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Investigating the Nature of Spatial Codes for Different Modes of Simon Tasks: Evidence From Congruency Sequence Effects and Delta Functions

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Simon effects have been observed to arise from different modes of spatial information (e.g., physical location, arrow direction, and location word). The present study investigated whether different modes of spatial information elicit a unitary set of spatial codes when triggering a spatially corresponding response code. A pair of two different Simon tasks was presented in alternation: location- and arrow-based Simon tasks in Experiments 1 and 2, word- and location-based Simon tasks in Experiment 3, and arrow- and word-based Simon tasks in Experiment 4. Responses were collected using unimanual aimed-movement responses. Cross-task congruency sequence effects (CSEs) were found in Experiments 1 and 2, indicating a shared set of spatial codes between physical locations and arrow directions. Conversely, the absence of CSEs in Experiment 3 suggested that physical locations and location words elicited different sets of spatial codes. In Experiment 4, a CSE was evident in the arrow-based Simon task but not in the word-based one, implying an overlap in the spatial attributes of arrow directions with those of location words. Distributional analyses of the Simon effects revealed that different modes of spatial information yielded distinct temporal patterns of its activation and dissipation, implying quantitative differences in the Simon effects. The cross-comparisons of the CSE and delta function data indicated that the quantitative similarities in spatial modes did not correspond to the qualitative similarities, suggesting a crucial finding that each set of data reflects different aspects of the nature of the spatial codes.

Public Significance Statement

Physical location, arrow direction, and location word are different forms of conveying spatial information. The present study investigates the relationships between these spatial modes by determining whether their spatial response conflicts are processed in a qualitatively similar manner. We suggest that while physical location and location word have largely distinct spatial properties, arrow direction shares an intimate relationship with physical location and a partial connection with location word.

Keywords: Simon task, spatial code, distributional analysis, congruency sequence effect

The spatial information of an object has been found to affect response selection regardless of whether it is relevant to the task instruction or not (e.g., Miles & Proctor, 2012; Thornton et al., 2013). For example, when observers are to make left-right responses to a nonspatial feature (e.g., color) of a target, often termed a task-relevant feature, presented either to the left or right of a fixation point, considered as a task-irrelevant feature, responses are prolonged and often erroneous when the target location does not correspond to the response location (i.e., is incongruent) compared to when it does (i.e., is congruent; see, for example, Zorzi et al., 2003). This influence of the spatial correspondence between stimulus location and response location on task performance is called the Simon effect (e.g., Lu & Proctor, 1995; Simon, 1990), which measures the cognitive conflicts between the activations of different response alternatives. The spatial feature of a stimulus can also be elicited without physical locations by centrally presenting location words (e.g., left or right; Khalid & Ansorge, 2013; Luo & Proctor, 2017; Pellicano et al., 2009) or symbols (e.g., left- or right-pointing arrow; Lu & Proctor, 2001; Proctor et al., 2009) as stimuli. These Simon tasks differ from other cognitive conflict tasks using spatial features of an arrow or a location word, such as spatial Stroop tasks, where spatial conflicts arise from the spatial codes of stimuli rather than response domains. The influence of spatial correspondence is not constrained to the horizontal orientation but extends to the vertical dimension (e.g., Stürmer et al., 2002; Többel et al., 2014; Vallesi et al., 2005). These Simon effects are due to spatial codes of stimuli affecting response selection, resulting in response conflicts (e.g., Hommel, 1993b) when the spatial code of a stimulus does not match with that of a correct response. However, it remains unclear

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whether spatial information conveyed through different spatial modes are qualitatively identical in how they are processed and represented.

In the Simon task, according to the dual-route model of response selection (De Jong et al., 1994; Kornblum et al., 1990), a stimulus code for a task-relevant target feature (e.g., color) slowly activates a response code via an indirect (or controlled) route of response selection based on the goal-oriented task rules. Concurrently, the spatial code for task-irrelevant spatial information (e.g., target location) automatically activates its spatially corresponding response code rapidly via a direct (or automatic) route of response selection driven by the natural or overlearned stimulus–response (S–R) associations (e.g., Ansorge & Wühr, 2004). Thus, if the response codes elicited by the task-relevant target feature and the task-irrelevant spatial feature differ, response selection is delayed compared to when they are identical. Because the spatial code for the task-irrelevant spatial information rapidly decays over time (Hommel, 1994) or is actively suppressed (Ridderinkhof, 2002), response time (RT)-based distributional analyses have shown a decreasing function of the Simon effect, with a smaller Simon effect for slower than for faster responses (De Jong et al., 1994; for a review, see Proctor et al., 2011). However, this decreasing delta function has only been consistently found for the horizontal location-based Simon effect. The vertical location-based Simon task yielded distinct time courses, showing increasing delta functions (Buetti & Kerzel, 2008; Proctor et al., 2003; Wiegand & Wascher, 2005) with larger Simon effects for slower than for faster responses. Moreover, the Simon effects elicited by arrows and location words were also found to increase across RT bins in most studies (Buetti & Kerzel, 2008; Proctor et al., 2003; Wiegand & Wascher, 2005). These different temporal dynamics of Simon effects raise the question of whether different patterns of delta functions imply different natures of spatial codes.

Wiegand and Wascher (2005) proposed that the Simon effects' varying time courses imply qualitatively different spatial codes and, thus, provide mode-specific spatial representations. Rapidly processed anatomical spatial codes, like the horizontal location-based Simon effect, depict the decreasing function of the Simon effects across the RT distribution. In contrast, slowly processed cognitive (or verbal) spatial codes, like the word-, arrow- and vertical location-based Simon effects, reveal an increasing or constant delta function (Gade et al., 2020; Wühr & Biebl, 2011). On the other hand, Ulrich et al. (2015) proposed that the patterns of the delta functions are mere traces of the different speeds of the stimulus activation. If the automatic activation of the spatial code develops early and then dissipates rapidly, the slope of the delta function tends to be negative, showing a decreasing Simon effect with increasing RT. If the automatic activation of the spatial code is slow, on the other hand, the slope tends to be positive, showing the largest Simon effect in the slowest response bin (e.g., Vu et al., 2005). Luo and Proctor (2020) also demonstrated distinct divergence points of activation for the physical locations, arrows, and location words when conveying spatial information, which were consequently reflected in the time courses they observed for their Simon effects. Thus, several pieces of evidence suggest that different patterns of delta functions reflect quantitative differences in the activation of spatial codes (Luo & Proctor, 2017; Töbel et al., 2014; Ulrich et al., 2015), while leaving open the question of whether the delta functional shapes imply shared or nonshared sets of spatial codes among different modes of spatial information.

Although much research has been conducted investigating whether different modes of spatial information activate a common set of spatial codes, results are not consistent (De Houwer et al., 2005; Luo & Proctor, 2017; Miles et al., 2009; Miles & Proctor, 2011; Notebaert et al., 2007; Proctor et al., 2009; Virzi & Egeth, 1985; Vu & Proctor, 2004). For example, Notebaert et al. (2007) claimed that physical location and location word activate a shared set of spatial codes by demonstrating a reversed location-based Simon effect when trials of the Simon task were intermixed with trials on which participants were asked to respond to the meaning of a centrally presented location word with an incompatible S–R mapping rule. Conversely, Proctor et al. (2009) suggested that the acquired short-term associations of the spatial mappings were qualitatively different in location words compared to physical locations and arrow directions. They investigated the relationships between two different modes of spatial information by examining how the elimination of spatial correspondence effects transferred when participants overlearned incompatible spatial mappings. After practicing incompatible mappings in one spatial mode and measuring the Simon effect in another spatial mode, the researchers found that physical location and arrow direction showed significantly reduced Simon effects based on acquired short-term associations of the other spatial mode's incompatible mappings. However, a more extended practice was required for word-based incompatible learning to eliminate the arrow-based Simon effect. Virzi and Egeth (1985) also suggested a model for which physical locations and location words activate different sets of spatial codes, based on their observation that spatial interference occurred only when translation from the spatial codes for one mode of spatial information to those for another mode of spatial information was necessary.

One possible alternative approach to exploring the distinction between shared and nonshared representations for different modes of spatial information is to examine how cognitive control over spatial information involved is shared in the congruency sequence effect (CSE; Gratton et al., 1992). The CSE, which refers to a reduced congruency effect observed after an incongruent trial compared to after a congruent trial (Kim et al., 2015; Notebaert & Verguts, 2011), appears in Simon tasks as well as in other cognitive conflict tasks, such as Stroop and flanker compatibility tasks (e.g., Duthoo et al., 2014; Jiménez & Méndez, 2013; Notebaert & Verguts, 2006). It has been suggested that this CSE is due to the top-down cognitive control modulating the conflict induced by task-irrelevant stimulus features (Botvinick et al., 2001; J. Lee & Cho, 2013; Notebaert & Verguts, 2008). According to this control view of the CSE, experiencing a conflict-present (i.e., incongruent) trial enhances the conflict modulation in the subsequent task through a feature-specific focus or domain-general cognitive control (e.g., Egner, 2008; Straub et al., 2022). A cross-task paradigm, where two different tasks are alternated on every trial, is largely used to examine the sequential modulation of the congruency effect between task conditions. By determining the circumstances in which the CSE appears, the findings from cross-task designs reveal how cognitive control operates (for a review, see Braem et al., 2014).

Regarding the mechanism underlying the CSE in the Simon task, lines of evidence indicate that cognitive control is exerted through a mechanism of inhibiting the activation of response codes triggered by the task-irrelevant spatial codes (Kim et al., 2015; J. Lee & Cho, 2013; Lim & Cho, 2021b; Soutschek et al., 2013; Stürmer et al., 2002). For example, Kim et al. (2015) demonstrated that employing different task-relevant stimulus dimensions (e.g., color vs. letter identity) between two Simon tasks did not impede the presence of the CSE. They determined that this was because cognitive control does not operate in a way to facilitate the task-relevant information and, instead, inhibitory processing could be shared between the two tasks due to the same task-irrelevant spatial dimension. By employing the same response mode and task-irrelevant spatial dimension for both tasks, significant cross-task CSEs were found between horizontal and vertical Simon tasks with different task-relevant dimensions (color vs. timbre) and stimulus modalities (visual task vs. auditory task; Y. S. Lee & Cho, 2023). The inhibitory nature of the cognitive control recruited by conflict was also found in an electroencephalogram study conducted by Stürmer et al. (2002), in which task-relevant and task-irrelevant lateralized readiness potential (LRP) signals were measured during a location-based horizontal Simon task. The results revealed clear task-irrelevant LRP activity after a congruent trial that was diminished after an incongruent trial. Stürmer et al. suggested that the control process triggered by successive Simon conflicts modulates the Simon effect by inhibiting the transmission of the output of the direct route to the motor execution system, which again highlights the significance of sharing the task-irrelevant stimulus spatial dimension in eliciting the CSE between two Simon tasks. Moreover, in their diffusion model for conflict tasks analysis, Koob et al. (2023) demonstrated that while suppressing task-irrelevant information is essential to generate the CSE, increased processing of task-relevant information is not. These findings imply that cognitive control reflected in the CSE is specific to the inhibitory control on the task-irrelevant spatial dimensions and corresponding response codes rather than to the facilitation of task-relevant dimensions.

Lim and Cho (2021b) used both the CSE and a distributional analysis to investigate the control mechanisms involved in horizontal and vertical location-based Simon tasks. By utilizing aimed-movement responses, the saliences of the horizontal and vertical dimensions were equated, and initiation time (IT), defined as the temporal elapse between target onset and home key release, and movement time (MT), defined as the temporal elapse between home key release and the press of a directional response key, were measured separately. The results revealed a CSE between the horizontal and vertical location-based Simon tasks in the MT data when participants performed both tasks with the same hand but not when they performed the horizontal Simon task with their left hand and the vertical Simon task with their right hand. This outcome indicates that response-related features can play a role in dissociating tasks and, thus, in modulating the common set of response conflicts in the Simon tasks (Braem et al., 2011; Janczyk & Leuthold, 2018; J. Lee & Cho, 2013). In addition, the presence of the CSE in MT and not in IT suggests that cognitive control is assumed over activated response codes mainly after a response movement is initiated. Furthermore, the outcome implies that the task-irrelevant response code is not entirely regulated before response initiation.

It is also important to note that in Lim and Cho's (2021b) experiment, when the cross-task CSE was evident between the horizontal and vertical Simon tasks in the MT data, decreasing delta functions were identified in the IT data for both tasks. In contrast, when participants performed one task with their right hand and the other with their left hand, resulting in no cross-task CSE in the MT data, a constant delta function was identified in the IT data for the vertical location-based Simon effect but a decreasing delta function for the horizontal location-based Simon effect. Consequently, the absence of the CSE in the MT data was accompanied by different time courses of the Simon effect in the IT data. This finding raises the question of whether the same temporal dynamic of the Simon effect should be observed for the shared cognitive control of spatial conflicts.

Present Study

Whether different spatial modes activate mode-specific or shared spatial codes, and especially, knowing the cognitive similarities among their processing is critical in understanding spatial cognition. By exploiting the cross-task CSEs and delta functions of their Simon effects, the present study investigated whether different modes of spatial information activate a shared set of spatial codes. It has been suggested that the control process triggered by Simon conflict inhibits the direct route along which the spatial codes for task-irrelevant spatial information automatically activate their spatially corresponding responses (Kim et al., 2015; Lim & Cho, 2021b; Soutschek et al., 2013; Stürmer et al., 2002). Thus, the presence of the CSE between two Simon tasks with different modes of spatial information depends on whether they activate shared sets of spatial as well as of response codes.

The different modes of spatial information used in the current study included physical location, arrow direction, and location word, each of which was examined in combination with another mode of spatial information during an experiment. Some differences and similarities have been suggested regarding inherent attributes and the way the spatial information is conveyed in each mode. While the spatial code for physical location is directly formed relative to a salient referent point, that for a location word is indirectly formed based on the learned knowledge of the arbitrary link between a word and its spatial meaning. The spatial code for arrow direction can be extracted indirectly from the symbolic meaning of the arrow, as well as directly from its asymmetrical physical properties (Miles & Proctor, 2012; Notebaert et al., 2007).

