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The Congruency Sequence Effect of the Simon Task in a Cross-Modality Context

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One of the prime measures of cognitive control is the congruency sequence effect (CSE), which refers to a reduced congruency effect following incongruent trials compared to congruent trials. Some researchers have argued that the conflict resolution process exerts its effect at the level of whole task-set, whereas others have argued that the control process applies to parts of a task-set. The present study examined whether the sequential modulation of the congruency effect transfers across two tasks even when they are highly distinguished by different stimulus sensory modalities. Participants performed auditory horizontal and visual vertical Simon tasks by using unimanual aimed movements. The cross-task CSE was obtained between the auditory and visual Simon tasks when the target modality was easily predicted in Experiment 1 and when the auditory and visual tasks were further distinguished by different task-relevant stimulus dimensions in Experiment 2. The results were replicated in a task-switching context in Experiment 3. These results indicate that cognitive control exerts its effect at a level of a specific component of a task-set instead of the level of a whole task-set itself.

Public Significance Statement

Cognitive control is the ability to regulate thoughts to focus on internal goals while ignoring strong internal predispositions. However, it is still unclear how exactly the control processes regulate conflicts. To justify the nature of the cognitive control process, the present study investigates the scope of the cognitive control systems. Here, we demonstrate that inhibitory control specifically applies to the place where response conflicts occur to reduce strong, unwanted habitual behaviors.

Keywords: cognitive control, congruency sequence effect, cross-modality, Simon effect


The ability to inhibit prepotent responses is a fundamental component of cognitive control (Miyake et al., 2000). Inhibitory control is responsible to regulate one's thoughts and behavior to focus on a goal while suppressing a strong internal predisposition or external distraction (Diamond, 2013). The inhibitory control has been tested using interference tasks, where participants are required to make a novel response to a target (task-relevant features) in the presence of distractor (task-irrelevant features) that is strongly associated with a habitual, unrequired response. In a Simon task, for instance, participants respond to a color of the target presented either to the left or right of a fixation cross while ignoring its location. Typically, responses become slower and less accurate when the target appears on the side opposite to the correct response (incongruent) than when it appears on the same side (congruent). This congruency effect occurs due to a response conflict regarding the task-relevant (e.g.,

color of the target) and task-irrelevant (e.g., location of the target) stimulus features that elicit different responses on incongruent trials (Kornblum et al., 1990).

Notably, the magnitude of this congruency effect has been found to be modulated by previous-trial congruency (Gratton et al., 1992). Typically, congruency effects are reduced following an incongruent trial relative to following a congruent trial, which is known as the congruency sequence effect (CSE). A growing body of research on the CSE suggests that the effect is a consequence of top-down cognitive control processes (Durstun et al., 2003; Egner et al., 2007; Kerns et al., 2004; MacDonald et al., 2000). According to the conflict monitoring theory originally proposed by Botvinick et al. (2001), once a conflict monitoring system detects the conflict between the responses elicited by task-relevant and task-irrelevant stimulus features, the system projects signals to a control mechanism to regulate the conflict by enhancing the processing of task-relevant features (Blais & Verguts, 2012; Egner & Hirsch, 2005; Verguts & Notebaert, 2008) and/or suppressing the processing of task-irrelevant features (Kim et al., 2015; J. Lee & Cho, 2013; Lim & Cho, 2021b; Stürmer et al., 2002). Consequently, this heightened control minimizes the response competition on the subsequent trial.

Although the CSE is well accounted for by the top-down cognitive control account, others suggested that the CSE is due to bottom-up stimulus and response feature-repetition priming (Hommel et al., 2004; Mayr et al., 2003) or contingency learning between task-irrelevant stimulus feature and its frequently associated

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response (Schmidt & De Houwer, 2011). Nevertheless, a number of studies reported robust CSEs even when both repetition-priming and contingency-learning confounds were controlled by alternating two different types of 2-alternative forced-choice task (2-AFC) in a trial-by-trial manner, indicating that top-down cognitive control plays a great role in the CSE (Kim & Cho, 2014; Lim & Cho, 2021a; Schmidt & Weissman, 2014). Recently, new accounts have attempted to address the phenomena of CSE by taking a hybrid approach combining the bottom-up repetition views with top-down control views (e.g., Egner, 2017; Jiménez & Méndez, 2013; Weissman et al., 2016). It is now generally accepted that multiple factors, such as bottom-up repetition priming, contingency learning, expectancy, and top-down control, contribute to the sequential modulation of the congruency effect.

One important question regarding the top-down cognitive control is how the control processes involved in the CSE regulate conflicts. Although some researchers argued that all kinds of conflict are resolved by one domain-general control process (e.g., Freitas et al., 2007; Kleiman et al., 2014), a substantial number of studies failed to find CSEs across two tasks with different task features (Akçay & Hazeltine, 2008, 2011; Egner & Hirsch, 2005; Egner et al., 2007; Funes et al., 2010; Kiesel et al., 2006; J. Lee & Cho, 2013; Lim & Cho, 2021b; Notebaert et al., 2006). Egner et al. (2007) proposed that conflicts are resolved by domain-specific control processes and that the factor determining domain-specific control is the source of conflict. Using a combined Stroop and Simon conflict task where participants were asked to make a left or right response to the color of a locational word (i.e., LEFT or RIGHT) presented either to the left or right of a central fixation point, a significant CSE was obtained within conditions representing the same type of conflict (Stroop–Stroop congruencies, Simon–Simon congruencies) but not between those representing different types of conflicts (Stroop–Simon congruencies, Simon–Stroop congruencies). According to Egner et al., the absence of the CSE between the Stroop and Simon congruencies is due to independent control processes that are recruited depending on the source of conflict. Additionally, Soutschek et al. (2013) proposed that the stimulus-based conflict, such as Stroop or flanker-compatibility congruencies, is regulated by biasing stimulus processing, whereas the response-based conflict, such as Simon congruency, is regulated by biasing response processing.

However, inconsistent with the source of conflict account, Akçay and Hazeltine (2008) found no CSE between two tasks with the same response-based conflict when the stimulus and response alternatives for one Simon task were located in the left hemispace and those for the other Simon task in the right hemispace. The authors suggested that the degree to which participants perceive the tasks as a single or different task determines whether the conflict is regulated by the same or different control processes. Thus, the scope of control is determined by task-set, which is how tasks are mentally represented, rather than the source of conflict (Akçay & Hazeltine, 2008; Hazeltine et al., 2011). According to the definition offered by Rogers and Monsell (1995), a task-set is a set of stimulus and response alternatives and task rules binding these alternatives together. It has been suggested that task-sets are either formed hierarchically (Schumacher & Hazeltine, 2016), where representations take stimulus features as inputs to form increasingly abstract representations, or nonhierarchically (Grant & Weissman, 2023; Hommel, 1998), where representation is a nonhierarchical organization of multiple independent binary bindings of task features.

Importantly, the task-set for a task is flexibly configured depending on how participants perceive the task. Thus, salient perceptual features, such as task-relevant features (Braem et al., 2014) or the sensory modality of task stimuli (Grant et al., 2020; Hazeltine et al., 2011), influence the formation of a task-set. Therefore, if two tasks are separated in terms of a salient feature, participants use this salient feature to divide a complex task into two or more simpler tasks, or different task-sets (Grant et al., 2022). Hazeltine et al. (2011) demonstrated that when two tasks were saliently distinguished by stimulus sensory modality (visual or auditory), a significant CSE was obtained within the same sensory modality (visual–visual or auditory–auditory), but not between the different sensory modalities (visual–auditory or auditory–visual). Yang et al. (2017) also found no CSE between auditory and visual conflict tasks, even when other features of the two tasks were cautiously controlled.

Moreover, the predictability of the task has been shown to influence the formation of the task-set. For example, Grant et al. (2020) used a cross-sensory modal prime-probe task, in which a distractor was presented before the onset of a target and participants were asked to ignore the distractor and to make a response to the target. In the experiments, when the sensory modality of directional target word (LEFT, RIGHT, UP, or DOWN) was always identical to that of the directional distracting word so that participants were able to predict the target's sensory modality based on the distractor's sensory modality, the CSE did not transfer across tasks with different sensory modalities. However, when the sensory modality of the target varied independently of the sensory modality of the distractor so that participants could not predict the target sensory modality, a significant CSE was obtained between two consecutive trials with different target sensory modalities. According to the authors, when the sensory modality of the target is predictable, different task-sets are formed for the two tasks depending on their sensory modality. However, when the sensory modality of the target is unpredictable, a single task-set is configured for the auditory and visual targets, resulting in the CSE across the different sensory modality tasks. Consequently, task predictability aids participants in using sensory modality to segregate stimulus-response pairs. As Akçay and Hazeltine (2008) suggested, Grant et al. (2020) also concluded that control scope is flexibly determined by how task-sets are configured.

