

# Control processes through the suppression of the automatic response activation triggered by task-irrelevant information in the Simon-type tasks<sup>☆</sup>



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## ABSTRACT

The congruency sequence effect, one of the indices of cognitive control, refers to a smaller congruency effect after an incongruent than congruent trial. Although the effect has been found across a variety of conflict tasks, there is not yet agreement on the underlying mechanism. The present study investigated the mechanism underlying cognitive control by using a cross-task paradigm. In Experiments 1, 2, and 3, participants performed a modified Simon task and a spatial Stroop task alternately in a trial-by-trial manner. The task-irrelevant dimension of the two tasks was perceptually and conceptually identical in Experiment 1, whereas it was perceptually different but conceptually identical in Experiment 2. The response sets for both tasks were different in Experiment 3. In Experiment 4, participants performed two Simon tasks with different task-relevant dimensions. In all experiments in which the task-irrelevant dimension and response mode were shared, significant congruency sequence effects were found between the two different congruencies, indicating that Simon-type conflicts were resolved by a control mechanism, which is specific to an abstract task-irrelevant stimulus spatial dimension.

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## 1. Introduction

To successfully perform a given task, performers should select task-relevant information and ignore task-irrelevant information. However, it is impossible to avoid task performance degradation caused by task-irrelevant information. One approach to exploring this degradation is to use congruency tasks such as the Simon, Stroop, and flanker-compatibility tasks. In these tasks, a target display contains both task-relevant and conflicting task-irrelevant information, and task performance is worse when the two types of information activate different versus the same responses (e.g., Kornblum, Hasbroucq, & Osman, 1990; MacLeod, 1991).

Moreover, it has been found that the congruency effect of the current trial varies as a function of congruency in the previous trial (e.g., Gratton, Coles, & Donchin, 1992). For example, Gratton et al. found that the flanker-compatibility effect was smaller when the target was flanked by incongruent distractors in the previous trial than when it was flanked by congruent distractors. This *congruency sequence effect* (also known as

the Gratton effect or conflict-adaptation effect) has been consistently observed in various experimental paradigms, including the Simon task and color and spatial Stroop tasks.

One of the most compelling theories for the congruency sequence effect is *conflict monitoring*, as suggested by Botvinick and colleagues (Botvinick, Braver, Barch, Carter, & Cohen, 2001). According to this theory, control mechanisms are recruited by a conflict monitoring module embedded in the dorsal anterior cingulate cortex (dACC), responding to the occurrence of response conflict, when the conflict monitoring module detects conflict between different responses, each of which is activated by task-relevant information and task-irrelevant information, respectively. It has been suggested that dorsal lateral prefrontal cortex (dLPFC) involves the regulation of the conflict by allocating differently weighted attention (Botvinick et al., 2001), resulting in enhanced processing of task-relevant information (Blais & Verguts, 2012; Egner & Hirsch, 2005; Funes, Lupiáñez, & Humphreys, 2010; Verguts & Notebaert, 2008; Verguts & Notebaert, 2009) and/or suppressed processing of task-irrelevant information (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). Many lines of evidence for this type of the account have been reported (Durstun et al., 2003; Egner & Hirsch, 2005; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000).

Egner and Hirsch (2005) conducted an fMRI study showing that conflict is regulated through cortical amplification of task-relevant information processing. They employed a facial Stroop task in which participants were asked to indicate whether the target stimulus was a politician or an actor. There was a significantly greater BOLD activity

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in the fusiform face area (FFA), which is specialized for face recognition processes (Kanwisher, McDermott, & Chun, 1997), on trials that followed an incongruent trial, but only when the face served as a target. When the face served as a distractor, there was no effect on BOLD activities in FFA. In contrast, Stürmer et al. (2002) found psychophysiological evidence suggesting that conflicts are regulated by suppression of task-irrelevant information in automatic route. They measured the lateralized readiness potential (LRP) when participants were performing a Simon task, and found that the initial incorrect activation on an incongruent trial was modulated by previous-trial congruency. Specifically, the initial incorrect activation on incongruent trial was evident when the previous trial was congruent, while it was reduced when the previous trial was incongruent. From these results, they concluded that automatic activation of task-irrelevant information induces an interference effect in the Simon task, and that this interference is reduced by suppressing the automatic route when conflict is detected in the previous trial.

However, Hommel, Proctor, and Vu (2004) noted that the congruency effect as a function of previous-trial congruency is completely confounded with the effect of feature integration in the conflict task in which both stimulus and response dimensions have only two alternatives. When a stimulus and a response occur in time, the features of the stimulus and response are integrated into a transient representation called *event file*. Because reactivating one feature of the event file activates the other features, performance on the subsequent trials is modulated by it. That is, responses are faster and more accurate when the features of the stimulus and response are either completely repeated or completely alternated in a trial sequence than when they are partial repeated. According to Hommel et al., because all congruent trials just after a congruent trial and all incongruent trials just after an incongruent trial are completely repeated or alternated but all congruent trials after an incongruent trial and all incongruent trials after a congruent trial are partial repeated, the congruency sequence effect occurs. In a similar vein, Mayr, Awh, and Laurey (2003) attributed the congruency sequence effect to the probability of stimulus repetition.

To avoid confounding feature integration or repetition priming and the correspondence between two successive trials, researchers have employed conflict tasks with a larger number of stimulus and response alternatives so that each trial type transition includes an equal proportion of the partial repetition and complete repetition trials (Akçay & Hazeltine, 2007). Other researchers removed exact repetition trials from their analyses (Kerns et al., 2004; Mayr et al., 2003; Ullsperger, Bylsma, & Botvinick, 2005). Although repetition priming clearly contributes to a sequential modulation of the congruency effect (Altmann, 2011), the findings that the congruency sequence effect has been obtained when feature integration or the repetition priming was controlled (Notebaert, Gevers, Verbruggen, & Liefvooghe, 2006; Ullsperger et al., 2005; Verbruggen, Notebaert, Liefvooghe, & Vandierendonck, 2006; Wühr & Ansorge, 2005) indicates that control mechanisms play a great role in the congruency sequence effect.

When the numbers of stimulus and response alternatives increase in order to avoid the confounding effect of the stimulus or response repetition, however, the congruency sequence effect is often confounded with the contingency of a distractor and the correct response (Mordkoff, 2012; Schmidt & De Houwer, 2011). That is, because the numbers of congruent and incongruent trials are equated, a congruent distractor is more frequently associated with the correct response than any other response, resulting in contingency learning. Thus, responses are faster and more accurate on the congruent trials than incongruent trials. Furthermore, Schmidt, Crump, Cheesman, and Besner (2007) showed that the contingency effect is greater after a high contingency trial than a low contingency trial. However, Kim and Cho (2014) and Schmidt and Weissman (2014) found the congruency sequence effect when the confounding effects of feature integration or repetition priming and the contingency between the distractor and correct response were both controlled.

### 1.1. Characteristics of control mechanism

Recently, many researchers have tried to reveal the scope of control and its exact underlying mechanism. Some have reported evidence for a domain-general control mechanism that regulates all types of conflict once it is recruited. For example, Freitas, Bahar, Yang, and Banai (2007) had participants perform horizontal and vertical arrow flanker tasks alternatively in a trial-by-trial manner in Experiment 1, a horizontal or vertical arrow flanker task and a color Stroop task in Experiment 2, and a horizontal or vertical arrow flanker task and a spatial Stroop task in Experiment 3. Significant sequential interactions between the congruency levels of different tasks were found in all experiments, indicating that all conflict was regulated by one domain-general control process.