To avoid the confounding effects of repetition priming (Hommel et al., 2004; Mayr et al., 2003) and contingency learning (Schmidt & De Houwer, 2011), horizontal and vertical Simon tasks consisting of different stimulus and response sets were alternated in a trial-by-trial manner (Kim & Cho, 2014; Lim & Cho, 2021a; Schmidt & Weissman, 2014). To equate the vertical and horizontal dimension saliences, unimanual aimed-movement responses were utilized (Lim & Cho, 2021b). By using the aimed movement response mode, ITs, which primarily reflect the time necessary to process task-relevant and irrelevant information for initiating a response, and MTs, which primarily reflect the time necessary to complete the regulation of the response conflicts to execute a response, were measured separately (Doucet & Stelmack, 1999). Importantly, even though the Simon effect was evident in both types of measures (Buetti & Kerzel, 2008, 2009; Lim & Cho, 2021b; Miller & Roüast, 2016), different time courses of the Simon effect have been consistently found in movement initiation measures but not in movement measures (Buetti & Kerzel, 2008, 2009; Lim & Cho, 2021b; Miller & Roüast, 2016), while the CSE has been found in movement measures but not in movement IT (Erb et al., 2016; Erb & Marcovitch, 2018; Lim & Cho, 2021b; Miller & Roüast, 2016; Scherbaum et al., 2010). Response selection and motor execution processes may not be clearly distinguishable; the initiation of a movement to make a response is likely to occur without the full completion of response selection (Buetti & Kerzel, 2008, 2009; Calderon et al., 2018; Erlhagen & Schöner, 2002; Hommel, 2009; Resulaj et al., 2009).

Regarding the Simon effect, if the evidence for a specific response surpasses that of the competing response or reaches a particular threshold, the response is likely to be initiated even when response selection is not fully completed (Buetti & Kerzel, 2008, 2009; Calderon et al., 2018). Accordingly, the changes in the activation of spatial codes for the task-irrelevant stimulus dimensions are evident in movement initiation measures. Moreover, because a task-irrelevant spatial code triggers the competing response code through the direct route once its activation reaches a certain threshold, the activation of the response code can persist even after the response is initiated (Buetti & Kerzel, 2009; Lim & Cho, 2021b). Consistent with this idea, the effect of the activation of spatial codes has been found to be evident even after a response is initiated (Kerzel & Buetti, 2012; Miller & Roüast, 2016; Scherbaum et al., 2010).

In a series of experiments, participants were asked to perform two Simon tasks with different modes of spatial information (see Figure 1 for an overview of the tasks). The horizontal arrow-based and vertical location-based Simon tasks were alternated in a trial-by-trial manner in Experiment 1, and the horizontal location-based and vertical arrow-based Simon tasks were presented in Experiment 2. If physical location and arrow direction activate a shared set of spatial codes, a cross-task CSE between the two tasks would occur because they share the direct route of response selection. However, if they activate different modes of spatial codes, no cross-task CSE would occur because they have different direct routes. The word-based and location-based Simon tasks were presented alternatively in a trial-by-trial manner in Experiment 3 and the word-based and arrow-based Simon tasks were presented in Experiment 4 to investigate whether location words share spatial codes with physical location and arrow direction, respectively. Likewise, if a common set of the codes is activated by the spatial information conveyed by the two modes of spatial information used in an experiment, a cross-task CSE would be observed. In line with previous studies (e.g., Erb et al., 2016; Erb & Marcovitch, 2018; Lim & Cho, 2021b; Miller & Roüast, 2016; Scherbaum et al., 2010), we expect the CSEs, if present, to be evident in the MT data rather than in the IT data.

Another goal of the present study was to examine whether the temporal dynamics of the Simon effects can reveal qualitative differences of these spatial modes. As in previous studies (Buetti & Kerzel, 2008, 2009; Lim & Cho, 2021b; Miller & Roüast, 2016), different time courses for different modes of the Simon effect, if present, would be more evident in IT than MT data, reflecting the time required to gain certain amounts of evidence for initiating a response triggered by task-relevant and task-irrelevant stimulus features. We expect the cross comparisons of the CSE and the delta function of the Simon effects to indicate whether different delta functional patterns indicate that different modes of spatial information activate mode-specific spatial codes.

Experiment 1

The goal of Experiment 1 was to investigate whether physical location and arrow direction activate a common set of spatial codes by examining the CSE between location-based and arrow-based Simon tasks. To minimize the confounding effects of feature integration (Hommel et al., 2004; Mayr et al., 2003) and contingency learning (Schmidt & De Houwer, 2011), successive repetition of the stimulus and response alternatives was fully avoided by presenting horizontal location-based (left or right) and vertical arrow-based (up or down) Simon tasks in an alternating sequence (Kim & Cho, 2014; Lim & Cho, 2021a; Schmidt & Weissman, 2014). Participants were asked to respond to the color of the target in both tasks. Participants responded with unimanual aimed movements to equalize the saliencies of the horizontal and vertical dimensions (Lim & Cho, 2021b; Proctor et al., 2003; Vu et al., 2005).

It has been suggested that cognitive control modulates the Simon conflict by inhibiting the activation of response codes that were automatically triggered by spatial stimulus codes via the direct route (Egner et al., 2007; Kim et al., 2015; Lim & Cho, 2021b; Soutschek et al., 2013; Stürmer et al., 2002). Thus, if the location of a target and the direction of an arrow activate a shared set of spatial codes, a CSE between the horizontal location-based and vertical arrow-based Simon tasks would occur, because the two tasks share the direct route of response selection that is subject to the inhibitory control triggered by the Simon conflict. However, if they activate different modes of spatial codes, no CSE would be observed because the two modes of spatial information activate the corresponding response codes via different direct routes of response selection. The cross-task CSE, if present, would be especially evident in the MT data as shown in previous studies (Erb & Marcovitch, 2018; Erb et al., 2016; Lim & Cho, 2021b; Miller & Roüast, 2016; Scherbaum et al., 2010), reflecting the efficiency of the conflict modulation depending on shared or nonshared sets of spatial codes. Moreover, we expect the IT data to reveal the temporal dynamics of the horizontal location-based and vertical arrow-based Simon effects, which would reflect the activation and dissipation speeds of each spatial code modulating the amounts of evidence for the competing responses (e.g., Buetti & Kerzel, 2008, 2009; Calderon et al., 2018; Doucet & Stelmack, 1999).

Method

Participants

A power analysis in G*Power 3.1.9.2 was conducted to determine the sample size needed to observe a critical two-way interaction between previous-trial and current-trial congruencies, that is, a cross-task CSE (Faul et al., 2009). An alpha (α) of .05 was combined with the effect size ($\eta_p^2 = .127$) of the two-way interaction that Y. S. Lee and Cho (2023, Experiment 1) observed within previous-trial congruency (congruent and incongruent), and current-trial congruency (congruent and incongruent) which used the same response method and the alternating-task paradigm as the current study. The results indicated that 34 participants would provide over 99% power to observe this interaction. A larger number of participants were employed concerning the critical testing of the two-way interactions in each mode of Simon tasks (Lim & Cho, 2021b). Therefore, 52 right-handed participants (17 males; $M_{age} = 23.21$) took part in Experiment 1, all recruited from Korea University.[1] All participants self-reported to have normal visual acuity and color vision, gave written consent before participating, and received a monetary reward of KRW 8,000 (approximately USD 7) after their participation. The current and following experiments were approved by the Institutional Review Board at Korea University (KUIRB-2020-0083-05).

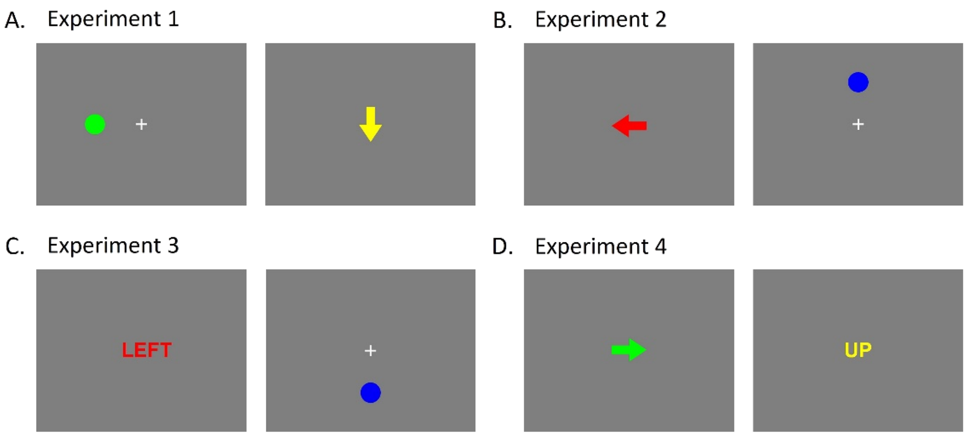
Apparatus and Stimuli

The experiment was conducted in a dimly lit sound-proof chamber. All experiments were programmed with Matlab software

[1] The sample size was increased from 40 to 52 for all experiments during the review process at the request of a reviewer. This adjustment did not influence the critical findings.

Figure 1

Illustrations of Target Displays Used in Experiment 1 (A), Experiment 2 (B), Experiment 3 (C), and Experiment 4 (D)



Note. The left panels indicate horizontal tasks, and the right panels indicate vertical tasks. See the online article for the color version of this figure.

(Version 2015a) using Psychtoolbox. Visual stimuli were presented on a 17-in. CRT monitor, at a viewing distance of about 60 cm. Responses were collected using the numeric keypad of a standard 101-key computer keyboard. The midpoints of the computer monitor and the numeric keypad were aligned with the participant's body midline.

Responses were collected using aimed-movement responses. The home key was the "5" key on the numeric keypad, and the direction response keys for "left," "right," "up," and "down" were the "4," "6," "8," and "2" keys, respectively. Participants were instructed to press the home key with their right index finger, to keep pressing the key until a response to the target was determined, and to respond to the target color by pressing one of the direction keys with the same finger.

All stimuli were presented on a black background. The experiment contained a horizontal location-based Simon task and a vertical arrow-based Simon task, alternated in a trial-by-trial manner. A white (RGB: 255, 255, 255; CIE color coordinates: $x = 0.270$, $y = 0.297$) fixation cross (approximately $0.3° \times 0.3°$ of visual angle) was presented at the center of the display as a fixation point. For the horizontal location-based Simon task, a red (RGB: 255, 0, 0; CIE color coordinates: $x = 0.581$, $y = 0.346$) or green (RGB: 0, 255, 0; CIE color coordinates: $x = 0.285$, $y = 0.599$) circle (approximately 1.78° in diameter) was presented at either the left or the right side of the fixation cross. The distance of the target circle from the fixation cross was approximately 3.13°. For the vertical arrow-based Simon task, a blue (RGB: 0, 0, 255; CIE color coordinates: $x = 0.152$, $y = 0.080$) or yellow (RGB: 255, 255, 0; CIE color coordinates: $x = 0.388$, $y = 0.513$) up- or down-pointing arrow (approximately $1.78° \times 2.65°$) was presented in the center of the screen (Figure 1A).

Procedure

Participants were to respond according to the target color. They were informed of the four stimulus–response mappings between the target color and its corresponding direction keys; to press the "left" direction key in response to the red target, and the "right" direction key in response to the green target in the horizontal location-based Simon task, and the "up" direction key in response to the blue and the "down" direction key in response to the yellow target in the vertical arrow-based Simon task.

Each trial started with a fixation cross, and participants were instructed to press the home key and to keep the home key pressed until the target (a circle or arrow) appeared and they had decided on their response. A target stimulus was presented 500 ms after the home key was pressed, until the home key was released or for a maximum of 250 ms. If the home key was released before the target appeared, the visual message "Press the home key" was presented. When the target appeared and the home key was released, the display went blank until any direction key was pressed or for a maximum of 2,000 ms. If no response was made within 2,000 ms or an incorrect direction key was pressed, an auditory tone of 750 Hz was presented for 150 ms. A blank display was presented for 1,000 ms before the beginning of the next trial.

After a practice block of 18 trials, participants performed eight blocks of the main experiment, each of which was composed of 98 trials. A 1-min break was given after each block of trials. The congruency sequence was pseudorandomly determined to equate the numbers of congruent trials after a congruent trial, congruent trials after an incongruent trial, incongruent trials after a congruent trial, and incongruent trials after an incongruent trial for the horizontal and vertical Simon tasks, respectively.

Data Analyses

Analyses on RTs were restricted to trials with correct responses. Along the time stamps of aimed-movement responses, IT was recorded as the time between the target onset and the moment the home key was released. MT was measured as the temporal interval between the home key release and the direction key press. The total reaction time (TT) was calculated by adding IT and MT. Considering a tradeoff between IT and MT, outliers were defined as the trials on which either MT or IT was more than 3 *SD*s away from its conditional mean for each participant. The first two trials of each block, outliers, and the trials following outliers or incorrect trials were excluded from the analyses, resulting in the exclusion of 7.22% of all trials.

Before the analyses of primary interest, a two-way repeated measures analysis of variance (ANOVA) was conducted on the TT as a function of current-trial congruency and task type to ensure the successful evocation of the location- and arrow-based Simon conflicts. While there were quantitative differences between the two spatial modes, both location-based, $F(1, 51) = 135.98$, $p < .001$, $MSE = 150$, $\eta_p^2 = .727$, and arrow-based Simon effects, $F(1, 51) = 419.27$, $p < .001$, $MSE = 209$, $\eta_p^2 = .892$, were evident. The significant main effect of task type, $F(1, 51) = 37.68$, $p < .001$, $MSE = 1{,}207$, $\eta_p^2 = .425$, and the interaction between current-trial congruency and task type, $F(1, 51) = 111.94$, $p < .001$, $MSE = 105$, $\eta_p^2 = .687$, indicated faster TTs ($M = 518$ ms) and a smaller Simon effect (28 ms) in the horizontal location-based Simon task than in the vertical arrow-based Simon task ($M = 561$ ms and a 58-ms Simon effect).

Then, to investigate whether the CSE would be found between the two tasks, mean correct ITs, MTs, TTs, and percent errors (PEs) were calculated for each participant as a function of previous-trial congruency (congruent vs. incongruent) and current-trial congruency (congruent vs. incongruent). Two-way repeated-measures ANOVAs were conducted on each participant's mean ITs, MTs, TTs, and PEs, with the two factors as within-subject variables.

Distributional bin analyses were also conducted on IT, MT, and TT, respectively, to compare temporal dynamics of the different Simon effects. Each participant's ITs and MTs were divided into five bins based on TT, and the mean ITs, MTs, and TTs were averaged into quintiles, respectively. Delta functions were calculated by subtracting the mean ITs, MTs, and TTs of the congruent trials from those of the incongruent trials in each bin, reflecting the size of the Simon effect in each time bin. To test the statistical difference between the delta functions of the two task types, quintile-averaged data were entered into three-way repeated-measures ANOVAs as a function of bin (1–5), current-trial congruency (congruent vs. incongruent) and task type (horizontal location-based Simon task vs. vertical arrow-based Simon task) as within-subject factors.

Transparency and Openness

We report how we determined our sample size. Data exclusions criteria are stated. The data sets, analysis codes, and research materials of all experiments are available at the Open Science Framework: https://osf.io/7fnu4/. Data were analyzed using MATLAB, Version 2019a. This study's design and its analyses were not preregistered.