However, several studies have shown a CSE between two tasks even when they did not share a single task-set (Kim et al., 2015; Lim & Cho, 2021b). Lim and Cho (2021b) found a CSE between horizontal and vertical visual Simon tasks, even though the two tasks had different task-relevant stimulus dimensions. This means that according to Rogers and Monsell's (1995) definition, they should be considered separate tasks. Furthermore, even when horizontal and vertical Simon tasks did share the same task-relevant dimension, no CSE was obtained when participants performed one task with their right hand and the other task with their left hand. Based on the findings that the presence of the CSE between two tasks was independent of whether they were represented as a single task-set, Lim and Cho suggested that the presence of the CSE between two Simon tasks depends on whether the tasks share the same task-irrelevant stimulus dimension and response mode which are the dimensions where inhibitory control triggered by Simon conflict is applied. Specifically, the control process triggered by the conflict between the responses elicited by task-relevant target feature and task-irrelevant target location suppresses the activation of a

response output by a spatial code for target location in an automatic route to reduce the response conflict. Thus, the scope of the control is determined by the level of components (task-irrelevant stimulus dimension and response mode) within a task-set, as suggested by the inhibition account (Kim et al., 2015; Lim & Cho, 2021b), rather than at the level of the whole task-set, as implied by the task-set account. However, there is a possibility that Lim and Cho found a significant CSE between a color horizontal Simon task and a letter vertical Simon task because the distinction between the two visual Simon tasks based on their task-relevant stimulus dimensions was not salient as much as the distinction based on the sensory modality of targets in Grant et al.'s (2020) experiments.

To examine the scope of cognitive control, the present study aimed to investigate whether the CSE occurs across two tasks with different task-sets. For this purpose, auditory horizontal and visual vertical Simon tasks were switched in a trial-by-trial manner. The sensory modality of the target was presented in a predictable task sequence to aid participants in using sensory modality to segregate the task-sets (Grant et al., 2020). The use of a predictable task sequence which promotes the formation of separate task-sets is the crucial test condition to investigate whether the CSE transfers across different task-sets. Grant et al. (2020) showed that the sensory modality of the distractors helps participants predict the target's sensory modality. In the present study, a predictable sequence of tasks will help participants predict the target's sensory modality.

In Experiment 1, participants were asked to make a leftward or rightward response to the meaning of a spoken color word presented to the left or right ear through a headphone in the auditory horizontal Simon task and an upward or downward response to the color of a visual target presented above or below the fixation cross in the visual vertical Simon task. In Experiment 2, participants were asked to perform an auditory timbre-discrimination horizontal Simon task and a visual color-discrimination vertical Simon task presented in an alternating sequence. In Experiment 3, participants performed the same tasks used in Experiment 2, but the tasks were switched every second trial.

To make the horizontal and vertical dimensions equally salient, as in Lim and Cho's (2021b) experiments, the unimanual aimed-movement response mode was adopted. The "5" key on the numeric keypad of a standard 101-key computer keyboard was used as the home key, the "4" and "6" keys of the keypad were used as directional keys for the horizontal Simon tasks, and the "8" and "2" keys of the keypad were used as directional keys for the vertical Simon tasks. Furthermore, by asking participants to release the home key when they had decided their response to the target, initiation times (ITs), which are the time elapse from the target onset to the moment when the home key is released, and movement times (MTs), which are the time elapse from the moment when the home key is released to the moment when a directional key is pressed, were recorded separately. ITs have been thought to reflect the information processing time until the response-selection stage and MTs reflect the information processing time after the response-selection stage. However, recent views suggest that response selection and execution are not clearly distinct stages so that responses can be initiated before response selection is completed (Buetti & Kerzel, 2008, 2009; Calderon et al., 2018; Erlhagen & Schöner, 2002; Hommel, 2009; Resulaj et al., 2009).

In the three experiments, because the auditory and visual Simon tasks were presented in a predictable way, the task-sets of the two

tasks should be formed separately based on their sensory modality. Thus, if the cognitive control applies at the level of the whole task-set, as Grant et al. (2020) suggested, no CSE would be observed across the two Simon tasks with different sensory modality presented in a predictable order. However, if the cognitive control applies at a level of components within a task-set, which is an automatic route of response selection, as Lim and Cho (2021b) suggested, a significant CSE would be observed across the two tasks because the task-irrelevant stimulus dimension of the two tasks was spatial information. Furthermore, if the top-down control process regulates the conflict by enhancing the processing of the task-relevant stimulus features, the CSE would be more evidence in the IT data than the MT data. On the other hand, if the control process regulates the conflict by suppressing the route along which the task-irrelevant spatial codes automatically activate their spatially corresponding response, as Lim and Cho suggested, the CSE would be more evident in the MT data than the IT data.

Experiment 1

The aim of Experiment 1 was to examine the cross-task CSE between two Simon tasks with different sensory modalities presented in a predictable way. For this purpose, participants performed auditory and visual color Simon tasks presented in a predictable task sequence. In the auditory color Simon task, a spoken color word was presented to the left or right ear through headphones. In the visual color Simon trials, a color square was shown either above or below central fixation. By using one hand, participants were asked to respond to the meaning of the spoken color word in the horizontal Simon task and the color of the square in the vertical Simon task, while ignoring the location that the spoken word or the square was presented. If different control processes are recruited for tasks having different task-sets, as Grant et al. suggested, no CSE would be obtained across the auditory horizontal and visual vertical Simon tasks because the two tasks were clearly distinguished by a predictable switch of sensory modality. On the other hand, if the specificity of control recruited by Simon-type conflict depends on the task-irrelevant stimulus dimension and response mode, a significant CSE would be observed across the two tasks because the tasks shared the same task-irrelevant spatial dimension and response modes (i.e., responding in one hand).

Method

Participants

The sample size was calculated using G*Power 3.1 (Faul et al., 2009). Based on the similar experiment conducted by J. Lee and Cho (2013, Experiment 1), where $\eta_p^2 = .0979$, a repeated-measures analysis of variance (ANOVA) with two-way interaction of previous-trial congruency (congruent or incongruent) and current-trial congruency (congruent or incongruent) was conducted. A correlation among repeated measures was 0.5, with the statistical power ($1 - \beta$) set at .95, and the α level at 5% was used. Our estimation showed that a minimum sample size of 32 would provide 98% power to observe a CSE between two tasks.

Thirty-two participants (20 female, 12 male; $M_{\text{age}} = 24.9$ years) from Korea University participated in Experiment 1. All of the participants were self-reported to have right-handedness, no deficit in visual acuity, color vision, or hearing. All of the participants signed

informed consent before the experiment and received KRW 8,000 (about seven U.S. dollars) after their participation. The data were collected in 2021. The current and following experiments were approved by the institutional review board of Korea University (KU-IRB-16-142-A-1).

Stimuli and Apparatus

The experiment was programmed using MATLAB software (Version 2015a) and the Psychophysics Toolbox Version 3 (PTB-3). Visual stimuli were presented on a 17-in. CRT monitor at a viewing distance of approximately 55 cm and auditory stimuli were presented through headphones (Creative Aurvana Live 51EF0060AA001). The sequence of displays and time course for the auditory and visual Simon tasks are illustrated in Figure 1A. The fixation point was a white ($R = 255$, $G = 255$, $B = 255$) cross ($0.3^\circ \times 0.3^\circ$ of visual angle) appearing at the center of the display. For the horizontal auditory Simon task, a spoken color word “빨강” (red in Korean; 62.4 dB) or “노랑” (yellow in Korean; 62.9 dB) by Korean female voice was presented either to the left or right ear through headphones while a blank visual display was presented (Figure 1B). Auditory stimuli were created by CLOVA Dubbing voice’s speech synthesis technology system (<https://clovadubbing.naver.com>). For the vertical visual Simon task, a square (approximately $1.51^\circ \times 1.51^\circ$), colored in blue ($R = 0$, $G = 0$, $B = 255$) or green ($R = 0$, $G = 255$, $B = 0$), was presented either above or below the fixation cross at an equal distance (approximately 5.4°). All visual stimuli were displayed on a black background ($R = 0$, $G = 0$, $B = 0$). The aimed movement responses were recorded with a standard 101-key computer keyboard. The “4,” “6,” “8,” and “2” keys on the numeric keypad were used as directional responses indicating “left,” “right,” “up,” and “down”,

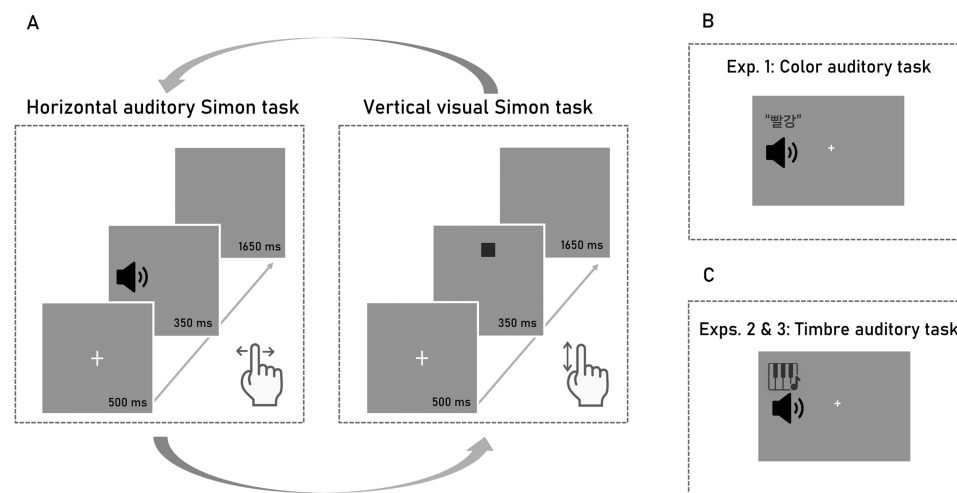
respectively. The “5” key, which is located at the center of the directional response keys, was used as the home key.