In contrast, other studies have shown that conflict is modulated by task-specific control mechanisms (Egner, 2007; Egner, Delano, & Hirsch, 2007; Funes et al., 2010; Kiesel, Kunde, & Hoffmann, 2006; Lee & Cho, 2013; Notebaert & Verguts, 2008). For example, a specific control mechanism might be recruited depending on the conflict type involved in the task (Egner et al., 2007; Funes et al., 2010). Egner et al. (2007) suggested that different sources of conflict are regulated by different control mechanisms because they must be regulated in different ways. The conflict of the Simon task is response-based conflict because conflict is induced by the overlap between the irrelevant stimulus dimension and the response dimension, whereas the conflict of the Stroop task is stimulus-based conflict because the conflict is induced by the overlap between the task-relevant and task-irrelevant stimulus information, as well as response-based conflict. In their experiment, participants were to respond to the color of a color word presented to the left or right of fixation, causing Simon conflict between the stimulus and response locations, and Stroop conflict between stimulus color and the meaning of it. They only found sequential modulation of the interference effect only between the same types of conflict but not between different congruencies.

Akçay and Hazeltine (2008) suggested that the domain of control might be determined by how the task is represented. They found sequential modulation of the congruency effect between two different Simon trials in which a red or green target stimulus was presented on the left or right box of either the left or right hemifield on  $n - 1$  trial and in the other hemifield on  $n$  trial, and participants were asked to respond to the stimulus color in either hemifield with the corresponding hand. That is, the same control mechanism was recruited for conflict in both hemifields because the task was represented as a single task, regardless of whether the target was presented in the right or left hemifield. However, when a red or green target was presented in the left or right side of one hemifield and a yellow or blue stimulus was presented in the left or right of the other hemifield, no congruency sequence effect was found between the hemifields. The authors suggested that different local control mechanisms were recruited to resolve conflict occurring in different hemifields because the task was divided into two different subtasks.

However, Akçay and Hazeltine (2008) did not clarify how task representations are structured. In other words, it is difficult to determine whether two tasks are represented as two different subtasks or a single task in a given situation in terms of their task structure concept. A task representation could be defined by sets of stimulus and response alternatives and the rule that binds them together (Rogers & Monsell, 1995). Monsell (2003) also suggested that a task-set is formed based on task instructions. The task-relevant stimulus dimension is important for constructing the mental representation of the task. If the task-relevant stimulus dimension is not shared between any two successive trials, the task representations may be separate.

Notebaert and Verguts (2008) also showed the importance of the task-relevant dimension in control. In their experiment, sequential modulation was obtained between Simon and SNARC (spatial numerical association of response code; Dehaene, Bossini, & Giraux, 1993)

congruencies when the task-relevant dimensions were shared, but not when they differed, between the two tasks. On the basis of these results, Verguts and Notebaert (2009) proposed a different account for the nature of control mechanism, according to which the congruency sequence effect occurs because the associations between task-relevant features and responses are strengthened after response conflict. Thus, as implied by Akçay and Hazeltine's (2008) account, Notebaert and Verguts' associative learning account suggests that control operates on the task-relevant dimension.

However, Funes et al. (2010) found that control is not necessarily exerted on the task-relevant dimension. In their Experiments 1 and 2, in which participants performed two tasks with the identical task-relevant dimension but different conflict types, sequential modulation was absent when the conflict type was alternated. Akçay and Hazeltine (2011) also found no sequential modulation between Simon and flanker congruencies when they had participants perform a four- or five-choice task containing two types of conflict sources. Thus, an alternative possibility is that conflict is modulated differently in terms of the conflict type. Soutschek, Müller, and Schubert (2013) suggested that stimulus-based conflict, such as Stroop and flanker-compatibility effects, is resolved through the amplification of the task-relevant dimension processing while response-based conflict, such as Simon-type effect, is resolved through the suppression of task-irrelevant dimension processing.

Lee and Cho (2013) found further evidence for the idea that local control mechanisms are not specific to the task-relevant stimulus dimension in the Simon-type tasks, such as Simon and spatial Stroop tasks. No congruency sequence effect was found between horizontal and vertical Simon congruencies in their Experiment 1A and between horizontal and vertical spatial Stroop congruencies in Experiment 1B, even though each task pair shared the same source of conflict and task-relevant stimulus dimension. However, a significant congruency sequence effect was obtained when participants were to perform horizontal Simon and spatial Stroop tasks on alternating trials with a single response set, even though the two tasks should be considered as separate tasks according to Rogers and Monsell's (1995) definition, as they had different task rules and different task-relevant dimensions. According to Lee and Cho, sequential modulation occurred between the two different tasks because control triggered by Simon-type conflict exerted on the automatic link between the stages processing the task-irrelevant spatial dimension and its lateralized response mode. Based on these results, Lee and Cho suggested that control mechanisms are specific to task-irrelevant dimensions and response mode in the Simon-type tasks to resolve response-based conflict.

In sum, Akçay and Hazeltine's (2008) and Verguts and Notebaert (2009) accounts imply that cognitive control amplifies the processing of task-relevant stimulus dimensions, whereas Lee and Cho's (2013) account suggests that cognitive control suppresses the automatic processing of conflicting task-irrelevant stimulus dimensions in the Simon-type task. Thus, it is necessary to further explore the mechanisms underlying cognitive control to reveal how domain-specific cognitive control operates. Four experiments were conducted to examine whether the congruency sequence effect in the Simon-type task is in part due to a control mechanism specific to the conflicting task-irrelevant stimulus dimension.

## 1.2. Present study

In Experiments 1, 2, and 3, a Simon task and a spatial Stroop task with the same task-irrelevant stimulus dimension but different task-relevant stimulus dimensions and task rules were performed on alternating trials. The spatial Stroop effect is due to the response-based (Simon-type) conflict between the response codes activated by task-relevant stimulus dimension and task-irrelevant stimulus dimension, like the Simon task, as well as the stimulus-based conflict between the task-relevant and task-irrelevant stimulus dimensions (e.g., Lu &

Proctor, 1995). That is, because interference arises between the irrelevant stimulus location and response location in the spatial Stroop task (Kornblum et al., 1990), the Simon-type conflict is evident in the task. If control triggered by Simon-type conflict relies more on suppressive processes of the task-irrelevant spatial information than facilitatory processes of the task-relevant information, as Lee and Cho (2013) suggested, a congruency sequence effect would occur between the two different task congruencies because the two tasks have the same task-irrelevant stimulus dimension. However, if it relies on facilitatory processes of the task-relevant information, no congruency sequence effect would be evident between them because the two tasks have different task-relevant dimensions. Participants were to respond with the same response set for both tasks in Experiments 1 and 2, and different response sets in Experiment 3. Experiment 1, in which participants performed an arrow version Simon task and an arrow spatial Stroop task alternatively, was intended to examine whether the congruency sequence effect occurs between two Simon-type tasks having different task-relevant dimensions and the same task-irrelevant dimension.

According to Lee and Cho (2013), control triggered by Simon-type conflict suppresses the link between the stages processing the task-irrelevant spatial dimension and response dimension. However, it is unclear whether the cognitive process is sensitive to perceptual or post-perceptual task-irrelevant stimulus feature representations. In Experiment 2, to clarify the locus of the control, participants were to perform a standard Simon task and a spatial Stroop task alternately in a trial-by-trial manner as in Experiment 1. However, unlike Experiment 1, the irrelevant spatial information was the left-right location of a color square in the Simon task, but a leftward or rightward pointing arrow presented at the center of the display in the spatial Stroop task. In other words, the task-irrelevant stimulus dimensions were conceptually identical (left and right) but perceptually different (location vs. arrow pointing) across the two tasks. That is, Experiment 2 was conducted to see whether the congruency sequence effect is obtained between two different Simon-type congruencies without perceptual feature priming between the two tasks.

Experiment 3 was conducted to test whether the congruency sequence effect between the Simon and spatial Stroop congruencies was due to response repetition priming. In Experiment 3, participants were to perform the Simon task with one response set and the spatial Stroop task with another response set to avoid response repetition between two successive trials. To see whether the nature of control triggered by the Simon-type conflict is inhibitory, participants were to perform color and shape Simon tasks with different task-relevant dimensions and response sets in alternating trials in Experiment 4. If control triggered by Simon conflict amplifies the task-relevant feature processing, no congruency sequence effect would occur between the two Simon congruencies. However, if it suppresses the task-irrelevant feature processing, a significant congruency sequence effect would be evident between the two Simon congruencies (see Table 1).