Results

IT

The main effect of current-trial congruency was significant, $F(1, 51) = 178.357$, $p < .001$, $MSE = 230$, $\eta_p^2 = .778$, showing a 28-ms Simon effect. The main effect of previous-trial congruency was also significant, $F(1, 51) = 31.4$, $p < .001$, $MSE = 51$, $\eta_p^2 = .381$, with a greater mean IT after incongruent ($M = 416$ ms) than after congruent trials ($M = 410$ ms), in a pattern of postconflict slowing (Verguts et al., 2011). Critically, however, the interaction between current-trial congruency and previous-trial congruency was not significant, $F(1, 51) = 2.83$, $p = .099$ (Figure 2A). An additional analysis using Bayes factors (BFs) was conducted to provide a more robust analysis supporting the lack of interaction. The BF for the interaction of previous-trial congruency and current-trial congruency revealed a BF_{01} of 1.42, which provides anecdotal evidence (Ortega & Navarrete, 2017) for the null hypothesis (JASP Team, 2022).

MT

The main effect of current-trial congruency was significant, $F(1, 51) = 73.02$, $p < .001$, $MSE = 147$, $\eta_p^2 = .589$, indicating a Simon effect (14 ms). The main effect of previous-trial congruency was not significant, $F(1, 51) < 1$, $p = .522$. Importantly, the interaction of previous-trial congruency with current-trial congruency was significant, $F(1, 51) = 6.72$, $p = .012$, $MSE = 12$, $\eta_p^2 = .116$, showing a reduced Simon effect after incongruent trials (13 ms), $F(1, 51) = 60.24$, $p < .001$, $MSE = 74$, $\eta_p^2 = .542$, compared to after congruent trials (16 ms), $F(1, 51) = 74.78$, $p < .001$, $MSE = 85$, $\eta_p^2 = .595$ (Figure 2B). An additional analysis was conducted to check whether the interaction between previous-trial congruency and current-trial congruency depended on the task type. A three-way repeated-measures ANOVA as a function of previous-trial congruency, current-trial congruency, and task type (horizontal location-based Simon task vs. vertical arrow-based Simon task) revealed that the three-way interaction among these variables was not significant, $F(1, 51) < 1$, $p = .582$, showing a significant CSE in both location-based, $F(1, 51) = 5.54$, $p = .022$, $MSE = 15$, $\eta_p^2 = .098$, and arrow-based Simon tasks, $F(1, 51) = 6.63$, $p = .013$, $MSE = 24$, $\eta_p^2 = .115$.

TT

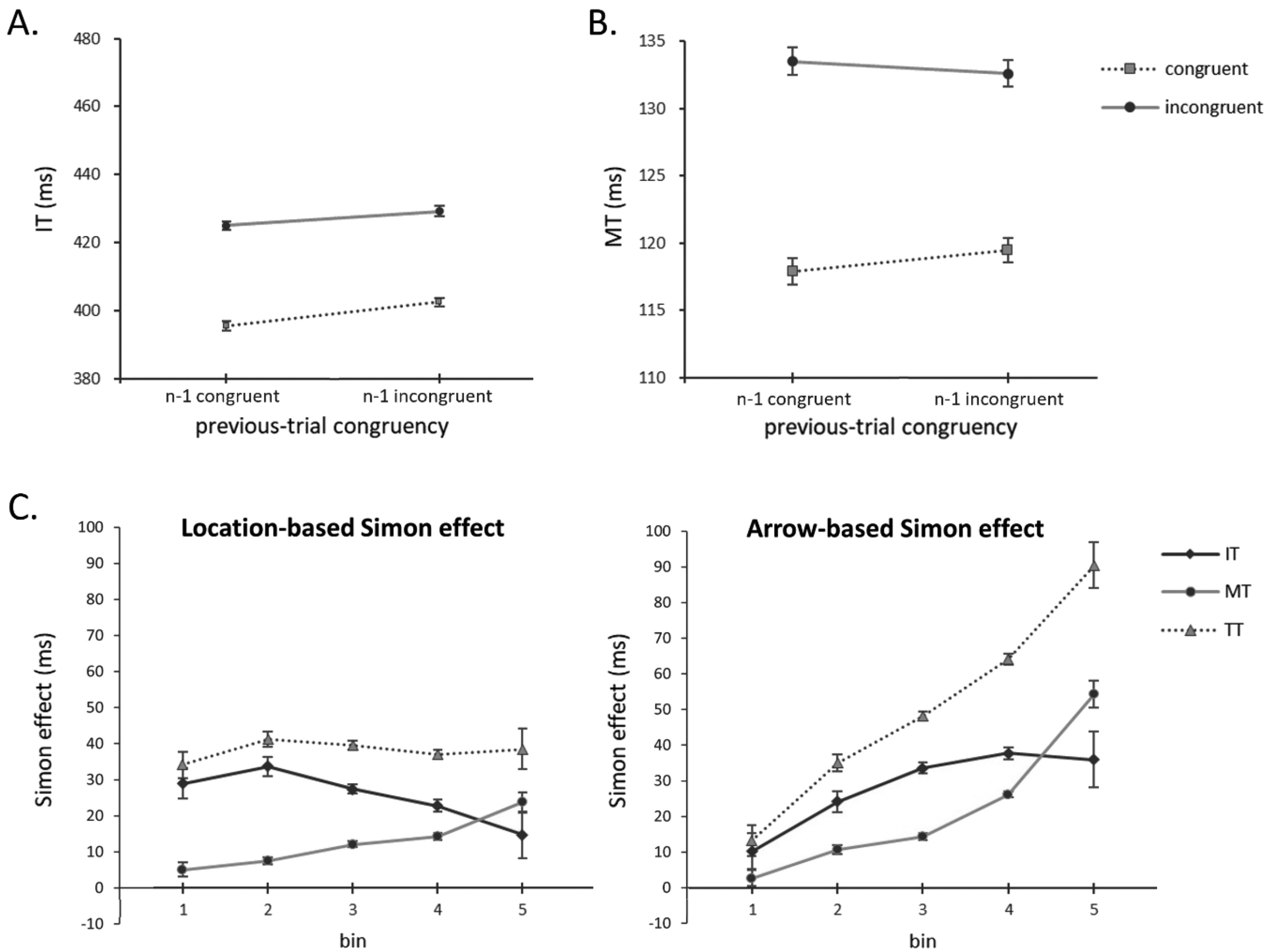
The main effect of current-trial congruency was significant, $F(1, 51) = 374.59$, $p < .001$, $MSE = 250$, $\eta_p^2 = .88$, showing a Simon effect of 42 ms. The main effect of previous-trial congruency was also significant, $F(1, 51) = 25.18$, $p < .001$, $MSE = 72$, $\eta_p^2 = .33$, with a greater mean TT after incongruent ($M = 542$ ms) than after congruent trials ($M = 536$ ms). The interaction between current-trial congruency and previous-trial congruency was again found, $F(1, 51) = 7.72$, $p = .008$, $MSE = 43$, $\eta_p^2 = .131$, indicating a CSE: a reduced Simon effect when the previous trial was incongruent (40 ms), $F(1, 51) = 271.43$, $p < .001$, $MSE = 153$, $\eta_p^2 = .842$, compared to when it was congruent (45 ms), $F(1, 51) = 375.09$, $p < .001$, $MSE = 140$, $\eta_p^2 = .88$. An additional three-way repeated-measures ANOVA as a function of previous-trial congruency, current-trial congruency, and task type revealed that the CSE between the two tasks was bidirectional, with the absence of the three-way interaction among the variables, $F(1, 51) < 1$, $p = .967$. The CSE was significant both in the location-based, $F(1, 51) = 6.51$, $p = .014$, $MSE = 64$, $\eta_p^2 = .113$, and arrow-based Simon tasks, $F(1, 51) = 4.66$, $p = .036$, $MSE = 94$, $\eta_p^2 = .084$.

PE

The overall PE was 2.32%, including 0.17% of the task confusion errors (vertical response to the horizontal task and vice versa). The main effects of current-trial congruency, $F(1, 51) = 35.01$, $p < .001$, $MSE = 11$, $\eta_p^2 = .407$, and previous-trial congruency, $F(1, 51) = 4.81$, $p = .033$, $MSE = 1.13$, $\eta_p^2 = .086$, were both significant, with higher PE on incongruent (3.65%) than on congruent trials (0.99%)

Figure 2

The Sequential Modulations and Delta Functions of Congruency Effects in Experiment 1



Note. (A) Mean ITs of Experiment 1 as a function of current-trial congruency and previous-trial congruency. (B) Mean MTs of Experiment 1 as a function of current-trial congruency and previous-trial congruency. (C) The magnitude of Simon effects across bins for the horizontal location-based (left panel) and vertical arrow-based Simon effects (right panel). Error bars show within-subjects standard error of the mean (Cousineau, 2005). IT = initiation time; MT = movement time; TT = total reaction time.

and after congruent (2.48%) than after incongruent trials (2.16%), which is considered part of the speed–accuracy tradeoff with the postconflict slowing effect obtained in IT data. The interaction between current-trial congruency and previous-trial congruency was significant as well, $F(1, 51) = 7.36$, $p = .009$, $MSE = 1$, $\eta_p^2 = .126$. The Simon effect was smaller after incongruent (2.22%), $F(1, 51) = 30.53$, $p < .001$, $MSE = 4$, $\eta_p^2 = .374$, than after congruent trials (3.11%), $F(1, 51) = 32.43$, $p < .001$, $MSE = 8$, $\eta_p^2 = .329$. The three-way interaction of previous-trial congruency, current-trial congruency, and task type was marginally significant, $F(1, 51) = 3.88$, $p = .054$, according to the additional three-way repeated measures ANOVA with those factors as independent variables. Even though reduced Simon effects were obtained after incongruent trials than after congruent ones in both tasks, a significant CSE was found in the arrow-based Simon task, $F(1, 51) = 9.51$, $p = .003$, $MSE = 4$, $\eta_p^2 = .157$. But not in the location-based Simon task, $F(1, 51) = 1.31$, $p = .257$, $MSE = 3$, $\eta_p^2 = .025$.

Distributional Analyses

The results indicated different time courses for the Simon effect in the two tasks in the TT data, with a significant three-way interaction of bin, current-trial congruency, and task type, $F(4, 204) = 72.72$, $p < .001$, $MSE = 376$, $\eta_p^2 = .588$. While the horizontal location-based Simon effect decreased over bins (41, 35, 29, 21, and 14 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 36.62$, $p < .001$, $MSE = 336$, $\eta_p^2 = .418$, the vertical arrow-based Simon effect increased (45, 58, 62, 68, and 78 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 34.43$, $p < .001$, $MSE = 439$, $\eta_p^2 = .403$, as responses became slower. The IT data also revealed a significant three-way interaction of bin, current-trial congruency, and task type, $F(4, 204) = 22.21$, $p = <.001$, $MSE = 264$, $\eta_p^2 = .303$, showing different time courses of the Simon effect for the two tasks. While the horizontal location-based Simon task revealed a decrease of the Simon effects across bins (35, 28, 22, 11, and 1 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 77.83$, $p < .001$, $MSE = 237$, $\eta_p^2 = .604$, the vertical arrow-based Simon task showed a constant function of the Simon effect across bins (33, 40, 38, 37, and 26 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 1.77$, $p = .19$ (Figure 2C). The significant three-way interaction was also present in the MT data, $F(4, 204) = 34.88$, $p < .001$, $MSE = 225$, $\eta_p^2 = .406$. The horizontal location-based Simon effects showed a relatively constant delta function (6, 7, 6, 10, and 13 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 2.96$, $p = .091$, while the vertical arrow-based Simon effects exhibited an increasing delta function (12, 18, 23, 31, and 52 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 50.53$, $p < .001$, $MSE = 448$, $\eta_p^2 = .498$.

Discussion

We observed a significant bidirectional CSE between the horizontal location-based and vertical arrow-based Simon tasks. As in Lim and Cho's (2021b) experiments, this sequential modulation of the Simon effect was evident in the MT but not in the IT data. The Simon effect was smaller after incongruent (13 ms) than after congruent trials (16 ms) in the MT data. This cross-task CSE indicates that the Simon conflicts elicited by target location and arrow direction were regulated within a shared control system. The direct route, through which the spatial codes for both target location and arrow direction activate their spatially corresponding response codes, was inhibited with enhanced efficiency. In contrast to the reversed Simon effect or no Simon effect following incongruent trials observed in other studies (e.g., Akçay & Hazeltine, 2008), the reduced Simon effect observed in the present experiment may be attributed to less effective control. However, a diminished form of CSE has been found when low-level repetition priming is minimized by alternating between two tasks having different stimulus and response sets, as in the current experiment (e.g., Lim & Cho, 2021b).

Moreover, it is also important to note that the two Simon tasks were presented in a predictable sequence due to trial-by-trial alternations. Because a predictable task sequence may further divide tasks and thus make it more difficult to generate the cross-task CSE (Grant et al., 2020), the current cross-task CSEs between the location- and arrow-based Simon tasks indicate a strong sharing of task-irrelevant dimensions. This finding suggests that the spatial modes of physical location and arrow direction evoke a shared set of spatial codes.

As in Luo and Proctor (2020, 2021), the horizontal location-based and vertical arrow-based Simon tasks showed different time courses of the Simon effect although a cross-task CSE between the two tasks was observed. A decreasing function for the location-based horizontal Simon effect and an increasing function for the arrow-based vertical Simon effect were found in the TT data. This distinction between the time courses of the two Simon effects was evident in the IT data rather than in the MT data, implying that the formation of the delta function was due to different speeds of the activation and the following dissipation of spatial codes, as Luo and Proctor (2020) suggested. That is, the shapes of the delta function observed in the present experiment suggest that physical location activates a spatial code with faster speed than the arrow direction. Moreover, the different patterns of results in IT and MT are consistent with previous studies (Buetti & Kerzel, 2008, 2009; Erb et al., 2016; Erb & Marcovitch, 2018; Lim & Cho, 2021b; Miller & Roüast, 2016; Scherbaum et al., 2010). ITs—which correspond to movement initiation measures in previous studies—captured the time-dependent nature of spatial code activations, while MTs—which correspond to movement measures—reflected the residual regulation of response conflicts (Calderon et al., 2018; Doucet & Stelmack, 1999).

It is important to note that, in contrast to the findings of Lim and Cho's (2021b) study, the cross-task CSE between the two tasks was observed even though the location-based horizontal and arrow-based vertical Simon tasks showed different time courses. These findings imply that different time courses do not necessarily indicate that the two modes of spatial information evoke different sets of spatial codes.