Procedure

After providing informed consent, participants performed the tasks in a dim-lit sound-proof chamber. The body midline of the participant and the numeric keypad were aligned with the center of the monitor. Participants were instructed to press one of the response keys on the numeric keypad depending on the color of the target stimulus as quickly and accurately as possible. The auditory horizontal and visual vertical Simon tasks were presented in an alternating sequence.

In each trial, when the fixation cross was presented, participants were asked to press the home key with their right index finger and to keep pressing the key until they decided their response to the target after it was presented. 500-ms after the home key was pressed, a target stimulus was presented for 350 ms or until the home key was released. After the target display, a blank display was presented for 1,650 ms. For the auditory horizontal Simon task, participants were instructed to press the “left” key to the spoken word “빨강” (red in Korean) and the “right” key to the spoken word “노랑” (yellow in Korean). For the visual vertical Simon task, participants were instructed to press the “up” key to the blue square and the “down” key to the green square. The stimulus-response mappings were not counterbalanced across participants. Participants were asked to make all responses with their right index finger only. If the release of the home key occurred before a target was presented, a visual feedback message was displayed, saying “Press the home key.” Each time the participant responded incorrectly or failed to respond within 2,000 ms after the target onset, a beep sound was played for 150 ms.

Figure 1
Illustration of Auditory and Visual Simon Tasks Used in Experiment 1, 2, and 3



Note. (A) An example of trial sequences. Auditory stimuli were presented in the horizontal axis and responded horizontally; visual stimuli were presented in the vertical axis and responded vertically. Auditory and visual Simon trials were presented in an alternating sequence. Participants were asked to make responses for both tasks with their right index finger. Examples for auditory stimuli in Experiment 1 (B) and Experiment 2 and 3 (C).

After a practice block of 36 trials, participants completed eight blocks of 98 trials, with 1-min breaks between blocks. The four sequential trial types of congruent trials followed by a congruent trial (cC), congruent trials followed by an incongruent trial (iC), incongruent trial followed by a congruent trial (cI), and incongruent trials followed by an incongruent trial were equally presented in the horizontal and vertical Simon tasks, respectively. Congruency for the first and second trials of each block was randomly determined.

Data Analyses

In the analyses, practice trials, the first two trials of each block, outlier defined as the trials with either IT or MT shorter or longer than 3 *SDs* than its conditional mean for each participant as outliers, trials following an outlier, or an incorrect trial were excluded from the analyses (about 10.21% of the total trials). Following these exclusions, individual mean correct total reaction times (TTs), ITs, MTs, and percentage errors (PEs) were calculated separately for the combination of previous-trial congruency (congruent, incongruent) and current-trial congruency (congruent, incongruent). Two-way repeated measures ANOVAs were conducted on mean TTs, ITs, MTs, and PEs with those variables as within-subject variables (Table 1). To further verify the results, additional repeated-measures Bayesian ANOVAs were conducted using JASP (JASP Team, 2022). Specifically, to evaluate the strength of evidence for the alternative over null hypotheses, Bayes factors in favor of the alternative hypothesis (i.e., BF_{10}) were computed. Similarly, to determine the strength of evidence for the null over alternative hypotheses, Bayes factors in favor of the null hypothesis (i.e., BF_{01}) were calculated. Raftery's (1995) criterion is used to interpret the Bayes factors. A Bayes factor of 1–3 is considered as weak evidence, 3–20 as positive evidence, 20–150 as strong evidence, and any value greater than 150 as very strong evidence.

Transparency and Openness

We report how we determined our sample size. Data exclusions criteria were stated. All data and research materials are available at (<https://osf.io/u8sfq>). Data were analyzed using MATLAB, Version 2019a. This study's design and its analysis were not preregistered.

Results

TT

The main effect of previous-trial congruency was significant, $F(1, 31) = 4.69$, $p = .03$, $MSE = 84$, $\eta_p^2 = .131$, $BF_{10} = 0.93$,

Table 1
Mean of TT, IT, MT (in ms), and PE in Experiment 1

| <i>N</i> – 1 congruency | Congruency | TT | IT | MT | PE |
|-------------------------|-------------|-----|-----|-----|------|
| Congruent | Congruent | 578 | 455 | 123 | 1.10 |
| | Incongruent | 618 | 481 | 137 | 2.38 |
| Incongruent | Congruent | 583 | 459 | 124 | 1.06 |
| | Incongruent | 619 | 485 | 134 | 2.71 |

Note. PE = percentage error; TT = total reaction times; IT = initiation time; MT = movement time.

with the mean TT significantly greater after incongruent trials ($M = 601$ ms) than after congruent trials ($M = 598$ ms). A significant Simon effect was observed, as the main effect of current-trial congruency was significant, $F(1, 31) = 191.89$, $p < .001$, $MSE = 242$, $\eta_p^2 = .860$, $BF_{10} = 1.35 \times 10^{+12}$. The mean TT was greater on incongruent trials ($M = 619$ ms) than congruent trials ($M = 580$ ms). There was no significant interaction between previous-trial congruency and current-trial congruency, indicating no CSE between the two tasks, $F(1, 31) = 1.57$, $p = .220$, $BF_{01} = 1.62$ (Figure 2).

IT

The main effect of previous-trial congruency was significant, $F(1, 31) = 11.94$, $p = .001$, $MSE = 46$, $\eta_p^2 = .278$, $BF_{10} = 6.14$, with the mean IT significantly greater after incongruent trials ($M = 472$ ms) than after congruent trials ($M = 468$ ms). A significant Simon effect was observed, as the main effect of current-trial congruency was significant, $F(1, 31) = 106.05$, $p < .001$, $MSE = 208$, $\eta_p^2 = .773$, $BF_{10} = 6.70 \times 10^{+8}$. The mean IT was greater on incongruent trials ($M = 483$ ms) than congruent trials ($M = 457$ ms). There was no significant interaction between previous-trial congruency and current-trial congruency, indicating no CSE between the two tasks, $F(1, 31) < 1$, $BF_{01} = 3.77$ (Figure 2).

MT

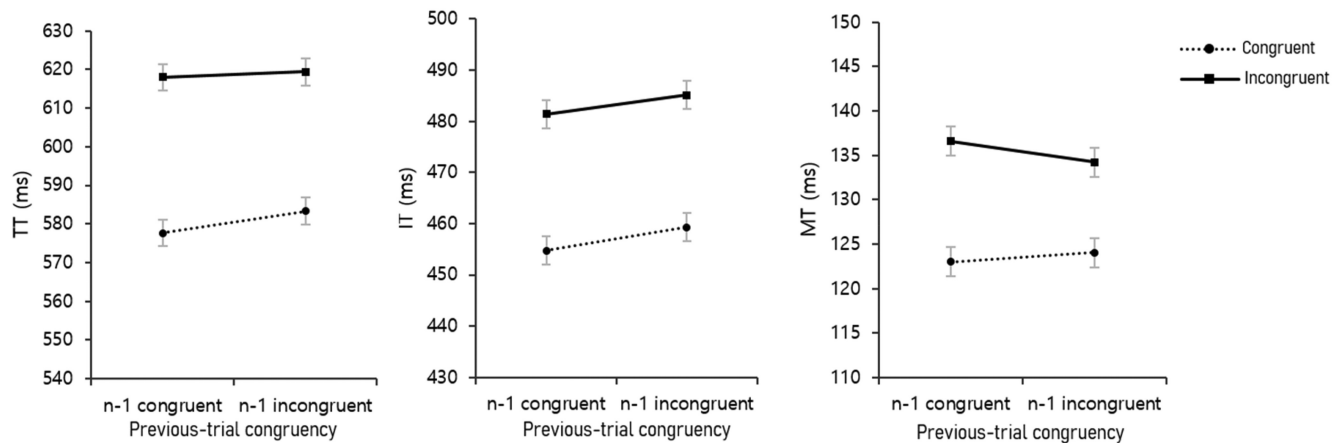
The main effect of previous-trial congruency was not significant $F(1, 31) < 1$, $BF_{01} = 3.67$. However, the main effect of current-trial congruency was significant, $F(1, 31) = 74.38$, $p < .001$, $MSE = 60$, $\eta_p^2 = .705$, $BF_{10} = 1.39 \times 10^{+7}$. The mean MT was greater on incongruent trials ($M = 135$ ms) than congruent trials ($M = 124$ ms). Unlike for the IT data, a significant interaction between previous-trial congruency and current-trial congruency was obtained, $F(1, 31) = 4.53$, $p = .041$, $MSE = 20$, $\eta_p^2 = .127$, $BF_{10} = 2.44$, indicating a CSE between the two tasks (Figure 2). The magnitude of the Simon effect was reduced after incongruent trials (10 ms), $F(1, 31) = 41.14$, $p < .001$, $MSE = 40$, $\eta_p^2 = .570$, $BF_{10} = 2.36 \times 10^{+4}$, compared to that of the effect after congruent trials (14 ms), $F(1, 31) = 71.82$, $p < .001$, $MSE = 41$, $\eta_p^2 = .698$, $BF_{10} = 3.40 \times 10^{+6}$.