If cognitive control processing triggered by Simon-type conflict in one task is specific to the task-irrelevant dimension, irrespective of the task-relevant stimulus dimension, a significant congruency sequence effect should be obtained between congruency in the two different tasks in all experiments. In addition, if control processes are not limited to the perceptual stage, significant sequential modulation should be found in Experiment 2. However, if the control mechanism is specific to the task-relevant stimulus features, as suggested by Akçay and Hazeltine (2008) and Verguts and Notebaert (2008), Verguts and Notebaert (2009), no congruency sequence effect should be obtained in tasks in all experiments because the task-relevant stimulus features differed between the two tasks.

## 2. Experiment 1

The aim of Experiment 1 was to examine whether the congruency sequence effect occurs between the congruencies of two different

**Table 1**  
Tasks and Response Sets in Experiments 1 to 4.

Experiment	Congruency A			Congruency B			Response sets
	Task	Relevant dimension	Irrelevant dimension	Task	Relevant dimension	Irrelevant dimension	
1	Simon	Color	Arrow	Spatial Stroop	Word	Arrow	Same
2	Simon	Color	Location	Spatial Stroop	Word	Arrow	Same
3	Simon	Color	Location	Spatial Stroop	Word	Location	Different
4	Simon	Color	Location	Simon	Shape	Location	Different

Simon-type tasks sharing the task-irrelevant stimulus dimension and response mode. Participants were asked to perform modified Simon and spatial Stroop tasks alternately in a trial-by-trial manner. In the Simon trials, in which a colored arrow pointing to either the left or right was presented at the center of the stimulus display as a target, they were instructed to respond to the color while ignoring the direction of the arrow. In the spatial Stroop trial, in which a directional word “좌” (left) or “우” (right) superimposed on a white arrow pointing to either the left or right was presented, they were instructed to respond to the meaning of the word while ignoring the direction of the arrow. Participants made left-right keypress responses to the task-relevant information using the same response set in both tasks. It was assumed that conflict would be induced between the responses activated by the task-relevant (color in the Simon task or direction word in the spatial Stroop task) and task-irrelevant (arrow) information. If the control mechanism triggered by Simon conflict is specific to the task-irrelevant conflicting stimulus dimension, there should be significant sequential modulation of the interference effect between the two different congruencies.

## 2.1. Method

### 2.1.1. Participants

Twelve undergraduate students (mean age = 23.5, 6 female) at Korea University participated in exchange for KRW 5000 (about 4 US dollars). All participants were right handed and had normal or corrected-to normal vision and color vision.

### 2.1.2. Stimuli and apparatus

Stimuli were controlled by E-Prime software (version 1.2, Psychology Software Tools, Pittsburgh, PA). Responses were made by pressing the leftmost or rightmost key among five keys on a Micro Experimental Laboratory 2.0 response box with the left and right index finger, respectively.

A white cross ( $L^* = 100, a^* = 0.01, b^* = -0.01; 0.67^\circ \times 0.67^\circ$ ) presented at the center of the display was used for the fixation point. For the spatial Stroop trials, a white arrow ( $1.72^\circ \times 1.43^\circ$ ) pointing to either the left or right was presented at the center of the screen. A black Korean character “좌” (left) or “우” (right;  $0.76^\circ \times 0.76^\circ$ ) was presented inside the arrow. For the Simon trials, a red ( $R = 255, G = 0, B = 0$ ; CIE:  $L^* = 53.23, a^* = 80.11, b^* = 67.22$ ) or green ( $R = 0, G = 255, B = 0$ ;  $L^* = 87.74, a^* = -86.18, b^* = 83.18$ ) arrow pointing to either the left or the right was presented at the center of the screen. Each feature of the task-relevant and task-irrelevant dimensions was equiprobably presented. All stimuli were presented on a black background on a 17-in CRT personal computer monitor and viewed at a distance of 60 cm.

### 2.1.3. Procedure

Participants performed the experiment individually in a dimly lit, soundproof chamber. Participants' body midline and the response box were aligned with the center of the monitor. At the beginning of each trial, the fixation point was presented for 1000 ms followed by a 1000-ms blank display (see Fig. 1). A target stimulus was presented for 250 ms. Spatial Stroop and Simon trials alternated in a trial-by-trial manner. Participants were instructed to respond to the meaning of the directional word on spatial Stroop trials, and the arrow color on Simon

trials within 2000 ms. For the spatial Stroop trial, participants pressed the leftmost button of the response box with their left index finger for the directional word “좌,” and the rightmost button with their right index finger for the directional word “우.” For the Simon trial, half of the participants pressed the leftmost button in response to the red arrow and the rightmost button in response to the green arrow; the other half of participants responded in the opposite way. For each task, half of the trials were congruent and the other half were incongruent. Participants were asked to respond as quickly and accurately as possible. A feedback tone was presented for 500 ms if the response was incorrect, or if no response was made within 2000 ms. There was one practice block of 34 trials and four test blocks of 145 trials. Half the trials were congruent and half were incongruent. There was a 20-s resting period between test blocks.

## 2.2. Results

The first two trials of each block, response times (RTs) shorter than 150 ms and longer than 1250 ms, and following two trials were excluded from data as outliers (4.1%). Moreover, trials with incorrect responses (7.35%) and the two trials following an error trial were removed from the RT data. In total, 17.75% of the trials were excluded from the analyses. Mean correct RTs and percentage of errors (PEs) were calculated for each participant as a function of  $n - 1$  trial congruency (congruent or incongruent), current-trial congruency (congruent or incongruent), and current task (spatial Stroop or Simon). Three-way repeated measures analyses of variance (ANOVAs) were conducted on mean correct RT and PE data with those variables as within-subjects factors (see Table 2).

### 2.2.1. RT

A significant congruency effect was obtained,  $F(1, 11) = 20.91, p = .0008, MSe = 1090, \eta_p^2 = .66$ . Mean RT was shorter for congruent trials ( $M = 472$  ms) than incongruent trials ( $M = 494$  ms). Importantly, the interaction of  $n - 1$  trial congruency and current-trial congruency was significant,  $F(1, 11) = 32.68, p < .0001, MSe = 243, \eta_p^2 = .75$ , indicating that the congruency effect following incongruent trials (9 ms),  $F(1, 11) = 3.93, p = .073, MSe = 487, \eta_p^2 = .26$ , was significantly smaller than the effect following congruent trials (35 ms),  $F(1, 11) = 34.08, p < .0001, MSe = 846, \eta_p^2 = .76$  (see Fig. 2). No other main effects or interactions were significant.

