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The Congruency Sequence Effect Is Modulated by the Similarity of Conflicts

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The congruence effect can be modulated by adjacent conflict conditions, producing the congruency sequence effect (CSE). However, many boundary conditions prevent the transfer of the cross-conflict CSE. A consensus has been achieved that the CSE reflects both top-down control and bottom-up associative learning, but neither perspective could perfectly interpret the various boundary conditions. Their imperfections recently inspired an integrative learning account of cognitive control, which predicts that conflict similarity affects the magnitude of the cross-conflict CSE. We examined this hypothesis with the spatial Stroop-Simon paradigm by introducing a compound condition containing both the Stroop and Simon components (Experiment 1). The conflict similarity was defined by the degree of component overlap, as manipulated by the polar angle of the target arrow in Experiments 2a and 2b and by the Euclidean distance of the target arrow in Experiments 3a and 3b. Mixed-effect modeling analyses indicated that, in all experiments, the cross-conflict CSEs were positively correlated with the similarity among conflict conditions. Specifically, the compound condition with equal Stroop and Simon components generated comparable CSEs with both the Stroop and Simon conditions (Experiment 1). When the compound condition was more similar to the Stroop than the Simon condition, a trend of a larger CSE was observed between the compound conflict and the Stroop condition than between the compound conflict and the Simon condition, and vice versa (Experiments 2 and 3). Our study revealed that the continuum of the cross-conflict CSE was modulated by conflict similarity, hence supporting the integrative learning account of cognitive control.

Keywords: congruency sequence effect, cognitive control, learning, similarity, transfer

Supplemental materials: https://doi.org/10.1037/xlm0001054.supp

In our daily lives, multiple dimensions of sensory inputs integrate to facilitate information processing. However, conflicts can arise and produce behavioral costs when different dimensions of one object are incongruent with each other. For instance, in the incongruent condition of the Stroop conflict, when judging the color of the word "red" printed in blue, longer reaction times (RTs) are required than in the congruent condition. This phenomenon is usually termed the congruency effect or stimulus-response compatibility (SRC) effect. The cognitive control system is responsible for detecting and resolving such conflicts.

Different Theories of the CSE

The adaptive feature of cognitive control is essential for the ability to flexibly address forthcoming events. This feature is reflected by the widely examined congruency sequence effect (CSE), which is also known as the conflict adaptation (CA)

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phenomenon (Duthoo et al., 2014; Gratton et al., 1992). After an incongruent trial, compared with a congruent trial, the SRC effect in the subsequent trial decreases. This flexible modulation has been consistently observed in many variants of conflict tasks, such as the Eriksen flanker task (Gratton et al., 1992), the Stroop task (Kerns et al., 2004), the Simon task (Kerns, 2006), and the prime-target task (Kunde, 2003).

As proposed by Gratton et al. (1992), the CSE occurs due to the expectancy of congruency repetition; in other words, people expect another incongruent/congruent trial after encountering an incongruent/congruent trial, benefiting conflict processing in congruency-repeated conditions. According to an influential conflict monitoring account, the CSE reflects the adaptation of cognitive control; after a conflict is detected, the conflicting information triggers a higher level of cognitive control and thus facilitates conflict resolution in the subsequent trial (Botvinick et al., 2001). However, evidence has suggested that the CSE could also be attributed to stimulus-based learning or memory processing (Mayr et al., 2003; Weissman et al., 2016); thus, several alternative accounts of the CSE have been proposed, such as the feature-integration account (Hommel et al., 2004), Hebbian learning account (Verguts & Notebaert, 2009), and contingency learning account (Schmidt, 2013); and so forth. According to these accounts, the CSE is merely a bottom-up effect, with no requirement of top-down control. Therefore, the congruency repetition expectation and conflict monitoring accounts are commonly regarded as top-down control-based perspectives, and the other accounts are regarded as bottom-up associative perspectives (Duthoo et al., 2014; Egner, 2014).

The Boundary Conditions of the CSE and Theoretical Controversies

Although a consensus was largely achieved that both the top-down control-based and bottom-up associative perspectives contribute to the occurrence of the CSE (Weissman et al., 2016), controversy continues on whether they could well explain the transferability of the CSE across conflicts. The transferability of the CSE can be examined by combining two conflict conditions in one task (Egner, 2008). If the CSE fails to transfer across the two conflicts, the feature that differs between the two conflicts acts as a boundary condition (Braem et al., 2014). The two perspectives interpret the boundary conditions differently.