To ensure that the CSE across tasks in MT data were symmetric between the directions of cross-modal (i.e., the CSE from visual to auditory stimuli and the CSE from auditory to visual stimuli), three-way repeated measures ANOVAs were conducted with previous-trial congruency, current-trial congruency, and task as within-subject variables. The three-way interaction of task with previous-trial congruency and current-trial congruency was not significant, $F(1, 31) = 1.45$, $p = .237$, $BF_{01} = 2.58$, indicating no transfer asymmetry.

PE

The main effect of current-trial congruency was significant, $F(1, 31) = 29.83$, $p < .001$, $MSE = 2.29$, $\eta_p^2 = .490$, $BF_{10} = 3.84 \times 10^{+3}$. PE was higher on incongruent trials (2.54%) than congruent trials (1.08%). No other main effect or interaction was significant.

Figure 2
The Sequential Modulation of the Congruency Effect in Experiment 1



Note. Average TT (left), average IT (center), and average MT (right) with respect to previous-trial congruency and current-trial congruency (dashed and solid lines respectively). Error bars indicate 95% confidence intervals for the mean (Loftus & Masson, 1994).

Discussion

Although no CSE was obtained in IT and TT, a significant CSE was observed across the auditory and visual Simon congruencies in MT, as demonstrated by Lim and Cho (2021b). The congruency effect was reduced on trials following incongruent trials (10 ms) compared to those following congruent trials (14 ms), indicating that the control process recruited by the auditory Simon conflict modulated the amount of visual Simon conflict and vice versa. However, no CSE was evident in IT showing a 26-ms congruency effect after incongruent trials which was comparable to a 27-ms congruency effect after congruent trials. These results indicate that the Simon-type conflict was controlled by biasing the response-related processing in later information-processing stages, not by biasing the perceptual processing of task-relevant or task-irrelevant stimulus features in earlier information-processing stages.

Inconsistent with what Grant et al. (2020) and Akçay and Hazeltine (2008) suggested, the same control process was recruited on the two tasks with different sensory modalities that were presented in a predictable way, even though the two tasks should be considered to have different task-sets. As Lim and Cho (2021b) and Kim et al. (2015) suggested, the CSE was transferred across the different sensory modality tasks because they shared the same task-irrelevant stimulus dimension (spatial dimension) and response mode (unimanual aimed movements). Thus, this finding indicates that top-down cognitive control triggered by a Simon conflict exerts its effect on the automatic route between task-irrelevant dimension to response mode to inhibit the transmission of response activation from spatial codes.

However, it should be noted that the auditory horizontal and visual vertical Simon tasks shared the conceptually identical task-relevant stimulus dimension of color. Thus, one may argue that the CSE was obtained between the auditory and visual tasks because they had the same task rules and task-relevant stimulus dimensions, which are critical components of a task-set. Indeed, according to Rogers and Monsell (1995), the initial task-set is formed based on the task instruction or task-relevant stimulus

dimension. Thus, it was likely to form a single-task representation for the two tasks. Therefore, we cannot rule out the possibility that the obtained CSE was due to the two tasks sharing the task-relevant stimulus dimension.

Experiment 2

The aim of Experiment 2 was to examine whether the CSE transfer across two tasks with different stimulus sensory modalities and conceptually different task-relevant stimulus dimensions. For this purpose, participants performed auditory horizontal musical-instrument and visual vertical color Simon tasks presented in a predictable task sequence. For the auditory Simon task, a piano or violin sound was delivered to either the left or right ear through headphones. Participants were asked to make a left- or right-aimed movement in response to the timbre of the target sound while ignoring the location of the sound. For the visual Simon task, a red or green square was presented either above or below the central fixation point. Participants were instructed to make an upward- or downward-aimed movement response to the color of the target square while ignoring the location of the target. The two tasks were performed with the right hand as in Experiment 1. Thus, the two tasks had conceptually different task-relevant stimulus dimensions, as well as different stimulus sensory modalities, but shared the task-irrelevant spatial dimension and response mode. If the boundary of the cognitive control involved in the CSE between two tasks is determined by whether they share a task-set or not, as the task-set account suggests, no CSE would transfer across the different sensory modality tasks because the auditory and visual tasks presented alternatively in every trial had different task-relevant stimulus dimensions, which are critical determinants for the boundary of task-sets. On the other hand, if the cognitive control triggered by Simon-type conflict is specific to the task-irrelevant stimulus dimension and response mode, the CSE would be observed between the auditory and visual Simon tasks because they shared the task-irrelevant spatial dimension and response mode.

Method

Participants

Another group of 32 participants (18 female, 14 male; $M_{\text{age}} = 25.0$ years) were recruited from the same pool as those in Experiment 1. All participants self-reported to have right-handedness, no deficit in visual acuity, color vision, or hearing. They signed informed consent before performing the task and received KRW 8,000 (about 7 U.S. dollars) after their participation. The data were collected in 2021.

Stimuli, Apparatus, and Procedure

The apparatus and stimuli were the same as those used in Experiment 1 with the following changes. For the horizontal auditory Simon task, the sound of a piano (62.4 dB) or violin (62.9 dB) with a musical frequency of B6 (1,760 Hz) was delivered to either the left or right ear of each participant through a headphone (Figure 1C). Participants were asked to press the “left” directional key when a piano sound was presented and to press the “right” directional key when a violin sound was presented. For the vertical visual Simon task, a colored square (approximately $1.51^\circ \times 1.51^\circ$) was presented either above or below the fixation point at an equal distance (approximately 5.4°). Participants were asked to press the “up” directional key when a red ($R = 255$, $G = 0$, $B = 0$) square was presented and to press the “down” direction key when a green ($R = 0$, $G = 255$, $B = 0$) square was presented.

Data Analyses

With the same exclusion criteria used in Experiment 1, 14.34% of trials were excluded from the following analyses. Following these exclusions, individual mean corrects TTs, ITs, MTs, and PEs were calculated separately for the combination of previous-trial congruency (congruent, incongruent) and current-trial congruency (congruent, incongruent). Two-way repeated measures ANOVAs were conducted on mean TTs, ITs, MTs, and PEs with those variables as within-subject variables (Table 2).

Results

TT

The main effect of previous-trial congruency was not significant, $F(1, 31) = 3.11$, $p = .087$, $MSE = 365$, $\eta_p^2 = .091$, $BF_{01} = 1.51$. However, the main effect of current-trial congruency was significant, $F(1, 31) = 84.8$, $p < .001$, $MSE = 452$, $\eta_p^2 = .732$, $BF_{10} = 4.07 \times 10^{+7}$. The mean TT was greater on incongruent trials ($M =$

717 ms) than congruent trials ($M = 682$ ms). A significant interaction between previous-trial congruency and current-trial congruency was obtained, $F(1, 31) = 8.37$, $p = .006$, $MSE = 274$, $\eta_p^2 = .212$, $BF_{10} = 11.85$, indicating a CSE between the two tasks (Figure 3). The magnitude of the Simon effect was reduced after incongruent trials (26 ms), $F(1, 31) = 40.53$, $p < .001$, $MSE = 270$, $\eta_p^2 = .566$, $BF_{10} = 2.13 \times 10^{+4}$, compared to that of the effect after congruent trials (43 ms), $F(1, 31) = 65.03$, $p < .001$, $MSE = 457$, $\eta_p^2 = .677$, $BF_{10} = 1.34 \times 10^{+6}$.

A further analysis of three-way repeated measures ANOVA of previous-trial congruency, current-trial congruency, and task as within-subject variables revealed that the three-way interaction of these variables was not significant, $F(1, 31) < 1$, $BF_{01} = 3.48$, indicating no transfer asymmetry.

IT

The main effect of previous-trial congruency was significant, $F(1, 31) = 6.75$, $p = .014$, $MSE = 221$, $\eta_p^2 = .178$, $BF_{10} = 1.61$. The mean IT was significantly greater after incongruent trials ($M = 567$ ms) than after congruent trials ($M = 560$ ms). The main effect of current-trial congruency was significant, $F(1, 31) = 71.74$, $p < .001$, $MSE = 238$, $\eta_p^2 = .698$, $BF_{10} = 2.39 \times 10^{+6}$. The mean IT was greater on incongruent trials ($M = 575$ ms) than congruent trials ($M = 552$ ms). The interaction between previous-trial congruency and current-trial congruency was marginally significant, $F(1, 31) = 3.83$, $p = .059$, $MSE = 249$, $\eta_p^2 = .109$, $BF_{10} = 2.14$. However, the pattern of this interaction did not indicate CSE (Figure 3).