### 2.2.2. PE

The main effect of task was not significant,  $F(1, 11) = 2.85, p = .1194, MSe = 28, \eta_p^2 = .21$ . Although performance tended to be more accurate for congruent (2.29%) than incongruent trials (4.64%), the main effect of current-trial congruency was not significant,  $F(1, 11) = 4.63, p = .0544, MSe = 57, \eta_p^2 = .30$ . However, there was a significant interaction between task and current-trial congruency,  $F(1, 11) = 6.8, p = .0244, MSe = 13, \eta_p^2 = .38$ . The congruency effect in the spatial Stroop task (1.13%),  $F(1, 11) < 1$ , was significantly smaller than the congruency effect in the Simon task (3.38%),  $F(1, 11) = 18.93, p = .0012, MSe = 18, \eta_p^2 = .63$ . In addition, the two-way interaction between current-trial congruency and  $n - 1$  trial congruency was significant,  $F(1, 11) = 34, p = .0001, MSe = 5, \eta_p^2 = .76$ . The congruency effect was 0.44% when  $n - 1$  trial was incongruent,  $F(1, 11) < 1$ , which was significantly smaller



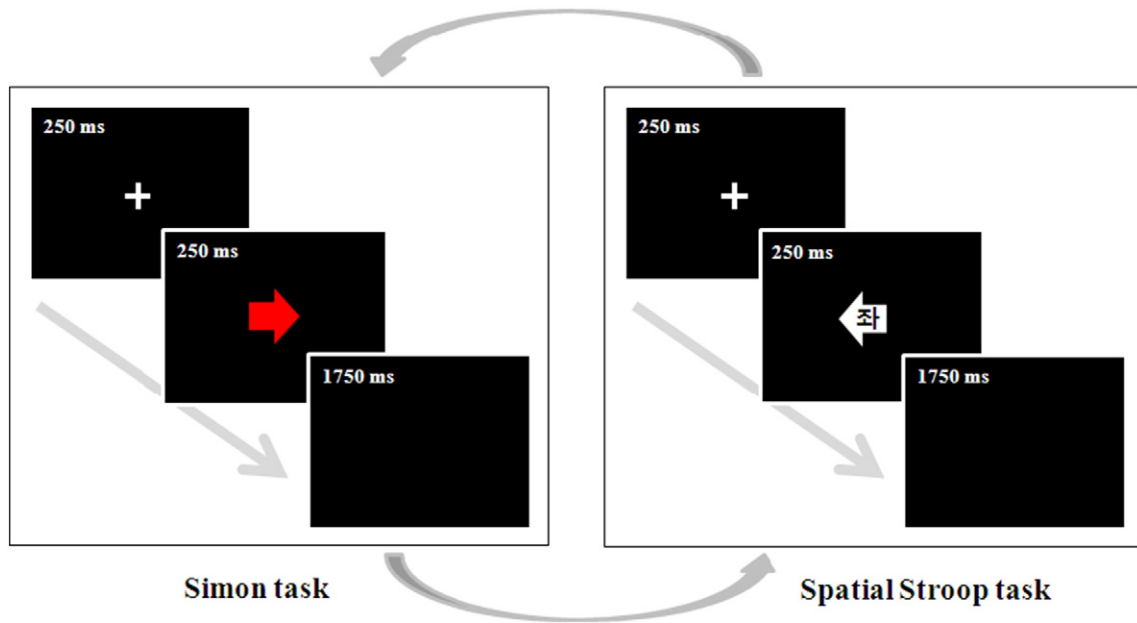


Fig. 1. An example of the trial sequences in Experiment 1.

than the effect of 4.26% obtained when  $n - 1$  trial was congruent,  $F(1, 11) = 24.03, p < .0001, MSe = 18, \eta_p^2 = .52$ . There was no other significant effect.

2.3. Discussion

As in Experiment 3 of Lee and Cho (2013), sequential modulation of the congruency effect was obtained between different Simon-type tasks with different task-relevant stimulus dimensions. A smaller Simon effect was obtained when the previous spatial Stroop trial was incongruent (12 ms and 1.28%) than when it was congruent (34 ms and 6.16%), and a smaller spatial Stroop effect was obtained when the previous Simon trial was incongruent (6 ms and  $-.40\%$ ) than when it was congruent (36 ms and 2.35%). Even though neither the task-relevant dimension nor the task rule was shared between the two tasks, the congruency effect of one task was modulated by the previous congruency of the other task. These results, with Lee and Cho's finding of no congruency sequence effect between two Simon-type congruencies having the same task-relevant dimension, indicate that control in the Simon-type task is specific to conflicting task-irrelevant dimensions. That is, a suppressive control mechanism operates on an automatic route through which the activation caused by task-irrelevant conflicting stimulus information travels to the stage dealing with the processing of a specific response dimension after detecting conflicting. Thus, if two tasks share this route, the congruency effect of one task varies as a function of the previous trial congruency of the other task.

Table 2  
Mean correct RTs (in ms) and PEs in Experiment 1 as a function of current task, current-trial congruency, and  $n - 1$  trial congruency.

Current trial	Previous trial							
	Simon task				Spatial Stroop task			
	n - 1 trial congruent		n - 1 trial incongruent		n - 1 trial congruent		n - 1 trial incongruent	
	RT	PE	RT	PE	RT	PE	RT	PE
Congruent	461	1.42	473	3.08	469	1.84	485	2.82
Incongruent	495	7.58	485	4.36	505	4.19	491	2.42
Effect	34	6.16	12	1.28	36	2.35	6	$-0.40$

3. Experiment 2

The results of Experiment 1 confirmed the hypothesis that control triggered by Simon-type conflict is specific to the conflicting task-irrelevant stimulus dimension in the Simon-type tasks. However, it should be noted that in the experiments showing the congruency sequence effect between the Simon and spatial Stroop congruencies, the task-irrelevant conflicting stimulus dimension (pointing arrow in Experiment 1; spatial location of the target in Experiment 3 of Lee and Cho (2013) was perceptually identical in the two tasks. Thus, one may argue that sequential modulation is specific to the perceptual dimension of the task-irrelevant information. However, it has been suggested that the Simon effect occurs because a spatial stimulus code, which is formed after stimulus identification, automatically activates its corresponding response code (e.g., De Jong, Liang, & Lauber, 1994; Kornblum et al., 1990). Because this spatial stimulus code is abstract in nature (e.g., Hommel, 1998), the Simon effect occurs regardless of whether the stimulus modality is visual or auditory (Lu & Proctor, 1995). In addition, a congruency sequence effect was found between visual and auditory stimulus modalities when participants performed two different prime-probe tasks in a random order (Hazeltine, Lightman, Schwarb, & Schumacher, 2011). Thus, it is expected that control triggered by Simon-type conflict operates on abstract spatial stimulus codes, rather than a specific perceptual dimension.

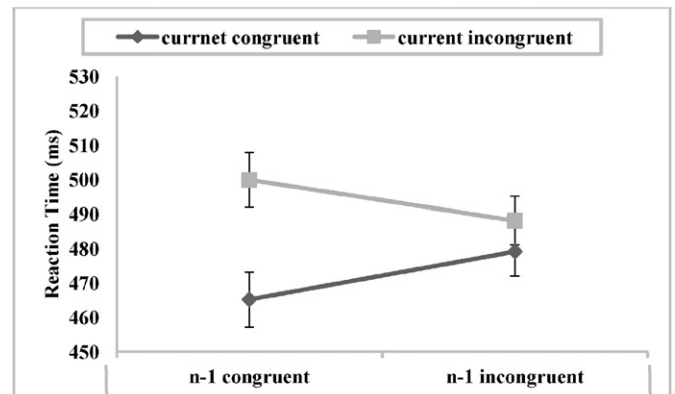


Fig. 2. Mean correct RTs as a function of  $n - 1$  trial congruency in Experiment 1.

The purpose of Experiment 2 was to examine whether control triggered by Simon-type conflict was specific to the perceptual dimension of the task-irrelevant spatial information or post-perceptual spatial stimulus codes. As in Experiment 1, participants were to perform Simon and spatial Stroop tasks alternately in a trial-by-trial manner. However, a color square was presented to the left or right of fixation in the Simon task and a directional word, “좌” (left) or “우” (right), was superimposed on a white arrow pointing to either the left or right in the spatial Stroop task. Even though the stimulus codes activated by task-irrelevant information were identical in both tasks, the task-irrelevant information was perceptually different. If cross-task modulation depends on the post-perceptual task-irrelevant spatial stimulus code, the congruency sequence effect would be evident between the two task-congruencies.

### 3.1. Method

#### 3.1.1. Participants

Twelve new undergraduate students (mean age = 22.8, 6 female, 1 left-handed) at Korea University participated in exchange for KRW 5000 (about 4 US dollars). All participants had normal or corrected-to-normal vision and color vision.