Experiment 2

In Experiment 1, even though the CSE transferred across the location-based horizontal and arrow-based vertical Simon tasks in MT, the two types of Simon effects exhibited different time courses in IT, suggesting that the spatial code was activated faster with the location-based spatial information than with the arrow-based spatial information. However, there is a possibility that the different delta plot patterns in the horizontal location-based and vertical arrow-based Simon tasks were the result of the different spatial orientations rather than the modes of spatial information because the orientations of the two tasks were fixed throughout Experiment 1. Unlike in horizontal location-based Simon tasks, increasing effect functions have been observed in vertical location Simon tasks in some experiments (e.g., Gade et al., 2020; Wiegand & Wascher, 2005). Moreover, Wühr and Biebl (2011) demonstrated that the horizontal location-based Simon effect is modulated by visual (nonverbal) working memory load to a larger extent than by verbal working memory load, suggesting the effect to be based on the interference from the visual representation of the stimulus location. In contrast, the vertical Simon effect is modulated by verbal working memory load to a larger extent than by visual working memory load, implying that the effect is based on the interference from the verbal representations of the stimulus location. The authors emphasized that the horizontal location-based and vertical location-based Simon effects differ qualitatively. Thus, it is possible that the cross-task CSE between location-based and arrow-based Simon effects depends on the respective stimulus orientations. Experiment 2 was thus conducted to replicate the findings of Experiment 1 with a horizontal arrow-based Simon task and a vertical location-based Simon task presented alternatively in a trial-by-trial manner.

Method

Participants

A new group of 52 right-handed participants (14 male, $M_{age} = 22.35$) were recruited from the same pool as in Experiment 1.

Apparatus and Stimuli

The apparatus and all stimuli were identical to those used in Experiment 1, with the following exceptions. For the horizontal arrow-based Simon task, a red (RGB: 255, 0, 0; CIE color coordinates: $x = 0.581$, $y = 0.346$) or green (RGB: 0, 255, 0; CIE color coordinates:

$x = 0.285$, $y = 0.599$) left- or right-pointing arrow (approximately 2.65° × 1.78°) was presented in the center of the screen. For the vertical location-based Simon task, a blue (RGB: 0, 0, 255; CIE color coordinates: $x = 0.152$, $y = 0.080$) or yellow (RGB: 255, 255, 0; CIE color coordinates: $x = 0.388$, $y = 0.513$) circle (approximately 1.78° in diameter) was presented either above or below the fixation cross (Figure 1B). The distance between the target circle and the fixation cross was approximately 3.13° of visual angle.

Procedure

All procedures were identical to those of Experiment 1, except that the horizontal arrow-based Simon task and the vertical location-based Simon task were alternated in a trial-by-trial manner in eight blocks of 98 trials.

Data Analyses

All analyses methods, factors and exclusion criteria were identical to those of Experiment 1. Following the same exclusion criteria used in Experiment 1, 8.49% of all trials were excluded from the analyses as outliers. A two-way ANOVA, as a function of current-trial congruency and task type on the TT data, revealed significant Simon effects in both arrow-based (43 ms), $F(1, 51) = 160.79$, $p < .001$, $MSE = 302$, $\eta_p^2 = .759$, and location-based Simon tasks (51 ms), $F(1, 51) = 306.51$, $p < .001$, $MSE = 221$, $\eta_p^2 = .857$). Meanwhile, faster TTs were shown in the horizontal arrow-based Simon task ($M = 535$ ms) than in the vertical location-based Simon task ($M = 567$ ms), $F(1, 51) = 20.23$, $p < .001$, $MSE = 2{,}558$, $\eta_p^2 = .284$.

Results

IT

The main effect of current-trial congruency was significant, $F(1, 51) = 140.77$, $p < .001$, $MSE = 384$, $\eta_p^2 = .734$, indicating a Simon effect (32 ms). The main effect of previous-trial congruency was also significant, $F(1, 51) = 35.17$, $p < .001$, $MSE = 74$, $\eta_p^2 = .408$, with a smaller mean IT after congruent ($M = 422$ ms) than after incongruent trials ($M = 430$ ms), indicating postconflict slowing. The interaction between current-trial congruency and previous-trial congruency, however, was not significant, $F(1, 51) = 2.72$, $p = .105$, indicating no CSE between the two tasks (Figure 3A). The lack of interaction was supported by a Bayesian repeated measures analysis, with a BF_{01} of 1.18 between previous-trial congruency and current-trial congruency, indicating anecdotal evidence for the null hypothesis (JASP Team, 2022).

MT

The main effect of current-trial congruency was significant, $F(1, 51) = 73.09$, $p < .001$, $MSE = 149$, $\eta_p^2 = .589$, showing a 15-ms Simon effect. The main effect of previous-trial congruency was significant, $F(1, 51) = 5.92$, $p = .019$, $MSE = 11$, $\eta_p^2 = .104$, with a greater mean MT after congruent ($M = 125$ ms) than after incongruent trials ($M = 124$ ms). The interaction between current-trial congruency and previous-trial congruency was significant, $F(1, 51) = 19.52$, $p < .001$, $MSE = 17$, $\eta_p^2 = .277$, indicating a reduced Simon effect after incongruent trials (12 ms), $F(1, 51) = 48.24$, $p < .001$, $MSE = 77$, $\eta_p^2 = .486$, compared to after congruent trials (17 ms), $F(1, 51) = 84.2$, $p < .001$, $MSE = 90$, $\eta_p^2 = .623$ (Figure 3B). An additional three-way repeated measures ANOVA with the task type as an additional factor was conducted to investigate whether the CSE was present in both directions of the tasks. The three-way interaction was not significant, $F(1, 51) < 1$, indicating no task-based differences in CSE occurrence. The CSE was significant in both arrow-based, $F(1, 51) = 10.8$, $p = .002$, $MSE = 37$, $\eta_p^2 = 175$, and location-based Simon tasks, $F(1, 51) = 10.4$, $p = .002$, $MSE = 30$, $\eta_p^2 = .169$.

TT

The main effect of current-trial congruency was significant, $F(1, 51) = 302.72$, $p < .001$, $MSE = 376$, $\eta_p^2 = .856$, showing a Simon effect of 47 ms. The main effect of previous-trial congruency was also significant, $F(1, 51) = 24.4$, $p < .001$, $MSE = 75$, $\eta_p^2 = .324$, with a greater mean TT following incongruent ($M = 554$ ms) than following congruent trials ($M = 548$ ms). As for MT, the interaction between current-trial congruency and previous-trial congruency was significant, $F(1, 51) = 11.97$, $p = .001$, $MSE = 88$, $\eta_p^2 = .19$, indicating a smaller Simon effect after incongruent (42 ms), $F(1, 51) = 296.02$, $p < .001$, $MSE = 157$, $\eta_p^2 = .853$, than after congruent trials (51 ms), $F(1, 51) = 222.82$, $p < .001$, $MSE = 306$, $\eta_p^2 = .814$. An additional three-way repeated measures ANOVA as a function of previous-trial congruency, current-trial congruency, and task type revealed no task-based differences in the interaction between the previous-trial and current-trial congruency, $F(1, 51) = 1.32$, $p = .255$, with a significant CSE in both arrow-based, $F(1, 51) = 11.36$, $p = .001$, $MSE = 148$, $\eta_p^2 = .182$, and location-based Simon tasks, $F(1, 51) = 5.12$, $p = .028$, $MSE = 123$, $\eta_p^2 = .091$.

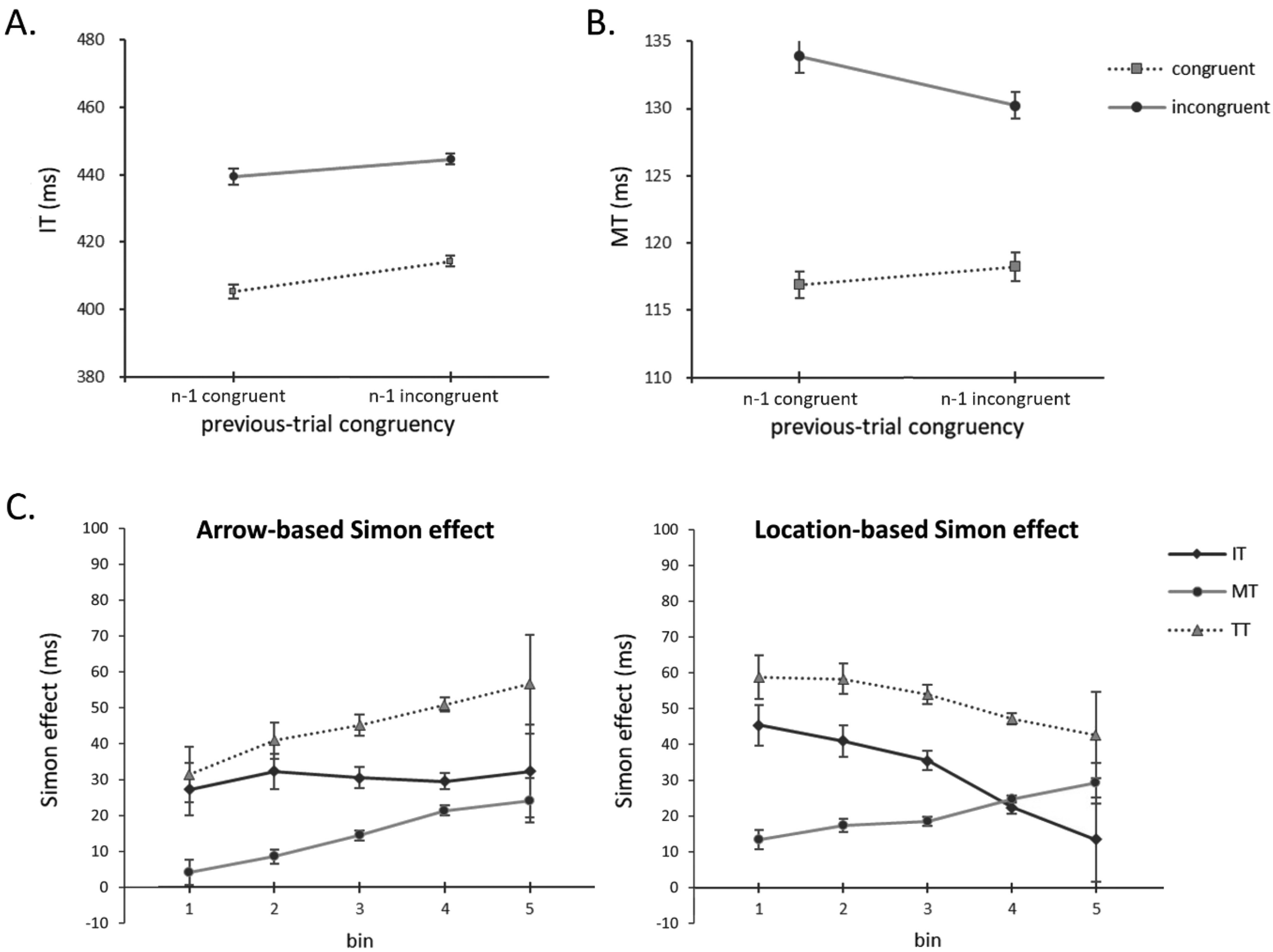
PE

The overall PE was 2.57%, including 0.25% of task confusion errors. The main effects of current-trial congruency, $F(1, 51) = 60.39$, $p < .001$, $MSE = 6$, $\eta_p^2 = .542$, and previous-trial congruency, $F(1, 51) = 6.24$, $p = .016$, $MSE = 2$, $\eta_p^2 = .109$, were significant, with a higher PE on incongruent (3.86%) than on congruent trials (1.28%), and after congruent (2.79%) than after incongruent trials (2.34%), each indicating a Simon effect and a postconflict adaptation after incongruent trials. The interaction between current-trial congruency and previous-trial congruency was significant, $F(1, 51) = 8.43$, $p = .005$, $MSE = 2$, $\eta_p^2 = .142$, showing a reduced Simon effect after incongruent trials (2.08%), $F(1, 51) = 16.51$, $p < .001$, $MSE = 2$, $\eta_p^2 = .477$, as compared to after congruent trials (3.07%), $F(1, 51) = 50.99$, $p < .001$, $MSE = 5$, $\eta_p^2 = .5$. As in MT and TT, the interaction between previous-trial congruency and current-trial congruency did not depend on task type, $F(1, 51) = 1.17$, $p = .286$, through an additional three-way repeated measures ANOVA with task type as an additional factor. Significant CSEs were found in both arrow-based, $F(1, 51) = 6.37$, $p = .015$, $MSE = 1$, $\eta_p^2 = .111$, and location-based Simon tasks, $F(1, 51) = 5.71$, $p = .021$, $MSE = 4$, $\eta_p^2 = .101$.

Distributional Analyses

The overall distributional patterns of the horizontal arrow-based and vertical location-based Simon tasks resembled those of

Figure 3
The Sequential Modulations and Delta Functions of Congruency Effects in Experiment 2



Note. (A) Mean ITs of Experiment 2 as a function of current-trial congruency and previous-trial congruency. (B) Mean MTs of Experiment 2 as a function of current-trial congruency and previous-trial congruency. (C) The magnitude of Simon effects across bins for the horizontal arrow-based (left panel) and vertical location-based Simon effects (right panel). Error bars show within-subjects standard error of the mean (Cousineau, 2005). IT = initiation time; MT = movement time; TT = total reaction time.

Experiment 1. Different time courses of the Simon effect were observed for the two tasks in the TT data, with a significant three-way interaction of bin, current-trial congruency, and task type, $F(4, 204) = 12.55$, $p = .001$, $MSE = 1{,}084$, $\eta_p^2 = .197$. While the vertical location-based Simon effect showed a decrease across the five bins (58, 58, 54, 47, and 42 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 8.6$, $p = .005$, $MSE = 556$, $\eta_p^2 = .144$, indicating a decreasing function, the horizontal arrow-based Simon effect tended to increase over bins (31, 40, 45, 50, and 56 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 6.1$, $p = .017$, $MSE = 1{,}503$, $\eta_p^2 = .107$ (Figure 3C). The same three-way interaction pattern was also found in IT, $F(1, 204) = 10.61$, $p = .002$, $MSE = 977$, $\eta_p^2 = .172$, showing a decreasing function for the vertical location-based Simon effect (45, 41, 35, 22, and 13 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 34.27$, $p < .001$, $MSE = 509$, $\eta_p^2 = .402$, and a constant function for the horizontal arrow-based Simon effect (27, 32, 30, 29, and 32 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 156) < 1$, $p = .753$. The time course difference between the two tasks was absent in the MT data, $F(4, 204) = 1.24$, $p = .271$. The MT data instead revealed a two-way interaction between bin and current-trial congruency, $F(4, 204) = 19.69$, $p < .001$, $MSE = 548$, $\eta_p^2 = .278$, showing an increasing function for both the vertical location-based Simon effect (13, 17, 18, 25, and 29 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 11.06$, $p = .002$, $MSE = 358$, $\eta_p^2 = .178$, and the horizontal arrow-based Simon effect (4, 9, 14, 21, and 24 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 19.18$, $p < .001$, $MSE = 367$, $\eta_p^2 = .273$.