MT

The main effect of current-trial congruency was significant, indicating a significant Simon effect, $F(1, 31) = 27.54$, $p < .001$, $MSE = 154$, $\eta_p^2 = .470$, $BF_{10} = 1.88 \times 10^{+3}$. The mean MT was greater on incongruent trials ($M = 142$ ms) than congruent trials ($M = 130$ ms). Importantly, the interaction between previous-trial congruency and current-trial congruency was significant, $F(1, 31) = 12.06$, $p = .001$, $MSE = 24$, $\eta_p^2 = .280$, $BF_{10} = 27.96$, indicating a significant CSE between the two tasks (Figure 3). The magnitude of the Simon effect was reduced after incongruent trials (8 ms) $F(1, 31) = 15.07$, $p < .001$, $MSE = 76$, $\eta_p^2 = .327$, $BF_{10} = 48.40$, compared to the effect after congruent trials (15 ms), $F(1, 31) = 33.28$, $p < .001$, $MSE = 101$, $\eta_p^2 = .517$, $BF_{10} = 4.73 \times 10^{+3}$.

A further analysis of three-way repeated measures ANOVA of previous-trial congruency, current-trial congruency, and task as within-subject variables revealed that the three-way interaction of these variables was not significant, $F(1, 31) < 1$, $BF_{01} = 10.78$, indicating no transfer asymmetry.

PE

The main effect of current-trial congruency was significant, $F(1, 31) = 10.02$, $p = .003$, $MSE = 9.56$, $\eta_p^2 = .244$, $BF_{10} = 11.21$. The PE was higher on incongruent trials (3.49%) than congruent trials (1.76%). No other main effect or interaction was significant.

Discussion

A significant CSE was obtained between the auditory and visual Simon tasks in TT and MT. As in Experiment 1, this sequential

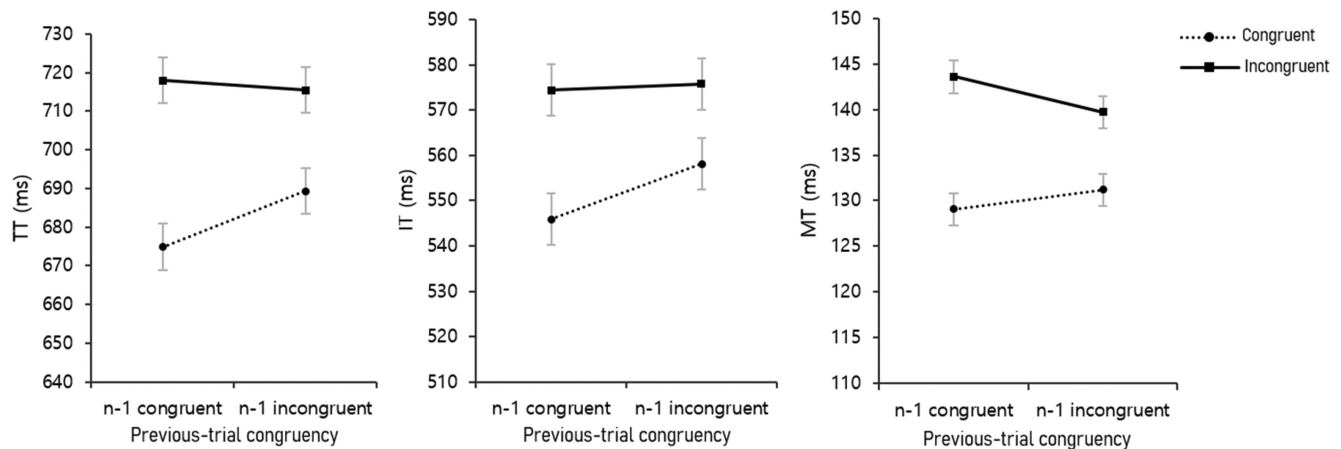
Table 2

Mean of TT, IT, MT (in ms), and PE in Experiment 2

| $N - 1$ congruency | Congruency | TT | IT | MT | PE |
|--------------------|-------------|-----|-----|-----|------|
| Congruent | Congruent | 675 | 546 | 129 | 1.74 |
| | Incongruent | 718 | 574 | 144 | 3.54 |
| Incongruent | Congruent | 689 | 558 | 131 | 1.78 |
| | Incongruent | 715 | 576 | 140 | 3.45 |

Note. PE = percentage error; TT = total reaction times; IT = initiation time; MT = movement time.

Figure 3
The Sequential Modulation of the Congruency Effect in Experiment 2



Note. Average TT (left), average IT (center), and average MT (right) with respect to previous-trial congruency and current-trial congruency (dashed and solid lines respectively). Error bars indicate 95% confidence intervals for the mean (Loftus & Masson, 1994).

modulation between them was reflected in the MT data but not in the IT data. A smaller congruency effect was obtained after incongruent trials (8 ms) than after congruent trials (15 ms) in the MT data. Although the IT data also showed a reduced congruency effect after incongruent trials (18 ms) than after congruent trials (29 ms), the mean IT on iI trials were greater ($M = 576$ ms) than cI trials ($M = 574$ ms), which is not a typical pattern of the CSE. Again, these results indicate that the Simon-type conflict was controlled by biasing the response-related processing in a later information processing stage, instead of biasing the perceptual processing of task-relevant stimulus dimension in an earlier processing stage.

Even though participants performed the two tasks with different task-relevant stimulus dimensions, the cognitive control recruited by the conflict of one task modulated the amount of the Simon conflict of the other task. Because the two tasks, which were presented in a predictable way, had different task-relevant dimensions and sensory modalities, it is unlikely that they were represented as a single task-set. Again, in line with Lim and Cho (2021b) and Kim et al. (2015), the control process recruited by response-based conflict relies on the inhibition to suppress the transmission of response activation from spatial codes in the automatic route to reduce the interference from task-irrelevant spatial information.

Experiment 3

Although Experiment 2 showed a significant CSE across tasks with different task-relevant dimensions and stimulus modalities that were presented in a predictable manner, the results do not provide any quantitative measurement of whether the tasks were represented as different task-sets. One way to investigate how the task-sets for two tasks are configured is to examine the switching cost between them, which is defined as the difference in task performance between repeating and switching trials (e.g., Allport et al., 1994). Rogers and Monsell (1995) suggested that task performance

decreases when the task switches from the previous trial as compared to when the task repeats, even when there is enough time to prepare for a new task in advance. This switching cost occurs because of the time taken to reconfigure the task-set for the subsequent new task on switching trials (Rogers & Monsell, 1995), or the interference from the previous task-set that is irrelevant to the current trial (Allport & Wylie, 2000; Allport et al., 1994), or involuntary activation of tasks through bottom-up stimulus-based priming effects (Koch & Allport, 2006).

The aim of Experiment 3 was to examine whether the results from Experiment 2 replicated in the switching task paradigm. For this purpose, participants performed the horizontal auditory instrument and vertical visual color Simon tasks in a predictable AABB sequence. It is important to note that the confound of bottom-up stimulus and response feature-repetition priming is inevitable with repeat trials (Hommel et al., 2004; Mayr et al., 2003). That is, the sequential modulation on repeat trials is due to the bottom-up stimulus and response feature-repetition priming, along with the top-down cognitive control. Therefore, we only examined the CSE on switch trials to minimize the confounding effect of repetition priming (Lim & Cho, 2021a). If the CSE observed in Experiment 2 was transferred across tasks with different task-sets, the switching cost, as well as the CSE, would be observed between the two tasks.

Method

Participants

Another group of 32 participants (15 female, 17 male; $M_{\text{age}} = 25.1$ years) were recruited from the same pool used in the previous experiments. All participants self-reported as being right-handed and having no visual acuity, color vision, or hearing impairments. They signed an informed consent form before performing the task and received KRW 10,000 (about nine U.S. dollars) after their participation. The data were collected in 2022.

Stimuli, Apparatus, and Procedure

The apparatus and stimuli were the same as those used in Experiment 2 with the following changes. For the horizontal auditory Simon task, participants were asked to press the “left” directional key when a violin sound was presented and to press the “right” directional key when a piano sound was presented. For the vertical visual Simon task, participants were asked to press the “up” directional key when a green ($R = 0, G = 255, B = 0$) square was presented and to press the “down” direction key when a red ($R = 255, G = 0, B = 0$) square was presented. Importantly, the horizontal auditory Simon task and vertical visual Simon task were presented alternatively after one repetition in a sequence of AABB.