#### 3.1.2. Stimuli and apparatus

Experimental stimuli, apparatus, and procedure were identical to those of Experiment 1, with the following exceptions. For the spatial Stroop trials, a white arrow ( $1.72^\circ \times 1.43^\circ$ ) pointing to either the right or left was presented at the center of the display. A black Korean character, “좌” (left) or “우” (right;  $0.76^\circ \times 0.76^\circ$ ), was presented within the arrows. For the Simon trials, a red or green square ( $1.05^\circ \times 1.05^\circ$ ) was presented to the right or left of fixation. The distance between the target stimulus and fixation was  $2.1^\circ$ . Participants were asked to make a response to the meaning of the target word in the spatial Stroop trials and to the color of the square in the Simon trials.

### 3.2. Results

As in Experiment 1, the first two trials of each block and RTs shorter than 150 ms and longer than 1250 ms were excluded from data as outliers (5.2%). Trials with incorrect responses (9.24%) and two trials following an error trial were removed from the RT data. In total, 21.24% of the trials were excluded from the RT analyses. Mean correct RTs and PEs were calculated for each participant as a function of  $n - 1$  trial congruency (congruent or incongruent), current-trial congruency (congruent or incongruent), and current task (spatial Stroop or Simon). ANOVAs were conducted on mean correct RT and PE data with those variables as within-subject factors (see Table 3).

#### 3.2.1. RT

The main effect of current-trial congruency was significant,  $F(1, 11) = 35.94, p < .0001, MSe = 580, \eta_p^2 = .77$ , indicating a 21-ms congruency effect. This effect was significantly interacted with current task,  $F(1, 11) = 13.17, p = .0040, MSe = 364, \eta_p^2 = .54$ . The size of the

**Table 3**  
Mean correct RTs (in ms) and PEs in experiment 2 as a function of current task, current-trial congruency, and  $n - 1$  trial congruency.

Current trial	Previous trial							
	Simon task				Spatial Stroop task			
	$n - 1$ trial congruent		$n - 1$ trial incongruent		$n - 1$ trial congruent		$n - 1$ trial incongruent	
	RT	PE	RT	PE	RT	PE	RT	PE
Congruent	479	6.04	483	5.83	461	1.19	467	0.83
Incongruent	496	6.31	487	4.42	498	7.73	491	4.35
Effect	17	-0.27	4	-1.41	37	6.54	24	3.52

Simon effect (11 ms),  $F(1, 11) = 4.77, p = .0515, MSe = 590, \eta_p^2 = .30$ , was smaller than that of the spatial Stroop effect (31 ms),  $F(1, 11) = 64.54, p < .0001, MSe = 354, \eta_p^2 = .85$ . Of particular interest, the interaction of  $n - 1$  trial congruency and current-trial congruency was also significant,  $F(1, 11) = 19.84, p = .001, MSe = 91, \eta_p^2 = .64$ . Separate analyses were conducted to examine the effect of current-trial congruency at each level of  $n - 1$  trial congruency. The congruency effect of 15 ms obtained after incongruent trials,  $F(1, 11) = 21.79, p = .0007, MSe = 238, \eta_p^2 = .66$ , was significantly smaller than that of 27 ms obtained after congruent trials,  $F(1, 11) = 40.34, p < .0001, MSe = 433, \eta_p^2 = .79$  (see Fig. 3). There was no other significant effect.

#### 3.2.2. PE

The main effect of current task was significant,  $F(1, 11) = 8.03, p = .0163, MSe = 27, \eta_p^2 = .42$ . PE was 3.48% for the spatial Stroop task and 5.7% for the Simon task. Even though the main effect of current-trial congruency was not significant,  $F(1, 11) = 2.68, p = .1299, MSe = 89, \eta_p^2 = .20$ , the current congruency was significantly interacted with current task,  $F(1, 11) = 5.89, p = .0336, MSe = 64, \eta_p^2 = .35$ . The separate analyses revealed a 5.03% spatial Stroop effect,  $F(1, 11) = 5.25, p = .0428, MSe = 116, \eta_p^2 = .32$ , and a reversed Simon effect ( $-0.58\%$ ),  $F(1, 11) < 1$ .

The interaction between current-trial congruency and  $n - 1$  trial congruency was significant,  $F(1, 11) = 5.87, p = .0338, MSe = 66, \eta_p^2 = .35$ . The congruency effect was smaller on trials following incongruent trials (1.05%),  $F(1, 11) < 1$ , than congruent trials (3.40%),  $F(1, 11) = 4.52, p = .0571, MSe = 61, \eta_p^2 = .29$ . No other term was significant.

### 3.3. Discussion

As in Experiment 1, a significant congruency sequence effect was obtained between the Simon and spatial Stroop congruencies, even though the task-irrelevant information was perceptually different between the two tasks. That is, the Simon effect was larger when the previous spatial Stroop trial was congruent (17 ms) than when it was incongruent (4 ms), and the spatial Stroop effect was larger when the previous Simon trial was congruent (37 ms) than when it was incongruent (24 ms). These results indicate that task-irrelevant stimulus location in Simon trials and arrow direction in spatial Stroop trials were mentally represented using common spatial codes. These spatial stimulus codes automatically activated their corresponding spatial response alternatives (De Jong et al., 1994; Kornblum et al., 1990). Consequently, a control mechanism specific to the dimension of the task-irrelevant stimulus code operated on the automatic activation of conflicting responses from the task-irrelevant spatial stimulus codes, rather than from specific task-irrelevant perceptual information.

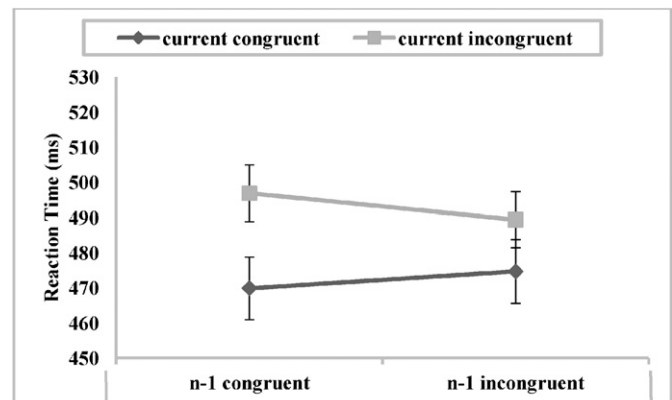


Fig. 3. Mean correct RTs as a function of  $n - 1$  trial congruency in Experiment 2.

### 4. Experiment 3

The results of Experiments 1 and 2 indicate that the control process in the Simon-type task is specific to the task-irrelevant dimension. However, because the same response set was used for both tasks, the congruency sequence effect between the spatial Stroop congruency and the Simon congruency was possibly due to response repetition, as Mayr et al. (2003) and Hommel et al. (2004) suggested. The present experiment was conducted to test this possibility. Participants performed a spatial Stroop task and a Simon task alternatively in a trial-by-trial manner. To eliminate response repetition, different response sets were used for each task. To increase the laterality of response alternatives, participants were to make responses with their index fingers for one task and with their middle fingers for the other task. According to Adam, Hommel, and Umiltà (2003), response alternatives for two tasks are processed distinctively when the response sets for the tasks are separated in terms of a salient feature, such as effector. Thus, even though different response sets were used for each task, the two tasks were assumed to share a single response mode because the two response sets differed in a non-salient feature (Kim & Cho, 2014).

If sequential modulation in the Simon-type task is caused by a control mechanism, which is specific to the automatic route between the stage processing the task-irrelevant conflicting stimulus feature and the stage processing its corresponding response mode, a significant congruency sequence effect should be obtained between the spatial Stroop and Simon congruencies. However, if the effect obtained in Experiments 1 and 2 and Lee and Cho's (2013) Experiment 3 was due to response repetition priming, no congruency sequence effect should be obtained.

#### 4.1. Method

##### 4.1.1. Participants

Sixteen new undergraduate students (mean age = 22.9, 7 male) from the same participant pool as the previous experiments participated.

