantowitz, B.H., Triggs, T.J., & Barnes, V.E. (1990). Stimulus-response compatibility and human factors. In R.W. Proctor & T.G. Reeve (Eds.), *Stimulus-Response Compatibility: An Integrated Perspective* (pp. 354-388). Amsterdam: North Holland

Lu, C.H., & Proctor, R.W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review, 2*, 174–207. https://doi.org/10.3758/BF03210959

Mediatonic Limited. (2021). *Fall Guys* [Video game]. Epic Games. https://www.fallguys.com/en-US

Michaels, C.F., & Schilder, S. (1991). Stimulus-response compatibilities between vertically oriented stimuli and horizontally oriented responses: The effects of hand position and posture. *Perception & Psychophysics*, *49(*4), 342-348. https://doi.org/10.3758/BF03205990

Michaels, C.F. (1988). S-R compatibility between response position and destination of apparent motion: Evidence of the detection of affordances. *Journal of Experimental Psychology: Human Perception & Performance*, *14*(2), 231-240. https://doi.org/10.1037/0096-1523.14.2.231

NetherRealm Studios. (2023). *Mortal Kombat 1* [Video game]. Warner Bros. Games. https://www.mortalkombat.com/en-us

Proctor, R. W., & Reeve, T. G. (Eds.). (1989). *Stimulus-response compatibility: An integrated perspective*. Elsevier.

Proctor, R.W., & Van Zandt, T. (2008). Human Factors in Simple and Complex Systems (2nd ed.). Taylor & Francis Group.

Proctor, R.W., & Vu, K.P. L. (2006). *Stimulus Response Compatibility Principles: Data, Theory, and Application* (1st ed.). Boca Raton, FL: CRC Press. https://doi.org/10.1201/9780203022795

Proctor, R.W., & Vu, K.P.L. (2016). Principles for Designing Interfaces Compatible With Human Information Processing. *International Journal of Human–Computer Interaction*, 32(1), 2-22. https://doi.org/10.1080/10447318.2016.1105009

Rizzolatti, G., Bertoloni, G., & Buchtel, H.A. (1979). Interference of concomitant motor and verbal tasks on simple reaction time: a hemispheric difference. *Neuropsychologia*, *17*(3-4), 323-330. https://doi.org/10.1016/0028-3932(79)90078-2

Sebanz, N., Knoblich, G., & Prinz, W. (2003). Representing others' actions: just like one's own? *Cognition*, *88*(3) B11-B21. https://doi.org/10.1016/S0010-0277(03)00043-X

Simon, J.R. (1990). The Effects of an Irrelevant Directional Cue on Human Information Processing. *Advances in Psychology*, *65*, 31-86. https://doi.org/10.1016/s0166-4115(08)61218-2

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*(3), 300–304. https://doi.org/10.1037/h0020586

Simon, J. R., Hinrichs, J. V., & Craft, J. L. (1970). Auditory S-R compatibility: Reaction time as a function of ear-hand correspondence and ear-response-location correspondence. *Journal of Experimental Psychology, 86*(1), 97–102. https://doi.org/10.1037/h0029783

Stins, J.F., & Michaels, C.F. (2000). Stimulus Response Compatibility for Absolute and Relative Spatial Correspondence in Reaching and in Button Pressing. *The Quarterly Journal of Experimental Psychology Section A*, *53*(2), 569-589. https://doi.org/10.1080/713755894

Strasser, H. (2022). Compatibility as guiding principle for ergonomics work design and preventive occupational health and safety. *Zeitschrift für Arbeitswissenschaft.* 76, 243–277. https://doi.org/10.1007/s41449-021-00243-0

Tucker, M., & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology: Human Perception & Performance*, *24*(3), 830-846. https://doi.org/10.1037//0096-1523.24.3.830

Wu, S., & Spence, I. (2013). Playing shooter and driving videogames improves top-down guidance in visual search. *Attention, Perception, & Psychophysics, 75*, 673-686. https://doi.org/10.3758/s13414-013-0440-2

Yamaguchi, M., & Proctor, R.W. (2006). Stimulus-response compatibility with pure and mixed mappings in a flight task environment. *Journal of Experimental Psychology: Applied*, *12*(4), 207-22. https://doi.org/10.1037/1076-898X.12.4.207

Yamaguchi, M., & Proctor, R.W. (2011). The Simon task with multi-component responses: two loci of response–effect compatibility. *Psychological Research, 75*, 214–226. https://doi.org/10.1007/s00426-010-0299-y

Yamaguchi, M., Wall, H.J., & Hommel, B. (2018). Sharing tasks or sharing actions? Evidence from the joint Simon task. *Psychological Research*, *82(*2), 385-394. https://doi.org/10.1007/s00426-016-0821-y

Zhao, X.J. (2022). *Sliding Puzzle AI Solver* (Version 1.5) [Mobile app]. App Store. https://apps.apple.com/us/app/sliding-puzzle-ai-solver/id6443604353