Data Analyses

With the same exclusion criteria used in previous experiments, 14.49% of trials were excluded from the following analyses. Following these exclusions, individual mean corrects TTs, ITs, MTs, and PEs were calculated separately for the combination of previous-trial congruency (congruent, incongruent), current-trial congruency (congruent, incongruent), and trial type (task-repeat, task-switch). Three-way repeated measures ANOVAs were conducted on mean TTs, ITs, MTs, and PEs with those variables as within-subject variables (Table 3).

Results

TT

The main effect of previous-trial congruency was significant, $F(1, 31) = 6.03, p = .019, MSE = 324, \eta_p^2 = .162, BF_{10} = 1.20$. The mean TT was significantly greater after incongruent trials ($M = 644$ ms) than after congruent trials ($M = 639$ ms). The main effect of current-trial congruency was significant, $F(1, 31) = 104.4, p < .001, MSE = 509, \eta_p^2 = .771, BF_{10} = 3.88 \times 10^{+8}$. The mean TT was greater on incongruent trials ($M = 656$ ms) than congruent trials ($M = 627$ ms). The main effect of trial type was significant, $F(1, 31) = 118.53, p < .001, MSE = 5,066, \eta_p^2 = .792, BF_{10} = 1.49 \times 10^{+9}$, indicating a significant 97-ms task-switching cost. The interaction between previous-trial congruency and current-trial congruency was significant, $F(1, 31) = 26.45, p < .001, MSE = 321, \eta_p^2 = .460, BF_{10} = 801$, indicating a significant CSE. The magnitude of the Simon effect was reduced after incongruent trials (17 ms) $F(1, 31) = 22.78, p < .001, MSE = 202, \eta_p^2 = .423,$

$BF_{10} = 414$, compared to the effect after congruent trials (40 ms), $F(1, 31) = 133.7, p < .001, MSE = 188, \eta_p^2 = .811, BF_{10} = 2.90 \times 10^{+9}$. The three-way interaction of previous-trial congruency, current-trial congruency, and trial type was significant, $F(1, 31) = 26.25, p < .001, MSE = 302, \eta_p^2 = .458, BF_{10} = 2.67 \times 10^{+7}$.

To exclude the effect of repetition priming, the data from task-switching trials and task-repeating trials were separately analyzed using two-way repeated-measures ANOVAs with previous-trial congruency and current-trial congruency as within-subjects variables. On task-repeating trials, the two-way interaction between previous-trial congruency and current-trial congruency was significant, $F(1, 31) = 48.32, p < .001, MSE = 340, \eta_p^2 = .609, BF_{10} = 3.23 \times 10^{+10}$. The magnitude of the Simon effect was smaller after incongruent trials (7 ms) $F(1, 31) = 3.12, p = .087, MSE = 279, \eta_p^2 = .091, BF_{10} = 0.91$, than after congruent trials (53 ms), $F(1, 31) = 169.54, p < .001, MSE = 262, \eta_p^2 = .845, BF_{10} = 4.71 \times 10^{+10}$. However, the data from task-switching trials showed no significant CSE between the tasks, $F(1, 31) < 1, BF_{01} = 3.89$ (Figure 4).

IT

The main effect of previous-trial congruency was significant, $F(1, 31) = 12.98, p = .001, MSE = 211, \eta_p^2 = .295, BF_{10} = 4.88$. The mean IT was significantly greater after incongruent trials ($M = 502$ ms) than after congruent trials ($M = 496$ ms). The main effect of current-trial congruency was significant, $F(1, 31) = 115.45, p < .001, MSE = 219, \eta_p^2 = .788, BF_{10} = 1.11 \times 10^{+8}$. The mean IT was greater on incongruent trials ($M = 509$ ms) than congruent trials ($M = 489$ ms). The main effect of trial type was significant, $F(1, 31) = 80.98, p < .001, MSE = 4,857, \eta_p^2 = .723, BF_{10} = 1.85 \times 10^{+7}$, indicating a significant 78-ms task-switching cost. The interaction between previous-trial congruency and current-trial congruency was significant, $F(1, 31) = 15.53, p < .001, MSE = 246, \eta_p^2 = .333, BF_{10} = 34.37$, indicating a significant CSE. The magnitude of the Simon effect was reduced after incongruent trials (12 ms), $F(1, 31) = 23.44, p < .001, MSE = 96.7, \eta_p^2 = .430, BF_{10} = 483$, compared to the effect after congruent trials (28 ms), $F(1, 31) = 93.35, p < .001, MSE = 127, \eta_p^2 = .750, BF_{10} = 5.40 \times 10^{+7}$. The interaction of current-trial congruency and trial type was marginally significant, $F(1, 31) = 3.41, p = .074, MSE = 173, \eta_p^2 = .099, BF_{10} = 0.55$. The magnitude of the Simon effect tended to be smaller on switch trials (17 ms), $F(1, 31) = 40.99, p < .001, MSE = 221, \eta_p^2 = .569, BF_{10} = 2.34 \times 10^{+4}$, than on repeat trials (23 ms), $F(1, 31) = 98.25, p < .001, MSE = 171, \eta_p^2 = .760, BF_{10} = 9.22 \times 10^{+7}$. The three-way interaction of previous-trial congruency, current-trial congruency, and trial type was significant, $F(1, 31) = 19.37, p < .001, MSE = 310, \eta_p^2 = .384, BF_{10} = 3.49 \times 10^{+6}$.

To exclude the effect of bottom-up repetition priming, the data from task-switching trials and task-repeating trials were separately analyzed using two-way repeated-measures ANOVAs with previous-trial congruency and current-trial congruency as within-subjects variables. On task-repeating trials, the two-way interaction between previous-trial congruency and current-trial congruency was significant, $F(1, 31) = 31.3, p < .001, MSE = 310, \eta_p^2 = .502, BF_{10} = 2.61 \times 10^{+7}$. The magnitude of the Simon effect was smaller after incongruent trials (6 ms) $F(1, 31) = 2.79, p = .105, BF_{01} = 1.29$, than after congruent trials (40 ms), $F(1, 31) = 84.75, p < .001,$

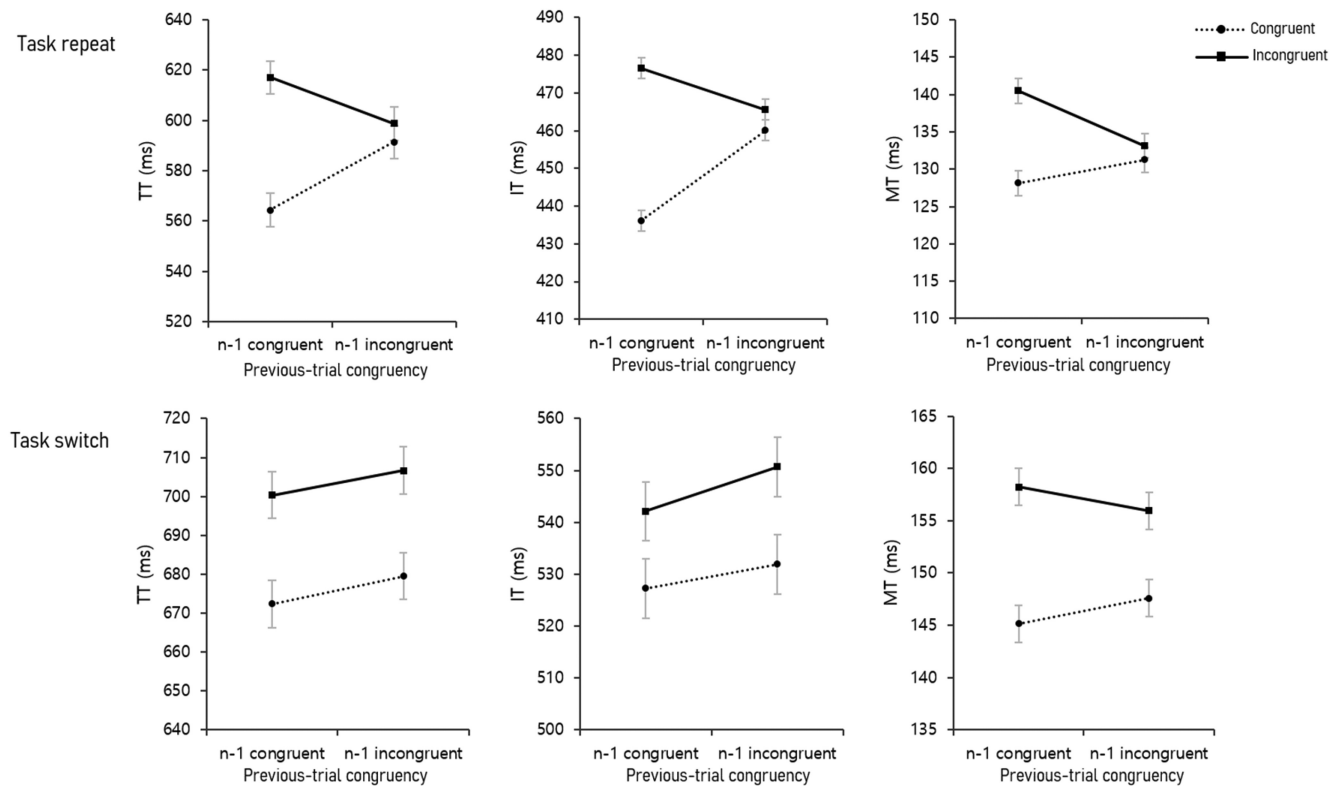
Table 3

Mean of TT, IT, MT (in ms), and PE in Experiment 3

| Task | $N - 1$ congruency | Congruency | TT | IT | MT | PE |
|--------|--------------------|-------------|-----|-----|-----|------|
| Repeat | Congruent | Congruent | 564 | 436 | 128 | 0.69 |
| | | Incongruent | 617 | 477 | 141 | 1.83 |
| | Incongruent | Congruent | 591 | 460 | 131 | 0.53 |
| | | Incongruent | 599 | 466 | 133 | 1.40 |
| Switch | Congruent | Congruent | 672 | 527 | 145 | 3.26 |
| | | Incongruent | 700 | 542 | 158 | 6.15 |
| | Incongruent | Congruent | 679 | 532 | 148 | 2.95 |
| | | Incongruent | 707 | 551 | 156 | 5.22 |

Note. PE = percentage error; TT = total reaction times; IT = initiation time; MT = movement time.