Discussion

Although the orientation assignments for the arrow-based and location-based Simon tasks were reversed in Experiment 2, the results replicated those of Experiment 1. The cross-task CSE between the horizontal arrow-based and vertical location-based Simon tasks was present in the MT data, revealing shared cognitive control for the spatial conflicts evoked by target location and arrow direction.[2]

More importantly, the vertical location-based Simon effect revealed a decreasing function, unlike in some studies that found increasing functions for vertical location-based Simon effects (e.g., Wiegand & Wascher, 2005). Although the slope of the delta function was flatter compared to the slope observed in Experiment 1, the horizontal arrow-based Simon effect again exhibited an increasing function. This shows that the time course of the Simon effect is specific to the mode of spatial information used in a given task, reflecting the activation and following dissipation speeds of the spatial codes each mode of spatial information triggers, apart from the orientation of the spatial codes. Moreover, unlike what was suggested in some previous studies (Gade et al., 2020; Wühr & Biebl, 2011), the consistent results obtained in Experiments 1 and 2 imply that the horizontal and vertical location-based Simon effects do not differ qualitatively but quantitatively when the saliences of the horizontal and vertical dimensions are equated.

Experiment 3

Location words are also known to evoke spatial codes, causing a word-based Simon effect (Khalid & Ansorge, 2013; Lu & Proctor, 2001; Proctor et al., 2009). The purpose of Experiment 3 was to investigate whether physical locations, which were found to share spatial codes with arrow directions in Experiments 1 and 2, also share those with location words. Though no previous study examined the CSE within word-based Simon tasks, our separate study discovered a significant CSE in word-based Simon tasks (N. Lee & Cho, 2024).[3] Thus, in Experiment 3, participants were to perform a horizontal word-based Simon task alternated with a vertical location-based Simon task in a trial-by-trial manner. A red or green location word, "LEFT" or "RIGHT," was presented at the center of the screen for the horizontal word-based Simon task. For the vertical location-based Simon task, as in Experiment 2, a blue or yellow circle was presented above or below a fixation point.

If location word and physical location activate a shared set of spatial codes, a cross-task CSE between the two Simon tasks would be observed in the MT data, as in the previous studies (Erb & Marcovitch, 2018; Erb et al., 2016; Lim & Cho, 2021b; Miller & Roüast, 2016; Scherbaum et al., 2010). However, if they activate mode-specific spatial codes, no CSE would be observed. In addition, as in Experiments 1 and 2, we expect a decreasing delta function of the location-based Simon effect in the IT data reflecting the rapid processing of location information. If the activation speed of the spatial codes for location words is slower than the activation speed of the codes for physical location, different time courses for the word-based and location-based Simon effects would be evident in IT.

Method

Participants

Utilizing the word-based CSE data we collected from a separate mouse-tracking study, we conducted a power analysis in G*Power 3.1.9.2 (Faul et al., 2009) to estimate the minimum sample size required to observe the CSE in word-based Simon tasks. The effect size ($\eta_p^2 = .377$) of the interaction between previous-trial congruency and current-trial congruency was combined with an alpha (α) of .05 and entered into the analysis, revealing that 12 participants would provide over 99% power to observe the CSE within a word-based Simon task. Another power analysis was conducted based on the critical two-way interaction found in Experiment 1 to calculate the minimum sample size required to observe the CSE present within different modes of Simon tasks. The smallest effect size ($\eta_p^2 = .116$ in Experiment 1, MT) of the interaction between previous-trial congruency and current-trial congruency was entered into the analysis with the same alpha ($\alpha = .05$) and showed that 38 participants would provide over 99% power to observe the cross-task CSEs. Given possible differences in the function of word-based and location-based Simon tasks in Experiment 3, a larger number of 52 participants were determined. A new group of 52 right-handed participants (25 male, $M_{\text{age}} = 23.91$) from the same pool as in the previous experiments participated in this experiment.

Apparatus and Stimuli

The apparatus and stimuli were identical to those used in the previous experiments, with the following differences. For the horizontal word-based Simon task, the word "LEFT" ($2.86° \times 1.21°$) or "RIGHT" ($4.52° \times 1.21°$), colored in either red (RGB: 255, 0, 0; CIE color coordinates: $x = 0.581$, $y = 0.346$) or green (RGB: 0, 255, 0; CIE color coordinates: $x = 0.285$, $y = 0.599$), was presented at the center of the display. For the vertical location-based Simon task, a blue (RGB: 0, 0, 255; CIE color coordinates: $x = 0.152$, $y = 0.080$) or yellow (RGB: 255, 255, 0; CIE color coordinates: $x = 0.388$, $y = 0.513$) circle (approximately 1.78° in diameter) was presented either above or below the fixation cross (Figure 1C).

Procedure

All procedures were identical to those of the prior experiments. The horizontal word-based Simon and the vertical location-based

[2] Additional analyses were conducted with the combined data from Experiments 1 and 2, having the total of 104 participants who performed the location-based and arrow-based Simon tasks in alternation. Repeated-measures ANOVAs with previous-trial congruency and current-trial congruency as within-subject variables and task type (location-based Simon task vs. arrow-based Simon task) as a between-subject variable revealed that there were no task type differences between the CSEs in the location-based and arrow-based Simon tasks. The three-way interaction between previous-trial congruency, current-trial congruency, and task type was not significant in all MT, TT and PE, $Fs(1, 102) < 1$, $ps > .376$. The interaction between previous-trial congruency and current-trial congruency also did not differ between Experiments 1 and 2 in all MT, TT, and PE, $Fs(1, 102) < 2.17$, $ps > .144$.

[3] A total of 32 participants were recruited. Horizontal and vertical word-based Simon tasks were presented in an alternating sequence. The stimuli and all task procedures were identical to the word-based Simon tasks used in Experiments 3 and 4 of the present study. Participants gave mouse-clicking responses via a standard computer mouse (Logitech G102 Prodigy Gaming Mouse). The x and y coordinates of the computer mouse trajectories were recorded at a sampling rate of 100 Hz. All stimuli and responses were controlled by the mousetrap plug-in (Kieslich & Henninger, 2017), implemented in the experimental software OpenSesame (Mathôt et al., 2012). Based on the two-way repeated measure ANOVA (with previous-trial congruency and current-trial congruency as within-subject factors), a significant CSE was found in the total movement times of the mouse responses $F(1, 31) = 18.73$, $p = .009$, $MSE = 387.59$, $\eta_p^2 = .377$, showing a smaller Simon effect after incongruent trials (36 ms) than after congruent trials (48 ms).

Simon tasks were alternated in a trial-by-trial manner in eight blocks of 98 trials.

Data Analyses

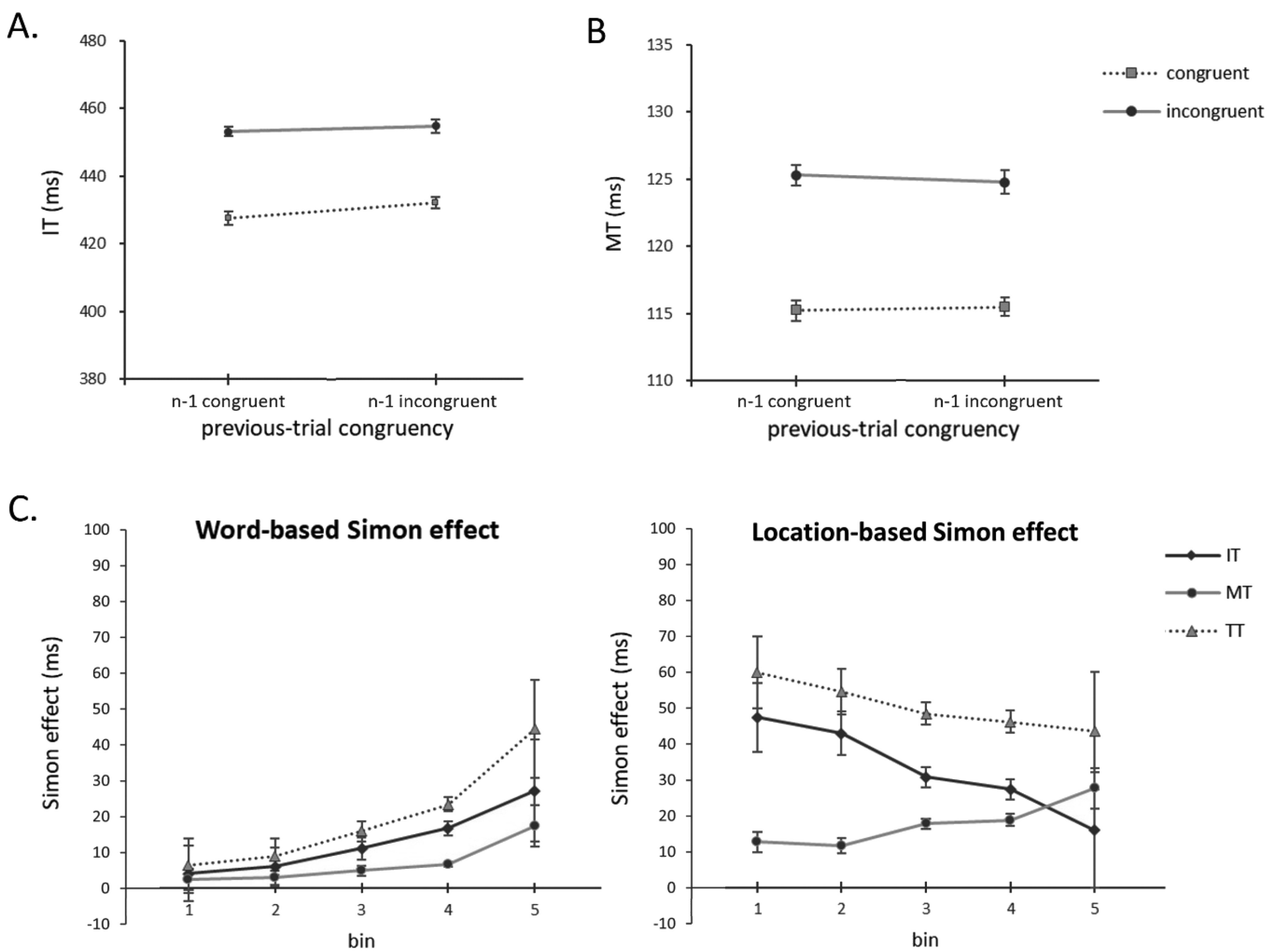
All analyses methods, factors, and exclusion criteria were identical to those of the prior experiments. Following the same exclusion criteria used in the previous experiments, 8.65% of all trials were excluded from the analyses as outliers. A two-way ANOVA as a function of current-trial congruency and task type on the TT data revealed significant Simon effects in both word-based, $F(1, 51) = 31.7$, $p < .001$, $MSE = 292$, $\eta_p^2 = .383$, and location-based Simon tasks, $F(1, 51) = 264.67$, $p < .001$, $MSE = 236$, $\eta_p^2 = .838$, enabling subsequent analyses. Faster TTs, $F(1, 51) = 11.76$, $p = .001$, $MSE = 2{,}163$, $\eta_p^2 = .187$, and a smaller Simon effect, $F(1, 51) = 39.1$, $p < .001$, $MSE = 302$, $\eta_p^2 = .434$, were shown in the horizontal word-based Simon task ($M = 551$ ms and a 19-ms Simon effect) compared to the vertical location-based Simon task ($M = 573$ ms and a 49-ms Simon effect).

Results

IT

The main effect of current-trial congruency was significant, $F(1, 51) = 127.63$, $p < .001$, $MSE = 235$, $\eta_p^2 = .714$, indicating a 24-ms Simon effect. The main effect of previous-trial congruency was also significant, $F(1, 51) = 5.37$, $p = .025$, $MSE = 92$, $\eta_p^2 = .095$, indicating postconflict slowing of 3 ms. As in the previous experiments, the interaction between current-trial congruency and previous-trial congruency was not significant, $F(1, 51) = 1.27$, $p = .266$, indicating no CSE (Figure 4A). An additional analysis with the BF for the interaction between previous-trial congruency and current-trial congruency also supported the null hypothesis,

Figure 4
The Sequential Modulations and Delta Functions of Congruency Effects in Experiment 3



Note. (A) Mean ITs of Experiment 3 as a function of current-trial congruency and previous-trial congruency. (B) Mean MTs of Experiment 3 as a function of current-trial congruency and previous-trial congruency. (C) The magnitude of Simon effects across bins for the horizontal word-based (left panel) and vertical location-based Simon effects (right panel). Error bars show within-subjects standard error of the mean (Cousineau, 2005). IT = initiation time; MT = movement time; TT = total reaction time.

with a BF_{01} of 1.91, showing anecdotal evidence for the null hypothesis (JASP Team, 2022).

MT

The main effect of current-trial congruency was significant, $F(1, 51) = 83.69$, $p < .001$, $MSE = 58$, $\eta_p^2 = .621$, showing an 10-ms Simon effect. The main effect of previous-trial congruency was not significant, $F(1, 51) < 1$, $p = .803$. Importantly, the interaction between current-trial congruency and previous-trial congruency was also not significant, $F(1, 51) < 1$, $p = .47$, showing no sign of the CSE (Figure 4B). Bayesian repeated measures analysis was conducted to determine whether the frequentist analysis confidently rejected H1, indicating the absence of the CSE between the location- and word-based Simon tasks. The Simon effect after congruent trial was 10 ms while Simon effect after incongruent trial was 9 ms. The BF, which was computed to compare the likelihoods of the null hypothesis to the alternative hypothesis, revealed a BF_{01} of 3.7, indicating moderate support (Ortega & Navarrete, 2017) for the null hypothesis.

TT

The mean TT was significantly greater on incongruent ($M =$ 579 ms) than congruent trials ($M = 561$ ms), $F(1, 51) = 266.81$, $p < .001$, $MSE = 221$, $\eta_p^2 = .84$. The main effect of previous-trial congruency was significant, $F(1, 51) = 4.76$, $p = .034$, $MSE = 96$, $\eta_p^2 = .085$, with a smaller mean TT after congruent ($M = 561$ ms) than after incongruent trials ($M = 564$ ms). However, the interaction between current-trial congruency and previous-trial congruency was not significant, $F(1, 51) = 1.5$, $p = .226$. The Simon effect after congruent trial and after incongruent trial was 32 and 35 ms, respectively. Evidence for the interaction was again not supported by the BF, showing a BF_{01} of 2.2, indicating anecdotal evidence for the null hypothesis (JASP Team, 2022). The TT data was analyzed further to ensure the absence of the CSE in both task modes. Previous-trial congruency, current-trial congruency, and task type (horizontal word-based vs. vertical location-based Simon tasks) were used as variables in the three-way repeated measures ANOVA. The analysis did not reveal any three-way interaction, indicating that the CSE was absent for both tasks, $F(1, 39) < 1$, $p = .44$.