##### 4.1.2. Stimuli and apparatus

Experimental stimuli, apparatus, and procedure were identical to those of Experiment 2, with the following exceptions. In the Simon task, a red or green square was presented to the left or right of fixation. Half of the participants were asked to respond to the red square by pressing the “f” key and the green square by pressing the “j” key with their left and right middle fingers, respectively. In the spatial Stroop task, a directional word “좌” (left) or “우” (right), written inside a white target square (1.05° × 1.05°), was presented to the left or right of fixation. Responses were made by pressing one of four keys on a standard computer keyboard with the index and middle fingers of both hands. Participants were asked to respond to “좌” by pressing the “g” key and “우” by pressing the “h” key with their index fingers. The other half of participants were to respond with their index fingers in the Simon task and with their middle fingers in the spatial Stroop task. Each trial began with a fixation cross. After 250 ms, the target square was presented for 250 ms. Responses were collected for a maximum of 1750 ms.

#### 4.2. Results

With the same exclusion criteria as in the previous experiments, 7.01% of trials were excluded from data as outliers. Trials with incorrect responses (4.26%) and two trials following an error trial were removed from the RT analyses. In total, 15.83% of the trials were excluded from the analyses. Mean RT and PE were calculated for each participant as a function of task (Simon or spatial Stroop), n – 1 trial congruency (congruent or incongruent), and current-trial congruency (congruent or incongruent). ANOVAs were conducted on mean RT and PE data (see Table 4) with those variables as within-subjects factors.

**Table 4**

Mean reaction time (in ms) and percent error in Experiment 3 as a function of task type, current-trial congruency, and n – 1 trial congruency.

Current trial	Previous trial							
	Simon task				Spatial Stroop task			
	n – 1 trial congruent		n – 1 trial incongruent		n – 1 trial congruent		n – 1 trial incongruent	
	RT	PE	RT	PE	RT	PE	RT	PE
Congruent	603	3.82	611	4.43	548	3.54	558	2.72
Incongruent	626	5.49	622	4.59	585	3.64	579	3.21
Effect	23	1.67	11	.16	37	.10	21	.49

##### 4.2.1. RT

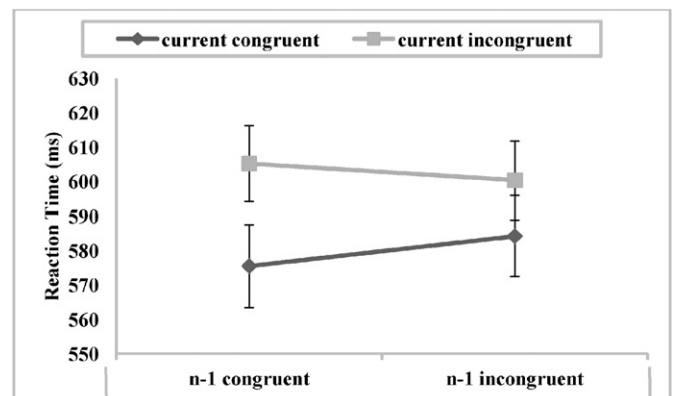
Unlike the previous experiments, the main effect of task type was significant,  $F(1, 15) = 5.60, p = .0318, MSe = 26,106, \eta_p^2 = .27$ . Mean correct RT for the spatial Stroop task was 48 ms faster than the Simon task. The main effect of current-trial congruency was significant,  $F(1, 15) = 18.70, p = .0006, MSe = 1799, \eta_p^2 = .55$ , indicating a congruency effect of 23 ms. Of particular interest, the interaction between current-trial congruency and n – 1 trial congruency was significant,  $F(1, 15) = 12.39, p = .0031, MSe = 238, \eta_p^2 = .45$ , such that the congruency effect was only significant when the n – 1 trial was congruent (29 ms),  $F(1, 15) = 30.88, p < .0001, MSe = 915, \eta_p^2 = .67$ . The congruency effect was not significant when n – 1 trial was incongruent (16 ms),  $F(1, 15) = 7.43, p = .0156, MSe = 1122, \eta_p^2 = .33$  (see Fig. 4). No other term was significant.

##### 4.2.2. PE

The main effect of current-trial congruency was significant,  $F(1, 15) = 5.92, p = .0279, MSe = 3.99, \eta_p^2 = .28$ , indicating a congruency effect of .61%. No other term was significant.

#### 4.3. Discussion

As in Experiments 1 and 2 of the present study and Lee and Cho's (2013) Experiment 3, a significant congruency sequence effect was obtained between the spatial Stroop and Simon congruencies in RTs. The magnitude of the spatial Stroop effect was smaller after a Simon incongruent trial (21 ms) than after a Simon congruent trial (37 ms), and the magnitude of the Simon effect was smaller after a spatial Stroop incongruent trial (11 ms) than after a spatial congruent trial (23 ms). Top-down sequential modulation was obtained without response repetition, replicating Kim and Cho's (2014) findings of a significant congruency sequence effect between two different color-flanker congruencies with different response sets.



**Fig. 4.** Mean RTs depicted as a function of n – 1 trial congruency in Experiment 3.

## 5. Experiment 4

In the previous experiments, significant congruency sequence effects were obtained between the Simon and spatial Stroop congruencies. These results imply that the control process triggered by Simon-type conflict suppressed the automatic activation of spatially corresponding response codes associated with spatial task-irrelevant stimulus features. Experiment 4 aimed to directly examine whether the control process triggered by Simon conflict exerts on the task-irrelevant spatial dimension. To this end, participants were asked to perform a color Simon task with one response set and a shape Simon task with another response set on alternating trials. In the color Simon task, participants were to respond to the color (red or green) of a square presented to the right or left of fixation. In the shape Simon task, they were to respond to the shape of a vertically or horizontally oriented rectangle presented to the right or left of fixation. As in Experiment 3, participants were to respond with their index fingers for one task, and their middle fingers for the other task. The two tasks have the same task-irrelevant dimension and response mode but different task-relevant dimensions. If control triggered by Simon conflict operates through the amplification of the task-relevant feature processing, no congruency sequence effect should be obtained between the two Simon congruencies. However, if it operates through the suppression of the task-irrelevant feature processing, a significant congruency sequence effect should be observed between the two Simon congruencies.

### 5.1. Method

#### 5.1.1. Participants

Twelve new undergraduate students (mean age = 23.3, 5 male) at Korea University participated. All reported normal or corrected-to-normal vision and color vision.

#### 5.1.2. Stimuli and apparatus

The stimuli and apparatus were identical to Experiment 3, with the following exceptions. In the color Simon task, a red ( $R = 255, G = 0, B = 0$ ; CIE:  $L^* = 53.23, a^* = 80.11, b^* = 67.22$ ) or blue ( $R = 0, G = 0, B = 255$ ;  $L^* = 32.30, a^* = 79.20, b^* = -107.86$ ) square ( $1.47^\circ \times 1.47^\circ$ ) was presented  $2.1^\circ$  to the left or right of fixation. Participants were to press the 'g' key in response to the red square and the 'h' key in response to the blue square with the index fingers of the left and right hand, respectively. A shape Simon task was used instead of a spatial Stroop task. In the shape Simon task, a vertical ( $1.47^\circ \times 0.49^\circ$ ) or horizontal ( $0.49^\circ \times 1.47^\circ$ ) white target rectangle was presented to the left or right of fixation. Participants were instructed to press the 'f' key in response to the vertical rectangle and the 'j' key in response to the horizontal rectangle with their left and right middle fingers, respectively.

### 5.2. Results

RTs shorter than 150 ms and longer than 1250 ms were excluded from data as outliers (5.41%). The first two trials of each block, trials with incorrect responses (9.13%), and two trials following an error trial were removed from the RT data. Based on these exclusion criteria, 25.76% of the trials were excluded from the RT analyses. Mean correct RTs and PEs were calculated for each participant as a function of  $n - 1$  trial congruency (congruent or incongruent), current-trial congruency (congruent or incongruent), and task (color Simon or shape Simon). ANOVAs with these variables as within-subjects factors were conducted on mean correct RT and PE data (see Table 5).