Figure 4
The Sequential Modulation of the Congruency Effect in Experiment 3



Note. Top panel: average TT (left), average IT (center), and average MT (right) with respect to previous-trial congruency and current-trial congruency (dashed and solid lines respectively) for task repeat. Bottom panel: average TT (left), average IT (center), and average MT (right) with respect to previous-trial congruency and current-trial congruency (dashed and solid lines respectively) for task switch. Error bars indicate 95% confidence intervals for the mean (Loftus & Masson, 1994).

MSE = 307, $\eta_p^2 = .732$, $BF_{10} = 1.90 \times 10^{+7}$. However, the data from task-switching trials showed no significant CSE between the tasks, $F(1, 31) < 1$, $BF_{01} = 2.88$ (Figure 4).

MT

The main effect of current-trial congruency was significant, $F(1, 31) = 35.31$, $p < .001$, MSE = 144, $\eta_p^2 = .532$, $BF_{10} = 1.19 \times 10^{+4}$. The mean MT was greater on incongruent trials ($M = 147$ ms) than congruent trials ($M = 138$ ms). The main effect of trial type was significant, $F(1, 31) = 78.16$, $p < .001$, MSE = 279, $\eta_p^2 = .716$, $BF_{10} = 1.89 \times 10^{+7}$, indicating a significant 18-ms task-switching cost. The interaction between previous-trial congruency and current-trial congruency was significant, $F(1, 31) = 43.92$, $p < .001$, MSE = 20, $\eta_p^2 = .586$, $BF_{10} = 2.66 \times 10^{+3}$, indicating a significant CSE. The magnitude of the Simon effect was smaller after incongruent trials (5 ms) $F(1, 31) = 9.9$, $p = .003$, MSE = 41, $\eta_p^2 = .242$, $BF_{10} = 9.97$, than after congruent trials (13 ms), $F(1, 31) = 67.17$, $p < .001$, MSE = 37, $\eta_p^2 = .684$, $BF_{10} = 1.86 \times 10^{+6}$. The interaction of current-trial congruency and trial type was marginally significant, $F(1, 31) = 3.84$, $p = .059$, MSE = 54, $\eta_p^2 = .110$, $BF_{10} = 1.14$. The magnitude of the Simon effect was greater on switch trials (11 ms) $F(1, 31) = 27.71$, $p < .001$, MSE = 132, $\eta_p^2 = .472$, $BF_{10} = 1.35 \times 10^{+3}$, than

on repeat trials (7 ms), $F(1, 31) = 24.76$, $p < .001$, MSE = 65, $\eta_p^2 = .444$, $BF_{10} = 6.68 \times 10^{+2}$. The three-way interaction of previous-trial congruency, current-trial congruency, and trial type was marginally significant, $F(1, 31) = 3.92$, $p = .056$, MSE = 34, $\eta_p^2 = .112$, $BF_{10} = 3.40$.

To exclude the effect of repetition priming, the data from task-switching trials and task-repeating trials were separately analyzed using two-way repeated-measures ANOVAs with previous-trial congruency and current-trial congruency as within-subjects variables. On task-repeating trials, the two-way interaction between previous-trial and current-trial congruency was significant, $F(1, 31) = 24.65$, $p < .001$, MSE = 35, $\eta_p^2 = .442$, $BF_{10} = 5.75 \times 10^{+4}$. The magnitude of the Simon effect was smaller after incongruent trials (2 ms) $F(1, 31) = 1.36$, $p = .252$, $BF_{01} = 2.25$, than after congruent trials (12 ms), $F(1, 31) = 41.19$, $p < .001$, MSE = 59, $\eta_p^2 = .570$, $BF_{10} = 2.40 \times 10^{+4}$. Furthermore, the data from task-switching trials also showed that the two-way interaction between previous-trial congruency and current-trial congruency was significant, $F(1, 31) = 9.03$, $p = .005$, MSE = 19, $\eta_p^2 = .225$, $BF_{10} = 5.73$, indicating a significant CSE between the two tasks without the compound of repetition priming (Figure 4). The magnitude of the Simon effect was smaller after incongruent trials (8 ms) $F(1, 31) = 14.28$, $p < .001$, MSE = 78, $\eta_p^2 = .315$, $BF_{10} = 38.64$, than after congruent trials (13 ms), $F(1, 31) = 37.12$, $p < .001$,

MSE = 73, $\eta_p^2 = .544$, $BF_{10} = 1.07 \times 10^{+4}$. A further analysis of three-way repeated measures ANOVA of previous-trial congruency, current-trial congruency, and task as within-subject variables were conducted. The three-way interaction of task with previous-trial congruency and current-trial congruency was not significant $F(1, 31) = 1.04$, $p = .316$, $BF_{01} = 2.58$, indicating no transfer asymmetry.

PE

The main effect of current-trial congruency was significant, $F(1, 31) = 21.33$, $p < .001$, MSE = 9.62, $\eta_p^2 = .407$, $BF_{10} = 332$. The PE was higher on incongruent trials (3.65%) than congruent trials (1.86%). The main effect of trial type was significant, $F(1, 31) = 43.12$, $p < .001$, MSE = 15, $\eta_p^2 = .581$, $BF_{10} = 5.37 \times 10^{+4}$, indicating a significant 3.28% task-switching cost. The interaction of current-trial congruency and trial type was significant, $F(1, 31) = 5.47$, $p = .026$, MSE = 7.23, $\eta_p^2 = .150$, $BF_{10} = 3.04$. The magnitude of the Simon effect was greater on switch trials (2.58%) $F(1, 31) = 13.85$, $p < .001$, MSE = 15.34, $\eta_p^2 = .308$, $BF_{10} = 39.86$, than on repeat trials (1.00%), $F(1, 31) = 21.34$, $p < .001$, MSE = 1.51, $\eta_p^2 = .407$, $BF_{10} = 477$. No other main effect or interaction was significant.

Discussion

The results of Experiment 2 were replicated in the task-switching paradigm. A 97-ms switching cost in the TT data, a 78-ms switching cost in the IT data and an 18-ms switching cost in the MT data were obtained between the horizontal auditory instrument and vertical visual color Simon tasks, implying that the two Simon tasks were unlikely to be represented as a single task-set. Moreover, in the switching trials, while no cross-task CSE was obtained between the two tasks in the IT data, it was transferred across the tasks in the MT data as in the previous experiments. A smaller congruency effect was obtained after the incongruent trials (8 ms) than after the congruent trials (13 ms), indicating that the cognitive control recruited by the conflict of one task modulated the amount of the Simon conflict of the other task. Again, and in line with the studies conducted by Lim and Cho (2021b) and Kim et al. (2015), the control process recruited by response-based conflict relies on the inhibitory control mechanism to modulate the transmission of response activation from spatial codes in the automatic route in order to reduce interference from task-irrelevant spatial information.

In the repeating trials, the congruency effect was sequentially modulated in both the IT and MT data. A smaller congruency effect was obtained after incongruent trials (6 ms in IT and 2 ms in MT) than after the congruent trials (40 ms in IT and 12 ms in MT). Unlike in the switching trials, CSEs were observed in the IT data. Since the presence of CSEs on repeating trials was confounded by repetition priming, these CSEs were possibly caused by the bottom-up stimulus and response feature-repetition priming. In contrast, the CSE obtained in the MT data was evident in both the switching and the repeating trials. Since repetition priming is minimized on switching trials, the presence of the CSE on switching trials possibly reflects top-down cognitive control.