PE

The overall PE was 3%, including 0.28% of task confusion errors. The main effect of current-trial congruency was significant, $F(1, 51) = 40.59$, $p < .001$, $MSE = 11$, $\eta_p^2 = .443$, with a higher PE on incongruent (4.37%) than congruent trials (1.64%). No other main effects or interactions were found, $F\text{s} < 2.38$, $p\text{s} > .129$, and the lack of interaction between previous-trial congruency and current-trial congruency was also supported by the BF_{01} of 1.52, indicating anecdotal evidence for the null hypothesis (JASP Team, 2022). The Simon effect was 2% after congruent trials and 3% after incongruent trials.

Distributional Analyses

The horizontal word-based and vertical location-based Simon tasks exhibited opposite time course patterns in TT, with a significant three-way interaction of bin, current-trial congruency, and task type, $F(4, 204) = 26.73$, $p < .001$, $MSE = 833$, $\eta_p^2 = .344$. The horizontal word-based Simon effect followed an increasing function (6, 9, 16, 23, and 44 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 28.98$, $p < .001$, $MSE = 724$, $\eta_p^2 = .362$, and the vertical location-based Simon effect a decreasing function (60, 55, 48, 46, and 44 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 9.24$, $p = .004$, $MSE = 473$, $\eta_p^2 = .153$ (Figure 4C). The three-way interaction was also significant in the IT data, $F(4, 204) = 39.74$, $p < .001$, $MSE = 594$, $\eta_p^2 = .438$, with an increase in the horizontal word-based Simon effect (4, 7, 11, 17, and 27 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 11.8$, $p = .001$, $MSE = 702$, $\eta_p^2 = .188$, and a decrease in the vertical location-based Simon effect (47, 43, 31, 27, and 16 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 49.6$, $p < .001$, $MSE = 321$, $\eta_p^2 = .493$. However, these increasing and decreasing delta functions were not found in the MT data, $F(4, 204) < 1$, $p = .813$, which showed increasing functions in both tasks (2, 3, 5, 7, and 17 ms for Bin 1, 2, 3, 4, and 5, respectively, in the word-based Simon effect and 13, 12, 18, 19, and 28 ms for Bin 1, 2, 3, 4, and 5, respectively, in the location-based Simon effect).

Discussion

Different from what we observed for the location-based and arrow-based Simon tasks, there was no cross-task CSE between the horizontal word-based and vertical location-based Simon tasks, revealing that the cognitive control for the conflict induced by the spatial codes for one mode of spatial information did not modulate the conflict induced by the spatial codes for the other mode of spatial information. Thus, the absence of the CSE between the two tasks indicates that the meaning of the location word and the physical location activate independent sets of spatial codes.

The results of the distributional analyses demonstrate different time courses for the horizontal word-based and the vertical location-based Simon tasks: an increasing function of the Simon effect in the horizontal word-based Simon task and a decreasing function of the effect in the vertical location-based Simon task in TT. Importantly, as in Experiments 1 and 2, these distinct patterns were reflected in IT rather than in MT. This is consistent with the idea that different delta functions merely indicate quantitative differences in the rate at which spatial codes are activated and dissipated. The slopes of delta functions depicted in Experiment 3 suggest that the activation of the spatial codes for physical locations was faster than the activation of spatial codes for location words (Luo & Proctor, 2020; Pellicano et al., 2009).

According to Luo and Proctor (2017), the mode similarity of location word and physical location is lower than that of arrow direction and physical location. The spatial codes for arrow directions are directly formed based on the asymmetry of physical properties, like the spatial codes for physical location, as well as indirectly from their learned arbitrary meaning (Miles & Proctor, 2011). In contrast, the spatial codes for location words are indirectly extracted from their arbitrary meaning. This difference possibly explains the presence of the CSE between the arrow-based and location-based Simon tasks but not between the word-based and location-based Simon tasks. Some may attribute such results to general task similarity rather than to inherent spatial mode properties, suggesting that the two modes of Simon tasks may have been perceived as entirely different tasks (or task sets) and, thus, encouraged different performance strategies (e.g., Grant et al., 2020). However, findings show that the CSEs can occur even when two Simon tasks are clearly dissociated by a salient task feature, such as stimulus modality (visual task vs. auditory task) and task-relevant dimension (color vs. timbre), if the tasks share a task-irrelevant domain (Y. S. Lee & Cho, 2023). Thus, we propose that the absence of the CSE is attributable to the qualitative difference between physical location and location word.

Experiment 4

While a CSE was observed between the arrow-based and location-based Simon tasks in Experiments 1 and 2, no CSE was found between the word-based and location-based Simon tasks in Experiment 3. Based on the results that physical locations share spatial codes with arrow directions but not with location words, the question arises of the relationship between the spatial codes for arrow direction and location words. Spatial information conveyed through arrow direction and location words are both known to contain symbolic attributes, which require prior learning of the associations between the symbols and their corresponding spatial codes.

Thus, Experiment 4 was conducted to examine whether a cross-task CSE occurs between the arrow-based and word-based Simon tasks. Participants were to perform horizontal arrow-based and vertical word-based Simon tasks alternated in a trial-by-trial manner. A red or green left- or right-pointing arrow was presented in the center of the screen for the horizontal arrow-based Simon task, as in Experiment 2, and a blue or yellow vertical location word, “UP” or “DOWN,” was presented centrally for the vertical word-based Simon task. Responses were aimed movements as in the previous experiments.

If arrow direction is qualitatively identical to physical location, no cross-task CSE would be observed between the horizontal arrow-based and vertical word-based Simon tasks, based on the results from Experiment 3. However, if arrow direction shares a strong symbolic nature with location word, the cross-task CSE would be observed between the two tasks in the MT data. Moreover, as in the previous experiments, if the activation speed of the spatial codes for location word and arrow direction differs, the patterns of the time courses for the two Simon effects would be distinguishable in IT.

Method

Participants

The power analysis in G*Power 3.1.9.2 (Faul et al., 2009) was identical to the one in Experiment 3. To estimate the sample size needed to observe the critical two-way interaction between previous-trial congruency and current-trial congruency, 52 participants were employed. A new group of 52 participants (18 male, $M_{age} =$ 22.68) were recruited from the same participant pool as in the previous experiment.

Apparatus and Stimuli

The stimuli used in the horizontal arrow-based Simon task were identical to those used in Experiment 1, using a red or green left- or right-pointing arrow. The vertical word-based Simon task consisted of two direction words, “UP” (2.38° × 1.21°) and “DOWN” (4.27° × 1.21°), colored in either blue (RGB: 0, 0, 255; CIE color coordinates: $x = 0.152$, $y = 0.080$) or yellow (RGB: 255, 255, 0; CIE color coordinates: $x = 0.388$, $y = 0.513$), presented at the center of the screen. The apparatus was identical to that used in the prior experiments (Figure 1D).

Procedure

All procedures were identical to those of the previous experiments. The horizontal arrow-based and the vertical word-based Simon tasks were alternated in a trial-by-trial manner in eight blocks of 98 trials.

Data Analyses

All analyses methods and factors were identical to those of the previous experiments. Following the exclusion criteria used in the previous experiments, 7.93% of all trials were excluded from the analyses as outliers. A two-way ANOVA as a function of current-trial congruency and task type on the TT data revealed significant Simon effects in both arrow-based, $F(1, 51) = 217.66$, $p < .001$, $MSE = 165$, $\eta_p^2 = .81$, and word-based Simon tasks, $F(1, 51) = 131.51$, $p < .001$, $MSE = 432$, $\eta_p^2 = .721$, enabling further analyses. Faster RTs, $F(1, 51) = 62.11$, $p < .001$, $MSE = 1{,}515$, $\eta_p^2 = .549$, and a smaller Simon effect, $F(1, 51) = 4.7$, $p = .035$, $MSE = 254$, $\eta_p^2 = .084$, were found in the horizontal arrow-based Simon task ($M = 541$ ms and a 37-ms Simon effect) compared to the vertical word-based Simon task ($M = 583$ ms and a 47-ms Simon effect).

Results

IT

The main effects of current-trial congruency, $F(1, 51) = 112.75$, $p < .001$, $MSE = 338$, $\eta_p^2 = .689$, and previous-trial congruency, $F(1, 51) = 18.31$, $p < .001$, $MSE = 77$, $\eta_p^2 = .264$, were significant, with a 27-ms Simon effect and a 5-ms postconflict slowing effect. The interaction between previous-trial congruency and current-trial congruency was not significant, $F(1, 51) = 1.7$, $p = .198$ (Figure 5A). The BF was computed to provide direct evidence for the likelihood of the null and alternative hypotheses. The lack of interaction was supported by a BF_{01} of 2.14, which provides anecdotal support for the null hypothesis.

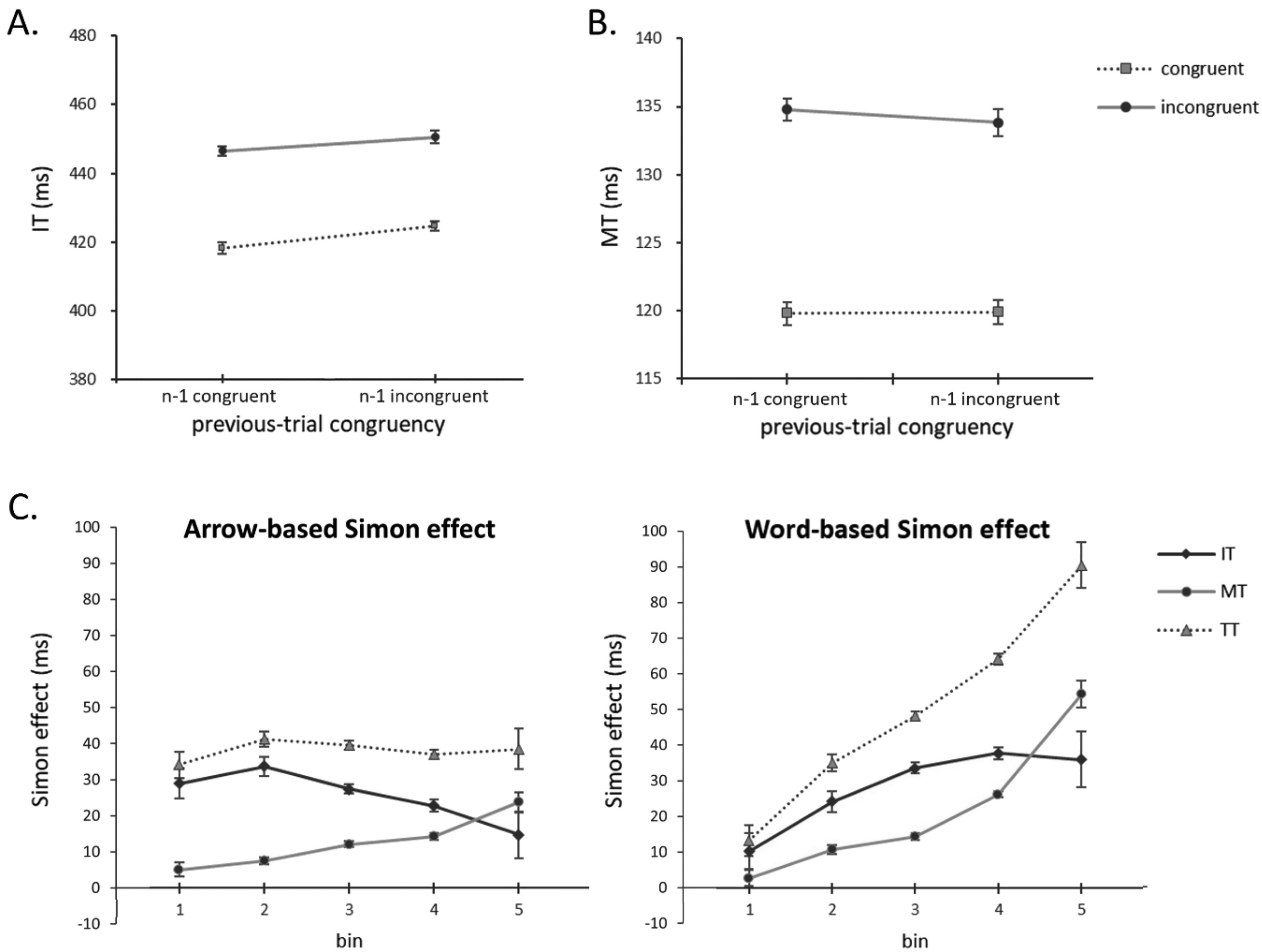
MT

The main effect of current-trial congruency was significant, $F(1, 51) = 119$, $p < .001$, $MSE = 91$, $\eta_p^2 = .7$, indicating a 14-ms Simon effect. Critically, the interaction between current-trial congruency and previous-trial congruency was not significant, $F(1, 51) = 1.26$, $p = .266$, showing a 15-ms Simon effect following congruent trials and a 14-ms Simon effect following incongruent trials. A Bayesian repeated measures ANOVA was conducted with previous-trial congruency and current-trial congruency to examine whether there was no CSE between the word- and arrow-based Simon tasks. The BF revealed a BF_{01} of 2.59, providing anecdotal support for the null hypothesis (JASP Team, 2022). The main effect of previous-trial congruency was not significant, $F(1, 51) < 1$, $p = .377$ (Figure 5B).

TT

The main effect of current-trial congruency was significant, $F(1, 51) = 265.04$, $p < .001$, $MSE = 338$, $\eta_p^2 = .839$, showing a

Figure 5
The Sequential Modulations and Delta Functions of Congruency Effects in Experiment 4



Note. (A) Mean ITs of Experiment 4 as a function of current-trial congruency and previous-trial congruency. (B) Mean MTs of Experiment 4 as a function of current-trial congruency and previous-trial congruency. (C) The magnitude of Simon effects across bins for the horizontal arrow-based (left panel) and vertical word-based Simon effects (right panel). Error bars show within-subjects standard error of the mean (Cousineau, 2005). IT = initiation time; MT = movement time; TT = total reaction time.