#### 5.2.1. RT

The main effect of the current-trial congruency was significant,  $F(1, 11) = 26.45, p < .001, MSe = 765, \eta_p^2 = .071$ , indicating a 20-ms Simon effect. This Simon effect interacted with task,  $F(1, 11) = 10.06,$

**Table 5**

Mean reaction time (in ms) and percent error in Experiment 4 as a function of task type, current-trial congruency, and  $n - 1$  trial congruency.

Current trial	Previous trial							
	Color Simon Task				Shape Simon Task			
	$n - 1$ trial Congruent		$n - 1$ trial Incongruent		$n - 1$ trial Congruent		$n - 1$ trial Incongruent	
	RT	PE	RT	PE	RT	PE	RT	PE
Congruent	531	0.92	537	0.91	532	0.96	544	0.96
Incongruent	552	0.90	542	0.92	572	0.90	561	0.91
Simon Effect	21	0.02	5	-0.01	31	0.06	7	0.05

$p = .0089, MSe = 263, \eta_p^2 = .48$ . The size of the color Simon effect (13 ms),  $F(1, 11) = 12.05, p = .0052, MSe = 342, \eta_p^2 = .52$ , was smaller than that of the shape Simon effect (28 ms),  $F(1, 11) = 27.34, p < .001, MSe = 686, \eta_p^2 = .71$ .

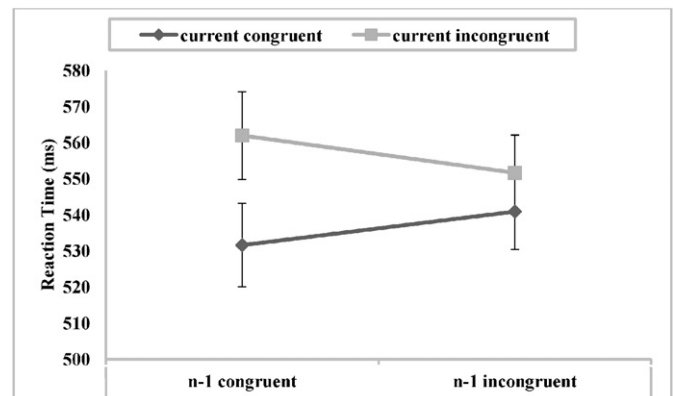
Importantly, the interaction of  $n - 1$  trial congruency and current-trial congruency was significant,  $F(1, 11) = 5.18, p = .044, MSe = 893, \eta_p^2 = .32$ , indicating a congruency sequence effect (see Fig. 5). Further analyses examined how the congruency effect on the current trial was modulated according to congruency on  $n - 1$  trial congruency. The magnitude of the Simon effect was larger after congruent trials (30 ms),  $F(1, 11) = 38.89, p < .001, MSe = 568, \eta_p^2 = .78$ , than incongruent trials (11 ms),  $F(1, 11) = 2.53, p = .14, MSe = 1090, \eta_p^2 = .18$ . No other term was significant.

#### 5.2.2. PE

The main effect of current-trial congruency was significant,  $F(1, 11) = 13.10, p < .001, MSe = 28.28, \eta_p^2 = .054$ , indicating a Simon effect of 2.78%. There was a significant interaction between current-trial congruency and task,  $F(1, 11) = 9.76, p = .0097, MSe = 24.61, \eta_p^2 = .47$ . The magnitude of the Simon effect was larger for the shape Simon task (5.02%),  $F(1, 11) = 21.33, p < .001, MSe = 28.31, \eta_p^2 = .66$ , than the color Simon task (0.54%),  $F(1, 11) = 0.29, p = .6035, MSe = 24.58, \eta_p^2 = .025$ . No other term was significant.

### 5.3. Discussion

The congruency effect of one Simon task was modulated by the other Simon congruency of the previous trial when the two Simon tasks had different task-relevant dimensions but the same task-irrelevant dimension and response mode. The Simon effect was more evident when the previous trial was congruent (30 ms) than when it was incongruent (11 ms). If the control process relies more on target processing, no congruency sequence effect should have been obtained. Moreover, as in Experiment 3, even though there was no response repetition between successive trials, sequential modulation was obtained between the two congruencies. That is, the congruency sequence effect was



**Fig. 5.** Mean RTs depicted as a function of  $n - 1$  trial congruency in Experiment 4.



obtained without any contribution from response repetition. These results imply that control triggered by Simon (or Simon-type) conflict relies on the suppression of the automatic link through which the spatial code for the task-irrelevant stimulus location activates its corresponding spatial response code.

## 6. General discussion

The present study investigated the exact mechanism of cognitive control underlying the congruency sequence effect. As in Lee and Cho's (2013) Experiment 3, significant sequential modulation of the congruency effect, which is an index of cognitive control (e.g., Botvinick et al., 2001; Egner et al., 2007), was found between a modified version of the Simon task and the spatial Stroop task in Experiment 1 when task-irrelevant spatial information was presented in the form of a left-right pointing arrow in both tasks. In addition, a significant congruency sequence effect was found when task-irrelevant stimulus features were conceptually identical but perceptually different between the two tasks in Experiment 2. This is consistent with the hypothesis that control operates on abstract spatial stimulus codes (Hazeltine et al., 2011).

It has been suggested that task-relevant and task-irrelevant features in a congruent task activate responses differently (De Jong et al., 1994; Kornblum et al., 1990). For example, in the standard Simon task, when a target stimulus is presented, the task-irrelevant stimulus feature (location) is transformed into a stimulus spatial code activating its corresponding response in the automatic route, whereas the task-relevant stimulus feature (e.g., color) is processed in the intentional route. Because the control mechanism triggered by Simon-type conflict for one task suppressed the automatic route of the task-irrelevant stimulus spatial codes activating a response, the conflict induced by the task-irrelevant stimulus for the other task was modulated as a function of congruency of the previous trial when the two tasks shared the task-irrelevant stimulus dimension in Experiments 1 and 2.

Similar supporting evidence was found in Experiments 3 and 4. When different response sets were used for different tasks to prevent response repetition, a significant congruency sequence effect was obtained between the Simon and spatial Stroop congruencies in Experiment 3 and between the color and shape Simon congruencies in Experiment 4. These results are inconsistent with the idea that the congruency sequence effect is solely due to stimulus or response repetition priming (Hommel et al., 2004; Mayr et al., 2003). One could argue that 'semantic' feature integration could have contributed to sequential modulation. However, the proportion of partial repetition trials did not vary as a function of previous-trial congruency and current-trial congruency in Experiments 3 and 4. Observing congruency sequence effects between two different types of congruency in the absence of response repetition indicates that a control mechanism triggered by conflict reduced the influence of the task-irrelevant spatial code on response selection in the Simon and spatial Stroop tasks.

In the spatial Stroop task, asymmetry in interference occurs as a function of task-irrelevant (relevant) stimulus dimension and response modality (e.g., Lu & Proctor, 2001; O'Leary & Barber, 1993; Virzi & Egeth, 1985). That is, the spatial Stroop effect occurs when participants are to make a left or right keypress response to the meaning of the word "left" or "right" presented to left or right of fixation, whereas no effect is obtained when they are to say "left" or "right" to it. However, when participants are to make a response to the location of the word, the opposite patterns are found. The asymmetry in the spatial Stroop effect has been attributed to the task-relevant and task-irrelevant stimulus dimensions (the location of the word and the meaning of the word) processed in different systems, each of which is closely linked with the keypress or vocal response mode (Virzi & Egeth, 1985), or the association strength of the task-irrelevant stimulus dimension with response mode relative to that of the task-relevant stimulus dimension with it (Lu & Proctor, 2001). Lu and Proctor (2001) also found that the spatial Stroop effect in response to a word (left or right) presented

inside of a left- or right-pointing arrow with keypress responses was larger than the effect in response to the direction of the pointing arrow. That is, even though the left- or right-pointing arrow is a symbolic stimulus, the direction of the arrow is spatially coded, like the location of a stimulus (e.g., Eimer, 1995). This claim was confirmed by the findings of the spatial Stroop effect when participants made keypress responses to the location of a left- or right-pointing arrow (Shimamura, 1987) and the direction of the arrow (Lupiañez & Funes, 2005).