General Discussion

It has been suggested that the sequential modulations of the congruency effect appear to be specific to a particular task-set, which is

flexibly formed based on a salient feature such as sensory modality (Hazeltine et al., 2011; Yang et al., 2017), task predictability (Grant et al., 2020) and task-relevant dimension (Braem et al., 2014). In the present study, three experiments were conducted to investigate whether the cross-task CSE occurs between two tasks when the distinction between them is clear and evident. In Experiment 1, a significant CSE was evident between the auditory horizontal and visual vertical color Simon tasks even though the tasks distinguished by salient stimulus sensory modality were presented in a predictable way. In Experiment 2, when the task-relevant dimensions of the auditory horizontal and visual vertical Simon tasks were different so that the distinction between the auditory and visual tasks was much more salient than in Experiment 1, a significant CSE was still obtained between the two tasks. In Experiment 3, when the two tasks were presented in an AABB sequence, a significant CSE was still observed on the switch trials even though a robust task-switching cost was obtained between them. Inconsistent with the task-set account, these findings indicate that the same control process was recruited across the tasks with different task-sets that were saliently distinguished by sensory modality, predictableness of target modality, and task-relevant stimulus dimension.

Notably, a weaker cross-modality CSE was observed in Experiment 1 than in Experiment 2, which is opposite to the prediction drawn from the task-set hypothesis. The results were possibly due to differences in task difficulty. Since the horizontal and vertical tasks were less saliently distinguished in Experiment 1, participants might have selected one from four response alternatives rather than one from two alternatives. It has been suggested that task difficulty increases with the number of response alternatives (e.g., Hick, 1952). This possibility is partially supported by task confusion rates between the two tasks. Participants inaccurately pressed a directional response key of the other task more frequently in Experiment 1 (10% of the total errors) than in Experiment 2 (7% of the total errors). It has been found that control processes are impaired when task difficulty is high because of the burden of control (Belke et al., 2008; Ditttrich & Stahl, 2012; Lavie, 2005, 2010; Lavie et al., 2004; Schmeichel, 2007).

Previous studies have shown that the control resolution process does not transfer across tasks with different sensory modalities (Grant et al., 2020; Hazeltine et al., 2011; Yang et al., 2017). For example, Hazeltine et al. used prime-probe tasks where both visual and auditory stimuli were arbitrary letters of "A," "B," "C," and "D." When participants were asked to respond to the target and ignore the distractor presented prior to the target, a modality-specific CSE was observed. Similarly, Grant et al. (2020) and Yang et al. (2017) found modality-specific CSEs when they used arbitrary word stimuli. It has been suggested that linguistic materials, including letters and words, are processed and represented in a modality-specific fashion (Booth et al., 2003; Carr & Pollatsek, 1985; Coltheart, 1985; Kurby & Zacks, 2013; Laberge & Samuels, 1974; Petersen et al., 1988; Rumelhart & McClelland 1982). Several word processing theories including the dual coding theory (Paivio, 1986) have suggested that visual and auditory words are processed through separate modality-specific codes, which access to articulatory and semantic stages independently. (Laberge & Samuels, 1974; Paivio, 1986; Rumelhart & McClelland 1982). For example, Petersen et al.'s (1988) positron emission tomography experiment, visually and auditorily presented word stimuli activated modality-specific regions of the brain (extrastriata occipital cortex for visual stimuli and

temporoparietal cortex for auditory stimuli) and no region was activated for both auditory and visual words, which is consistent with the modality-specific codes view of linguistic information. Furthermore, the priming effect was observed to be reduced when the sensory modalities of prime and probe words were altered (auditory to visual or visual to auditory) compared to when they were repeated within the same modality (visual to visual or auditory to auditory; Joyce et al., 1999). Since the previous studies used arbitrary word stimuli with different modalities, a separate set of modality-specific codes was formed in visual and auditory words. Thus, the control mechanisms recruited by conflict in visual and auditory word tasks exert their effects on different task-irrelevant stimulus dimensions, consequently leading to the absence of the CSE across different sensory modalities.

It is noteworthy that Grant et al. (2020) found no cross-sensory modality CSE when the target's sensory modality was predictable in Experiment 1. However, a significant cross-sensory modality CSE was found when the target's sensory modality was unpredictable even though linguistic stimuli were used as distractor and target stimuli in Experiment 2, demonstrating the importance of task-sets in cognitive control involved in the CSE. This finding indicates that a single control mechanism can regulate conflicts between two tasks if the representations of the tasks are indistinguishable. By contrast, the cross-modality CSEs obtained in the present study, in which different task-sets for two tasks could be easily configured based on the predictable sequence of target sensory modality, are inconsistent with the idea that cognitive control is implemented at the level of the whole task-set. Instead, our findings suggest that cognitive control exerts its effect on a specific component within a task-set especially, the place where response conflict causes. Thus, if two tasks share a component of task-sets that is subject to the cognitive control triggered by the response conflict, the CSE can transfer across the tasks even when they are represented as different task-sets.

Response-based conflict, such as Simon conflict, has been well known to be resolved through the inhibition placed on the automatic activation of response codes elicited by the spatial codes for task-irrelevant stimulus spatial dimension (Egner et al., 2007; Soutschek et al., 2013; Stoffels, 1996; Stürmer et al., 2002). According to Stürmer et al., during performing a Simon task, responses are activated through two different parallel routes; One is the slow conditional route in which stimulus codes for goal-related task-relevant information trigger response codes based on a given task rule. The other is the unconditional automatic route, in which spatial codes for stimuli trigger their spatially corresponding response codes (De Jong et al., 1994; Kornblum et al., 1990). When the conditional route and unconditional route activate different responses, the inhibitory control blocks transmission of spatial codes of the unconditional route to the response output after an incongruent trial.

Consistent with this inhibition view, the cross-task CSE was found between the Simon tasks because the two tasks shared a set of spatial codes for stimuli and response modes. Since the spatial codes activate response codes through the unconditional automatic route in the present study, sharing the same set of spatial codes means that the automatic activations of response codes for both tasks occur via the same unconditioned automatic route. Furthermore, as in Lim and Cho's (2021b) experiments, significant CSEs were obtained only in the MT data but not in the IT data. The finding is another evidence supporting that the inhibitory control

recruited by Simon conflict is applied to an unconditional automatic route of response selection to decrease the prompt activation of response codes, which affects the motor programming processing after a response is initiated (Lim & Cho, 2021b).

However, one critical question regarding the inhibition account is whether visual and auditory stimuli share a common set of spatial codes. It has been suggested that the mental representations of space are not formed exclusively through direct perceptual inputs but rather by perceptual spatial information that converges into an amodal symbolic representation (Bollini et al., 2020; Bryant, 1997; Denis & Cocude, 1989; Jackendoff, 1987; Landau & Jackendoff, 1993; Loomis et al., 2013). Bryant (1997) proposed that spatial information is processed separately for each sense, including vision, hearing, and touch, but that the information is combined into a central spatial representation system that provides a common format for inputs with different sensory modalities. The notion is supported by several studies demonstrating that lesions in the parietal cortex and hippocampus, which are related to the encoding of spatial information, produce deficits in spatial performance in tasks involving all sensory modalities (Kritchevsky, 1988). Consistent with this view, although the sensory modalities of the two Simon tasks were different in the present study, both the auditory and visual Simon tasks shared the same automatic route for processing amodal spatial codes. Thus, sharing the same automatic route consequently leads CSEs between them, even if the spatial codes are formed for auditory and visual stimuli.

Importantly, Kreutzfeldt et al. (2016) found a modality-specific CSE whereby participants performed an auditory and visual location judgment task in which the congruency was determined by whether the simultaneously presented visual and auditory stimuli activated the same or different responses. When a cue indicated the target modality, the CSE was present only when the sensory modality was repeated but not when it was switched. However, unlike our experiments, in which the two tasks share the automatic route eliciting response conflict, the task-irrelevant distracting stimulus dimension for one task was the task-relevant stimulus dimension for the other task in Kreutzfeldt et al.'s experiment. Consequently, the inhibitory control on the route through which a distracting stimulus activates its corresponding response on the previous trial might have been weakened to activate the correct response when the task was switched, possibly resulting in no cross-modality CSE.

There are important limitations to the generalizability of our studies (Simons et al., 2017). Participants in the present study were required to produce an uncommon, instructed response to a task-relevant stimulus feature in the presence of task-irrelevant features with strong habitual response associations. Therefore, we expect the results to generalize to situations in which people experience similar situations where task-relevant processing pertains to more novel or weakly established behavior against a well-learned or habitual response to task-irrelevant processing. We also believe that the results will be reproducible with participants from similar subject pools such as young adults who could perform a simple choice task with more than 80% accuracy. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

Conclusion

In the present study, inconsistent with the task-set account, cross-task CSEs were evident between two Simon tasks even when they

were highly distinguished based on their different sensory modalities, different task-rules, and the predictiveness of the target sensory modality. Note that the visual and auditory Simon tasks shared the task-irrelevant dimension and response mode. Thus, as the inhibition account suggests, these findings imply that the control process triggered by Simon conflict is implemented on a component of a task-set, which is the route where spatial codes for task-irrelevant stimulus location automatically activate their spatially corresponding response code, not on the whole task-set.

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