Simon effect of 42 ms. The main effect of previous-trial congruency was also significant, $F(1, 51) = 12.99$, $p = .001$, $MSE = 91$, $\eta_p^2 = .203$, indicating postconflict slowing of 5 ms. The interaction between current-trial congruency and previous-trial congruency was nonsignificant, $F(1, 51) = 2.87$, $p = .096$, showing a 40-ms Simon effect after incongruent trials and 42-ms Simon effect after congruent trials. However, an additional three-way repeated measures ANOVA—as a function of previous-trial congruency, current-trial congruency, and task type—revealed a three-way interaction, $F(1, 51) = 7.91$, $p = .007$, $MSE = 122$, $\eta_p^2 = .134$. The interaction between previous-trial congruency and current-trial congruency was evident in the horizontal arrow-based Simon task, $F(1, 51) = 13.65$, $p = .001$, $MSE = 84$, $\eta_p^2 = .211$. A smaller Simon effect was noted after incongruent trials (32 ms), $F(1, 51) = 157.06$, $p < .001$, $MSE = 173$, $\eta_p^2 = .755$, than after congruent trials (42 ms), $F(1, 51) = 187$, $p < .001$, $MSE = 242$, $\eta_p^2 = .786$, indicating the presence of a CSE. Such interactions were absent in the vertical word-based Simon task, $F(1, 51) < 1$, $p = .394$, showing a 45-ms Simon effect after congruent trials and a 48-ms Simon effect after incongruent trials. The BF was computed to test the likelihood of the null hypothesis for the lack of the CSE in the word-based Simon task. The lack of interaction was supported by a BF_{01} of 3.4, which provides moderate evidence for the null hypothesis.

PE

The overall PE was 2.5%, including 0.38% of task confusion errors. The main effect of current-trial congruency was significant, $F(1, 51) = 71.07$, $p < .001$, $MSE = 6$, $\eta_p^2 = .582$, with a higher PE on incongruent (3.92%) than congruent trials (1.01%). The main effect of previous-trial congruency, $F(1, 51) = 1.43$, $p = .237$, and the interaction between current-trial congruency and previous-trial congruency did not reach significance, $F(1, 51) = 2.9$, $p = .094$, having the Simon effect of 3% both when previous trial was congruent and incongruent. The

Bayesian repeated measures ANOVA revealed a BF_{01} of 1.31, indicating anecdotal evidence for the null hypothesis (JASP Team, 2022).

Distributional Analyses

A significant three-way interaction of bin, current-trial congruency, and task type was observed in the TT data, $F(4, 204) = 69.42$, $p < .001$, $MSE = 598$, $\eta_p^2 = .576$. Separate analyses showed that the interaction of current-trial congruency and bin was not significant in the horizontal arrow-based Simon task, $F(4, 204) < 1$, $p = .656$, but significant in the vertical word-based Simon task, $F(4, 204) = 112.23$, $p < .001$, $MSE = 778$, $\eta_p^2 = .688$ (Figure 5C). The magnitudes of the Simon effect were constant in the horizontal arrow-based Simon task (34, 41, 39, 37, and 38 ms for Bin 1, 2, 3, 4, and 5, respectively), but they increased in the vertical word-based Simon task (13, 35, 48, 64, and 90 ms for Bin 1, 2, 3, 4, and 5, respectively). The differences in the time courses of the Simon effect were more prominent in the IT data, indicated by a significant three-way interaction of bin, current-trial congruency, and task type, $F(4, 204) = 20.35$, $p < .001$, $MSE = 689$, $\eta_p^2 = .285$. A decreasing function was observed from the second bin for the horizontal arrow-based Simon effect (29, 34, 27, 22, and 15 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 20.7$, $p < .001$, $MSE = 191$, $\eta_p^2 = .289$, and an increasing function up to the fourth bin for the vertical word-based Simon effect (10, 25, 34, 38, and 36 ms for Bin 1, 2, 3, 4, and 5, respectively), $F(4, 204) = 9.17$, $p = .004$, $MSE = 1{,}192$, $\eta_p^2 = .152$. However, these differences in the time courses between the two types of Simon effects were not evident in the MT data, although the three-way interaction was also significant, $F(4, 204) = 26.14$, $p < .001$, $MSE = 278$, $\eta_p^2 = .339$, with increasing delta functions both for the horizontal arrow-based (5, 8, 12, 14, and 24 ms for Bin 1, 2, 3, 4, and 5, respectively) and vertical word-based Simon effects (3, 11, 15, 26, and 54 ms for Bin 1, 2, 3, 4, and 5, respectively) and a steeper slope in the arrow-based than the word-based Simon effect.

Discussion

A CSE was observed in the sequence of word-based to arrow-based Simon tasks, indicating the transfer of enhanced cognitive control from the word-based Simon effect to the arrow-based Simon effect. However, no CSE was obtained in the sequence of arrow-based to word-based Simon tasks. The unidirectional CSE in the arrow-based Simon task implies that arrow direction possesses a shared spatial attribute with location words where the control mechanism exerted inhibition, resulting in a decreased arrow-based Simon effect. In contrast, the absence of the CSE in the word-based Simon task implies that the primary spatial attribute subjected to inhibitory control in the arrow-based Simon task differs from that in the word-based Simon task.

The distributional analyses revealed different time courses for the Simon effect between the arrow-based and word-based Simon tasks, with a relatively constant function in the arrow-based Simon effect compared to an increasing function in the word-based Simon effect. Consistent with the previous experiments, the IT data rather than the MT data was responsible for these different time courses of the Simon effect, which is again consistent with the account that the pattern of the delta plot of the Simon effect is determined by the activation speed of the spatial codes. The IT data showed that the size of the arrow-based Simon effect decreased across bins while that of the word-based Simon effect increased across bins, implying that the direction of an arrow evoked a spatial code with a faster speed compared to the location word (Luo & Proctor, 2020).

Cross-Experiment Comparison Analyses

Additional cross-experiment comparisons were conducted to comprehensively evaluate the distinctions among spatial modes in Simon tasks when examining the presence or absence of the CSEs. A comparative analysis was performed between the CSE results of Experiments 2 and 3, where the horizontal location-based Simon task was employed with the vertical arrow-based (Experiment 2, CSE present) and word-based Simon tasks (Experiment 3, CSE absent). Additionally, a comparison was made between the CSE results of Experiments 2 and 4, involving the vertical arrow-based Simon task with the horizontal location-based (Experiment 2, CSE present) and word-based Simon tasks (Experiment 4, unidirectional CSE present).

The repeated-measures ANOVAs were conducted on the IT, MT, TT, and PE data of Experiments 2 and 3, and Experiments 2 and 4, with previous-trial congruency and current-trial congruency as within-subject variables and experiment as a between-subject variable. The main effect of experiment was not found for both pairs of experiments, $Fs(1, 102) < 1$, $ps > .409$. However, the critical three-way interactions between previous-trial congruency, current-trial congruency, and experiment were significant in the MT data for both between Experiments 2 and 3, $F(1, 102) = 7.45$, $p = .007$, $MSE = 16$, $\eta_p^2 = .068$, and between Experiments 2 and 4, $F(1, 102) = 7.23$, $p = .008$, $MSE = 14$, $\eta_p^2 = .066$, indicating that the CSE results differed between experiments. The three-way interaction was absent in the other measures, $Fs(1, 102) < 2.97$, $ps > .088$. The interaction between current-trial congruency and experiment was significant between Experiments 2 and 3 in IT, $F(1, 102) = 5.7$, $p = .019$, $MSE = 310$, $\eta_p^2 = .053$; MT, $F(1, 102) = 5.87$, $p = .017$, $MSE = 104$, $\eta_p^2 = .054$; and TT, $F(1, 102) = 14.91$, $p < .001$, $MSE = 298$, $\eta_p^2 = .128$, showing larger Simon effects in Experiment 2 (47 ms in TT) than in Experiment 3 (34 ms in TT). No other interactions were found between Experiments 2 and 4, $Fs(1, 102) < 2$, $ps > .16$.

These cross-experiment comparisons shed light on whether the presence or absence of the CSE between two Simon tasks is dependent on combinations of physical-location, arrow-direction, and location-word modes. The relationship between spatial codes elicited by physical location and arrow direction exhibited distinctions from the relationship between those by physical location and location word, as well as from that between those by arrow direction and location word. These findings provide more robust evidence that the absence of the CSE in Experiments 3 and 4 demonstrates qualitative differences from the close association of spatial codes activated by physical location and arrow direction observed in Experiment 2, allowing for the interpretation that different natures of spatial codes were reflected in the CSEs.

General Discussion

The Cross-Task CSE: An Indicator of Common or Independent Sets of Spatial Codes

It has been suggested that the CSE occurs in Simon tasks due to the inhibitory cognitive control placed on the direct route through which spatial codes elicited by task-irrelevant spatial information automatically activate their spatially corresponding response codes (Kim et al., 2015; Lim & Cho, 2021b; Soutschek et al., 2013; Stürmer et al., 2002). In the present study, to investigate whether different modes of spatial information activate a unitary set of spatial codes, we examined whether the CSE occurs between two Simon tasks with different modes of spatial information, but sharing conflict source, task-relevant stimulus dimension, and response mode. In Experiments 1 and 2, the cross-task CSE was observed between the location-based and arrow-based Simon tasks in the MT data. These results indicate that a common set of spatial codes was formed for physical location and arrow direction. Consequently, effect of the inhibitory control exerted via the direct route was transferred between the two tasks, enhancing cognitive control in subsequent task. In contrast, no CSE was observed between the location-based and the word-based Simon tasks in Experiment 3, indicating that the task-irrelevant spatial code was qualitatively different between the two tasks. This difference resulted in the formation of direct routes for the word-based Simon task that were separate from those of the location-based Simon task. Interestingly, in Experiment 4, a CSE was observed in the arrow-based Simon task but not in the word-based Simon task, suggesting an asymmetrical relationship regarding the shared spatial codes between arrow direction and location word. While the inhibitory control through the direct route of the word-based Simon task could be transferred to that of the arrow-based Simon task, the direct route of the word-based Simon conflicts did not receive any sequential benefit in terms of inhibitory control.

Beneath the absence of the CSE in the word-based Simon tasks, other task-related factors, such as task-switching costs or task-performing strategies during task alternation, may have impeded the effectiveness of the sequential modulation of conflicts. For instance, the strategically distinct representation of the word-based Simon task may have encouraged distinct task sets (e.g., Schumacher & Hazeltine, 2016). However, the research has consistently identified a CSE between two tasks that were dissociated by salient factors, such as different task rules (Kim et al., 2015; Lim & Cho, 2021b) or different stimulus modalities (Y. S. Lee & Cho, 2023). Therefore, we maintain that the absence of the CSE in the current findings was not entirely due to the exploitation of differences in task sets.

The similarities among the attributes underlying the different modes of spatial information have been suggested as a possible ground for the discrepancies in sharing spatial codes (e.g., Miles & Proctor, 2011; Proctor et al., 2009). The spatial information of physical location contains a visuospatial attribute (Notebaert et al., 2007). Thus, a spatial code for physical location of a stimulus is directly extracted from a physical property of it. Specifically, visuospatial codes for physical location are formed relative to a salient reference object in the environment (Hommel, 1993a) or to shift the focus of attention to a peripheral stimulus (Stoffer, 1991; Umiltà & Nicoletti, 1992), requiring the identification and discrimination of the stimulus' physical structures. In contrast, the spatial information of a location word contains a semantic-spatial attribute. Thus, a spatial code for a location word is indirectly extracted from its learned meaning (Notebaert et al., 2007). Unlike visuospatial codes, semantic-spatial codes are not formed in relation to a visual reference point but rather through an arbitrary conceptual meaning to which a word (object) is linked. Importantly, the spatial mode of arrow direction has both visuospatial and semantic-spatial attributes, both of which induce Simon conflict. The spatial information for arrow direction relies on visuospatial attributes by directly and rapidly extracting its meaning from the asymmetrical structure of their physical properties (pointers that extend from one side of the body). In addition, it relies also on semantic-spatial attributes by conveying information indirectly and slowly from their acquired abstract meaning of the symbol (e.g., Jakobsen et al., 2013; Luo & Proctor, 2019).

The present study elucidates the relationship between the spatial codes and their underlying spatial attributes through shared or non-shared cognitive control. The mode-general transfer of cognitive control occurred when visuospatial codes were used for task-irrelevant spatial information in both tasks, indicating that physical location and arrow direction activate a common set of spatial codes. No transfer was observed when the conflict was caused by visuospatial codes in one task and semantic-spatial codes in the other task, indicating that spatial codes of physical location and location word are distinctly processed during conflict resolution. These dissociated forms of relationship suggest that different spatial modes differ not only in how they convey spatial information but also in how they are cognitively represented after the activation. Interestingly, arrow direction, a mode considered to possess both attributes, only demonstrated a bidirectional exchange of spatial codes with physical location and not with location word, suggesting that the two types of attributes are not equally utilized within the spatial processing of arrow direction: arrow direction is fundamentally more visuospatial than semantic-spatial (Miles & Proctor, 2012). This asymmetrical reliance of spatial attribute was also evident when examining with location words. Because the spatial conflict of arrow direction is primarily visuospatial, the inhibitory control of arrow direction does not extend to that of location words, which are purely semantic-spatial. On the other hand, the conflict regulation of location words can be transferred to arrow direction, enhancing the conflict resolution of semantic-spatial code present within the arrow direction.

This distinct categorization of spatial modes has also been found in other studies (Luo & Proctor, 2017; Proctor et al., 2009). Luo and Proctor supported the distinctiveness of location words over physical locations and arrow directions. In their experiments, when location words were eccentrically presented, the word-based Simon effect was erased by a prominent location-based Simon effect. In contrast, when arrows were eccentrically presented, a small arrow-based Simon effect coexisted with a location-based Simon effect, suggesting that the conflicts elicited by arrow direction and physical location do neither compete nor erase each other. Proctor et al. also observed a closer proximity of the physical location to the arrow direction than to the location words by demonstrating that the transfer of practice with a spatially incompatible stimulus–response mapping to the performance of a subsequent Simon task was evident between the spatial codes for physical location and arrow direction in a bidirectional way but not between the spatial codes for word meaning and physical location or arrow direction. The authors suggested that spatial codes for physical locations and arrow directions are represented and processed in a similar way, but those for location words are not.