Thus, in the present study, the spatial Stroop effect occurred because of the strong link of the task-irrelevant word location or arrow direction with the keypress-response mode. It is also important to note that the Simon effect occurred because of this strong link between the task-irrelevant stimulus location or arrow direction and keypress-response mode (e.g., Kornblum et al., 1990; Lu & Proctor, 2001). Accordingly, if the strength of the link between the task-irrelevant stimulus dimension and response mode decreases, the amount of conflict should decrease. The findings of the present study suggests that suppressive control triggered by the Simon-type conflict exerted on the automatic link of the task-irrelevant stimulus dimension with the keypress-response mode to weaken its association after conflict, resulting in a reduced impact of the task-irrelevant spatial information.

### 6.1. Control mechanisms specific to the task-irrelevant stimulus dimension

Many researchers have suggested that task-relevant processing is amplified after conflict (Braem, Verguts, & Notebaert, 2011; Egner & Hirsch, 2005; Egner et al., 2007; Funes et al., 2010; Verguts & Notebaert, 2008; Verguts & Notebaert, 2009). For example, Verguts and Notebaert (2008) included a Hebbian learning mechanism in their model of cognitive control to explain the congruency sequence effect. According to this model, conflict on incongruent trials raises arousal through a neuromodulatory system, and this facilitates the binding of task-relevant stimulus feature and response via a Hebbian learning process, according to the currently activated task-relevant rule. Although Akçay and Hazeltine (2007, 2008) did not explicitly mention that the control mechanism is specific to the task-relevant dimension, the control mechanism should be specific to the task-relevant stimulus dimension if control depends on the structure of the task representation, as they suggested. However, sequential modulation of the congruency effect was repeatedly obtained between the Simon and spatial Stroop tasks that shared the task-irrelevant dimension but not task-relevant dimension and task rule in Experiments 1, 2, and 3. Sequential modulation was evident between two Simon tasks that had different target dimensions in Experiment 4. Moreover, no significant congruency sequence effect was obtained between a color horizontal Simon congruency and a color orthogonal Simon congruency when participants were to perform the two tasks alternatively in a trial-by-trial manner with the same response set (Lee & Cho, 2013). If, for example, the associations of task-relevant stimulus features (color) and responses are strengthened after conflict, as Verguts and Notebaert suggested, no sequential modulation of the congruency effect should have been obtained between the Simon and spatial congruencies and a significant congruency sequence effect should have been obtained between two tasks having the same task-relevant stimulus feature and different task-irrelevant stimulus features. These results imply that the control process involved in the Simon and spatial Stroop tasks is not specific to the task-relevant feature but to the task-irrelevant conflicting stimulus features.

The task-irrelevant dimension-specific control mechanism could operate two ways; inhibition of the task-irrelevant stimulus spatial-code processing after an incongruent trial (Stürmer et al., 2002) and facilitation of it after a congruent trial (Compton, Huber, Levingson, & Zheutlin, 2012). However, most accounts regarding the congruent sequence effect suggest that control operates after detecting conflict. In addition, many researchers have shown that conflict in Simon task trials is resolved by suppressing automatic activation caused by task-irrelevant spatial stimulus codes (e.g., Hommel, 1994; Ridderrinkhof, 2002). This

selective suppression is strategically adjusted to inhibition demands (Hübner & Mishra, 2013). If the congruency sequence effect is due to a control mechanism that resolves conflict within a trial, the sequential modulation between two different types of congruency obtained in the present experiments may be due to a control mechanism that is specific to the task-irrelevant dimension, as Stürmer and colleagues (Stürmer et al., 2002; Stürmer & Leuthold, 2003) suggested. Nonetheless, it is possible that suppressive control was found because of the type of conflict in the Simon and spatial Stroop tasks. The spatial Stroop effect may not just involve stimulus-based conflict between task-relevant and task-irrelevant features, but also response-based conflict between stimulus and response locations. It has been suggested that the control mechanism involved in response-based conflict, such as in the Simon task, is specific to the task-irrelevant stimulus dimension, whereas the control mechanism recruited for stimulus-based conflict, such as in Stroop and flanker tasks, is specific to the task-relevant stimulus dimension (Egner et al., 2007; Soutschek et al., 2013). Schlaghecken and Martini (2012) also suggested that different control operations respond to different types of conflict. According to their context adaptation model, the responsiveness of the visuomotor system adjusts as context of conflict changes, by increasing or decreasing the activation speed and response threshold.

Moreover, Funes et al. (2010) found no congruency sequence effect between the arrow flanker compatibility and spatial Stroop congruency when the two tasks shared task-relevant and task-irrelevant dimensions. They suggested that because the Stroop-type task and the flanker-compatibility task involved fundamentally different types of conflict, different control mechanisms were recruited to resolve each type of conflict (e.g., Magen & Cohen, 2007). That is, the conflict of the flanker-compatibility task is resolved by the control of visual attention, whereas the conflict of the Stroop-like task is resolved by controlling processing of the task-relevant or task-irrelevant dimension. However, even if the domain of control is determined by the source of conflict, the control mechanism should be specific to the task-relevant or task-irrelevant stimulus dimension.

## 6.2. Control mechanisms specific to the response dimension

It was found that the control mechanism is also specific to response mode (Braem et al., 2011; Hazeltine et al., 2011; Kim & Cho, 2014; Lee & Cho, 2013; but also see Schmidt & Weissman, 2014). That is, the congruency sequence effect between two different tasks has only been obtained when the two tasks share the response mode. For example, Lee and Cho found no sequential modulation of the congruency effect between the Simon and spatial Stroop congruency when participants were to respond with one hand for the Simon task and the other hand for the spatial Stroop task in their Experiment 2. Braem et al. (2011) also found no congruency sequence effect when participants performed a vertical Simon task with their hands and a horizontal Simon task with their feet, whereas a significant congruency sequence effect between horizontal and vertical Simon congruencies was obtained when the response sets were shared.

Sequential modulation was evident between two different congruencies when one task was performed with the index fingers and the other task with the middle fingers of the two hand in Experiments 3 and 4, whereas no sequential modulation was obtained between two Simon congruencies when one task was performed with the left hand and the other with the right hand (Akçay & Hazeltine, 2008). Moreover, in Kim and Cho's (2014) experiments, in which participants were to perform two different color flanker-compatibility tasks alternately in a trial-by-trial manner, no sequential modulation between the two congruencies was obtained when one task was performed with one hand and the other task with the other hand, while the congruency effect varied as a function of the previous-trial congruency when the tasks were performed with different fingers of the same hand. When the response sets for two tasks were separated in terms of a salient

feature, such as hand, no congruency sequence effect was obtained between the two tasks. These results imply that a control mechanism biases response activations at a stage where the features defining all response alternatives within a task are being processed. Thus, if two tasks share features that define the response alternatives, the control mechanism triggered by the conflict of one task affects the congruency effect of the other task (Koch, Gade, & Philipp, 2004; Philipp & Koch, 2005).

## 6.3. Conclusion

It has been suggested that the magnitude of the congruency effect is modulated by the association strength of the task-irrelevant stimulus dimension with the response mode relative to that of the task-relevant stimulus dimension with it (Lu & Proctor, 2001). The present study demonstrated that the strength of the association between the task-irrelevant abstract stimulus spatial codes and the response mode decreased after conflict. In other words, the domain of the control mechanism triggered by Simon-type conflict is determined by the conflicting task-irrelevant stimulus dimension and response mode. Although many related issues still require investigation, these results help clarify the mechanism underlying cognitive control, and contribute to building a concrete and comprehensive architecture of cognitive control.

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