While the distinct attributes of location words from physical locations have been consistently confirmed, some take a flexible view on the spatial codes for arrow direction. For example, Miles and Proctor (2012) suggested that the processing of arrow direction could be based on either a structural discrimination strategy (visuospatial-based) or a semantic discrimination strategy (semantic-spatial-based). In other words, instead of invariably exploiting both strategies or focusing on only one strategy, the arrow direction can exhibit either a visuospatial or semantic-spatial attribute, depending on which strategy is more advantageous to the task at hand. Consequently, they demonstrated that arrow direction can exhibit a higher proximity to physical location in one task context (e.g., when spatial information is task-relevant) and be closer to location word in another (e.g., when spatial information is task-irrelevant). The current study's analysis of arrow-based Simon tasks also supported the finding that arrow direction processing can be influenced by both attributes. The arrow-based Simon task revealed a bidirectional sharing of cognitive control with the location-based Simon task, revealing a strong set of visuospatial attributes inherent in the arrow-direction code. In contrast, when alternating between the arrow-based Simon task and the word-based Simon task, arrow direction processing showed an ability to benefit from the semantic-spatial processing, allowing for the modulation of arrow-based Simon conflicts through the prior inhibition of word-based spatial codes. However, diverging from the flexible viewpoint, the current study emphasizes the preeminence of the visuospatial attribute in the arrow-based spatial code. The spatial codes associated with arrow direction were more intimately shared with those associated with physical location, implying that the dominant and more robust processing of arrow direction is visuospatial than semantic-spatial. Consequently, we propose that the spatial attribute of arrow direction maintains its intrinsic properties, possessing both visuospatial and semantic-spatial attributes with a predetermined priority of visuospatial attributes. The absence of CSE in the word-based Simon task in Experiment 4 implies that arrow direction processing could not perfectly adjust to the semantic discrimination strategy proposed in the flexible perspectives.

Research has suggested that the orientation of the location codes also affects the nature of spatial codes. The physical locations of the vertical dimension may be represented in verbal–spatial codes, having qualitatively distinct characteristics from the physical locations in the horizontal dimension which are represented in visuospatial codes (Gade et al., 2020; Wiegand & Wascher, 2005; Wühr & Biebl, 2011). However, the results of Experiments 1 and 2 in the present study counter these claims, demonstrating that the vertical location codes were not qualitatively or quantitatively different from the horizontal location codes. It was found that the cross-task CSE between the location-based and arrow-based Simon tasks, as well as the patterns of delta plots of the Simon effects, did not vary depending on the orientation of the spatial dimension. Moreover, if the vertical location-based Simon task relies on the verbal–spatial codes, as Gade et al., and Wühr and Biebl suggested, the spatial codes for the vertical location-based Simon task should have shared a set of verbal–spatial codes with the horizontal word-based Simon task, resulting in a CSE between the two tasks. However, in Experiment 3, no cross-task CSE was found between the tasks, indicating that the vertical location-based Simon effect was caused by the interference of visuospatial codes just as the horizontal location-based Simon effect.

After experiencing conflict, postconflict slowing has often been found alongside a reduced congruency effect (e.g., Rey-Mermet & Meier, 2017; Verguts et al., 2011). It has been suggested that the response conflict in the previous trial not only recruits the control process involved in the CSE, but also increases the response threshold of a motoric output (Erb et al., 2016). With a higher response threshold, responses are slowed regardless of current-trial congruency. In the present study, unlike the cross-task CSE, cross-task postconflict slowing was consistently found in all experiments. More importantly, postconflict slowing was evident only in ITs, in contrast with the cross-task CSEs occurring in MTs, indicating that a spatial mode-general mechanism slows the upcoming response by affecting an earlier response-related process after experiencing a conflict.

Delta Functions: Time Courses of the Simon Effect

Our distributional analyses of the different modes of Simon effects revealed different time courses of spatial code activation and following dissipation. The location-based Simon effect followed a decreasing function regardless of orientation (Experiments 1, 2, and 3). On the other hand, the arrow-based Simon effect exhibited an increasing (Experiments 1 and 2) or a relatively constant function (Experiment 4), and the word-based Simon effect showed an increasing function (Experiments 3 and 4). Moreover, the delta functions observed in the IT data determined the overall pattern of the time course for each type of Simon effect, while the delta functions in the MT data did not reflect any difference between the spatial modes, as in previous studies (Buetti & Kerzel, 2008, 2009; Lim & Cho, 2021b; Miller & Roüast, 2016). This finding provides evidence that different time courses of the Simon effect indicate quantitative differences in the earlier response processing among different modes of spatial information, reflecting the speeds of the activation and following dissipation of spatial codes (Luo & Proctor, 2020). In the current study, the fastest activation of the spatial codes was found for physical location, followed by the slower activation of arrow direction and the slowest for word meaning.

Ellinghaus et al. (2018) specified the patterns of delta functions as a pulse-like function, tracking the time-courses of the automatic activation of the task-irrelevant spatial information followed by dissipation. In their diffusion model for conflict tasks, the output of the automatic process decreases after reaching its maximum due to active inhibition (Ridderinkhof, 2002) or spontaneous decay (Hommel, 1994). Thus, if the rapid automatic activation of spatial codes is followed by the rapid dissipation of activation, a decreasing function of the Simon effect is formed (De Jong et al., 1994). In contrast, if the automatic activation of spatial codes is not as fast and then followed by dissipation, an inverted U-shaped function is found (Ulrich et al., 2015).

Proctor et al. (2011) stated that the distributional functions of the Simon effect reflect the time course of the activation of the task-irrelevant spatial codes, but also extended the discussion by suggesting that the activation speed is not the only factor determining the slope of the delta plot. It has been suggested that other task contexts, including response-related features, can also influence the time course of the Simon effect (Buhlmann et al., 2007; Lim & Cho, 2021b; Wascher et al., 2001). Wascher et al. found that the horizontal location-based Simon effect increased across the RT distribution when participants were asked to press the left key with their right index finger and the right key with their left index finger, while it decreased across RT bins when they were asked to press the left key with their left index finger and the right key with their right index finger. Lim and Cho (2021b) found different delta function patterns for the vertical location-based Simon effect depending on whether participants performed the horizontal and vertical location-based Simon tasks with one hand or different hands. The present study also revealed the possibility for flexibility in the shapes of delta functions. The arrow-based Simon effect increased across the IT distributions in Experiments 1 and 2 but remained relatively constant or even depicted partly a decreasing function in Experiment 4, indicating that the task context, that is how the arrow-based Simon task was alternated with other tasks (location-based Simon task in Experiments 1 and 2 and word-based Simon task in Experiment 4), influenced the time course of the activation of spatial codes for arrow direction. Nevertheless, the relatively flatter slopes of the delta function observed in the arrow-based Simon effect compared to the faster location-based Simon effect and slower word-based Simon effect suggest that the delta functions are shaped primarily by the temporal aspect of the Simon effect.

It is important to note that the vertical version of the location-based Simon effect has been reported to show inconsistent results in distributional analyses. An increasing function of the delta plot was found in some studies (e.g., Buetti & Kerzel, 2008; Proctor et al., 2003; Wiegand & Wascher, 2005), and a decreasing delta function of the delta plot, like the horizontal location-based Simon effects, in other studies (e.g., Lim & Cho, 2021b). Wiegand and Wascher (2005) suggested that the time courses of Simon effects can be modulated by the saliencies of the vertical dimensions, which vary depending on how the stimulus and response alternatives are aligned and represented within a task. According to Proctor et al. (2003), the salience of the response influences the response activation via the direct route, affecting the strength and automaticity of the task-irrelevant spatial information: The more salient the spatial dimension, the stronger and faster the activation of response codes. Therefore, when using bimanual responses, as most studies do, the relative salience of the vertical dimension is usually weaker than that of the horizontal dimension because the two response alternatives of the vertical dimension are horizontally distinguished by the two hands, whereas the two response alternatives of the horizontal dimension are distinguished horizontally in terms of the body midline (Proctor et al., 2003). In line with the activation speed account, the increasing function of the vertical location-based Simon effect stems from the relatively weak salience of the vertical dimension, resulting in slow activation speeds of the spatial codes for the physical locations. When we equalized the saliences of the horizontal and vertical dimensions by adopting an unimanual response mode in the present study, as in Lim and Cho (2021b), a decreasing function was consistently observed for the vertical location-based Simon effect. Consequently, different time courses of Simon effects do not simply imply qualitative differences of different types of spatial information (See Appendix for "Distributional Analyses of the Congruency Sequence Effect").

Do Different Forms of Delta Functions Reflect Mode-Specific Spatial Codes?

In the present study, the transfer of the CSE between two Simon tasks and the similarities between the time courses of their Simon effects were found to be independent of each other. A cross-task CSE was observed between the location-based and arrow-based Simon tasks in MT, despite the opposite delta function patterns for the two tasks in IT. Moreover, although the arrow-based and word-based Simon effects showed similar increasing functions in the IT data, no CSE was found between them in MT in Experiment 4. These findings indicate that the similarity between two tasks in the time course of the Simon effect is not informative of whether the Simon effects observed in the two tasks stem from mode-general or mode-specific spatial codes. In addition, the cross-task CSE was traced in MTs, whereas the mode-specific time courses of the Simon effects were traced in ITs.

This dissociation in terms of data highlights that the mechanism underlying the active or passive dissipation pattern of the spatial code after the automatic activation is evidently independent of how the elicited spatial codes are represented and processed in the conflict modulation mechanism. The activation and dissipation process occurring in the earlier processing stages is targeted on the spatial code that was automatically formed. This process reflects the quantitative aspects of the given spatial code, which may alter based on different saliencies or contexts. The findings of the present study suggest that the temporal patterns of activation to dissipation of spatial codes do not provide information about the qualitative similarities of the processed spatial codes. On the other hand, the inhibitory control in the later response stages is targeted on the direct route where a spatial code triggers a response code. The direct route contains the qualitative natures of the spatial codes, and thus is the key for dissociating the shared or nonshared relationships between the spatial codes.

Conclusion

The present study provides evidence supporting the qualitative distinction of physical location, arrow direction, and location word in their characteristics. Despite the distinct modes in how they convey spatial information, they elicit specific spatial codes that are closely related to their individual characteristics. Utilizing visuospatial attributes to convey spatial information, physical location and arrow direction shared a common set of spatial codes, resulting in the cross-task CSEs between the location-based and arrow-based Simon tasks. In contrast, physical location and location word, which exploit two distinct attributes, visuospatial attributes and semantic-spatial attributes, respectively, were unable to share a common set of processing. While its properties partially overlap with those of location word, arrow direction is primarily visuospatial in nature.

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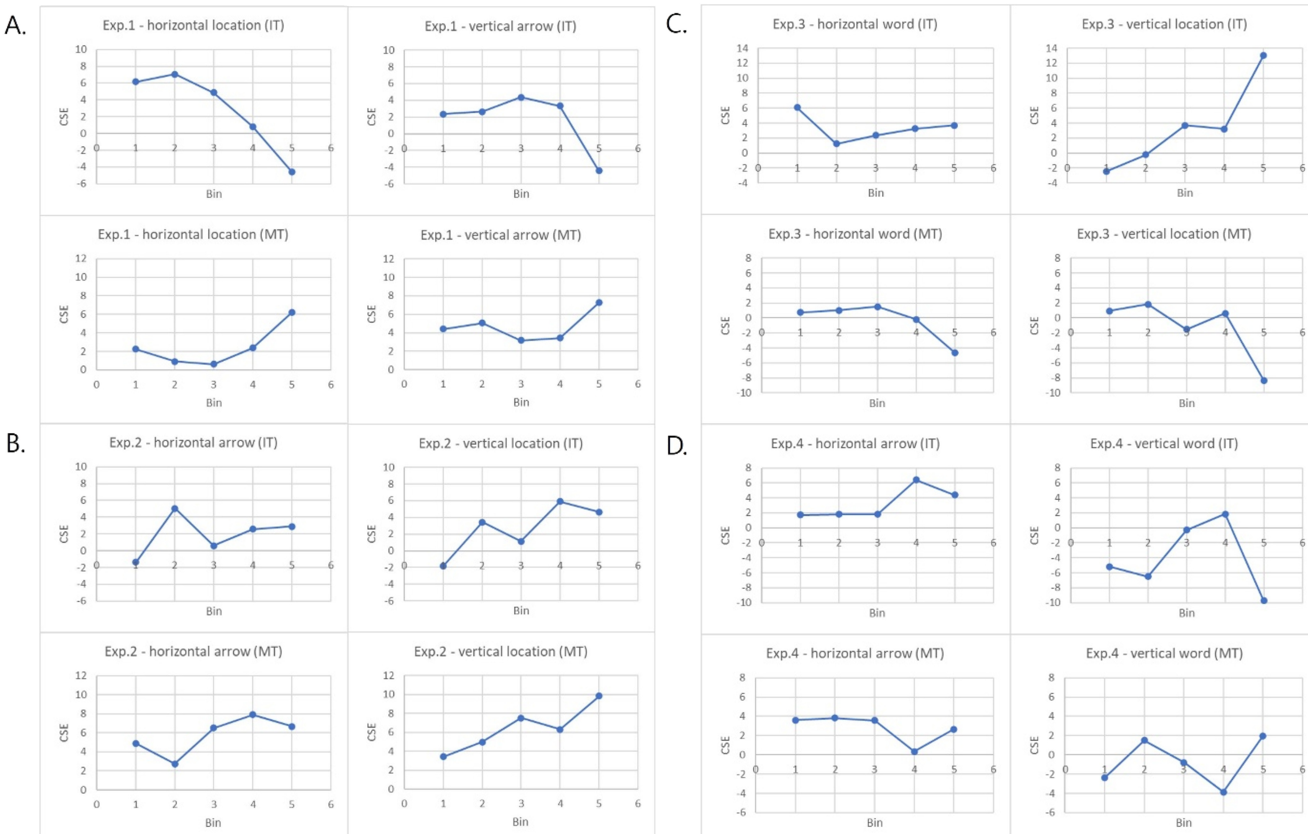
Appendix

Distributional Analyses of the Congruency Sequence Effect

Additional distributional bin analyses were conducted to examine the temporal dynamics of the CSEs. Based on the TT bins of each participant as a function of previous-trial congruency, current-trial congruency, and task type, delta functions were calculated to reflect the size of the CSE (the size of the Simon effect after congruent trials—the size of the Simon effect after incongruent trials) in each time bin (see Figure A1). To test the statistical difference between the delta functions of the two task types, quintile-averaged IT and MT data for each task were subjected to three-way repeated-measures ANOVAs as a function of bin (1–5), previous-trial congruency (congruent vs. incongruent), and current-trial congruency (congruent vs. incongruent) as within-subject factors. It is important to note that further subdivision of bins with the within-subject factor of previous-trial congruency resulted in a reduction in the number of trials in each bin by half. In our experiments, when PE is 0%, there were 19–20 trials in each bin. In all tasks response measures from Experiments 1 to 4, the three-way interaction between previous-trial congruency, current-trial congruency and bin was not significant in both IT and MT, Fs$(1, 51) < 2.43$, ps $> .125$, implying no systematic delta functions of CSEs in all modes of task.

(*Appendix continues*)

Figure A1
The Magnitude of CSEs Across Bins for IT and MT in Experiment 1 (A), Experiment 2 (B), Experiment 3 (C), and Experiment 4 (D)



Note. Exp. = experiment; CSE = congruency sequence effect; IT = initiation time; MT = movement time. See the online article for the color version of this figure.

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