The control-based perspectives interpret the boundary condition by dividing cognitive control into different conflict processing loops (Egner, 2008). A successful application of this perspective is the boundary of conflict type (Egner et al., 2007). According to the dimensional overlap structure of conflict paradigms (Kornblum et al., 1990), Stroop and flanker conflicts result from an overlap between task-relevant and task-irrelevant stimulus dimensions, both of which are of the so-called stimulus-stimulus (S-S) type. In contrast, the Simon conflict results from an overlap between task-irrelevant stimuli and response dimensions and thus is of the stimulus-response (S-R) type. Previous studies have found that the CSE can transfer across different conflicts within the S-S type (Freitas et al., 2007; Kleiman et al., 2014), as well as across conflicts within the S-R type (Kim et al., 2015; Kunde & Wuhr, 2006; Notebaert & Verguts, 2008), but not across these two types (Akcay & Hazeltine, 2011; Egner et al., 2007; Forster & Cho, 2014; Verbruggen et al., 2005; Wendt et al., 2006; Wuhr et al., 2015). To interpret the CSE boundary, the control-based accounts evolved from domain-general (Botvinick et al., 2001) to domain-specific (Egner, 2008). Instead of an all-purpose control system, Egner (2008) assumed that each conflict type underlies specific cognitive control subunits.

However, the domain-specific control-based account appears unable to explain all possible boundary conditions. In addition to conflict type, previous studies have revealed other boundary conditions in which the CSE transfers within a domain but not across domains, including sensory modality (Yang et al., 2017) task sets (Grant et al., 2020; Hazeltine et al., 2011), and even task-irrelevant stimulus (Spape & Hommel, 2008). It is possible that future studies could report more boundary conditions of the CSE. According to the control-based domain-specific view, cognitive control should be divided into highly specific mechanisms by these boundary conditions. This view is unlikely to be true because "it would be biologically implausible to assume a large number of preexisting conflict-control loops ready for use" (Abrahamse et al., 2016, p. 697).

Conversely, the associative-based perspectives attribute the occurrence of the CSE to merely the bottom-up feature association (Hommel et al., 2004; Mayr et al., 2003). According to these perspectives, boundary conditions are determined by the alternation of stimuli. However, evidence suggests that the associative factors are neither sufficient nor necessary in determining the boundary condition. For instance, the CSE was found to transfer across flanker and Stroop conflicts even when consecutive trials contained obvious stimulus alternation (Freitas et al., 2007; Freitas & Clark, 2015), suggesting that stimulus-based change might not be the key to the boundary condition of the CSE. Moreover, several studies have reported boundary conditions of the CSE when the feature integration and/or contingency learning confounding was removed (Akcay & Hazeltine, 2011; Grant et al., 2020; Weissman, 2020), which could not be explained by the associative perspectives.

The Integrative Learning Account of Cognitive Control

To resolve the imperfections of the control-based and associative perspectives, an integrative learning account of cognitive control was proposed (Abrahamse et al., 2016; Egner, 2014). Accordingly, the learning process could occur at not only the concrete stimulus level but also the abstract level. Therefore, as an abstract cognitive function, cognitive control could also make trial-by-trial adjustments in the form of learning. In general, different abstract levels of features (including cognitive control) that are simultaneously occurring could be bound into an event file (Frings et al., 2020), favoring the upcoming conflict resolution if some of the contextual features are repeated (Egner, 2014; Weissman et al., 2016). The integrative learning account of cognitive control has two major advantages over the top-down control-based and bottom-up associative-based perspectives. First, this account suggests that cognitive control could be bound with contextual information and show domain-specific features; thus, this account can be used to interpret findings regarding both concrete stimulus boundaries (e.g., Braem et al., 2011; Spape & Hommel, 2008) and the boundary of the CSE after excluding bottom-up learning features (Akcay & Hazeltine, 2011; Grant et al., 2020; Weissman, 2020). Second, the integrative learning account of cognitive control also provides a framework for the prediction of when the CSE transfers and the degree of such transfers. This account predicts that the degree of the CSE varies as a function of representational overlap (Abrahamse et al., 2016). In contrast, the previous top-down domain-general/specific account treated the CSE transfer as a dichotomous index; thus, a consensus could not be reached based on the accumulated evidence for both sides (for a review, see Braem et al., 2014). Although the bottom-up accounts also predict that CSE transfer occurs when there is stimulus/response overlap, these accounts suffered from a very narrow definition of the overlapping components (i.e., concrete features) and could not be used to interpret the observation of CSE transfer across conflicts with very different stimuli (e.g., Freitas & Clark, 2015). To fix this problem, the integrative learning account of cognitive control goes a step further and considers the overlapping representations of not only lower-level features but also higher-level cognitive control representations as contextual cues of CSE transfer.

While the first advantage of the integrative learning account of cognitive control (i.e., interpreting the boundary of the CSE) has been extensively discussed in the previous literature (Abrahamse et al., 2016; Egner, 2014) and further supported by recent studies (Cracco et al., 2020; Ruitenberg et al., 2019), the second advantage (i.e., the prediction of when the CSE transfers and the degree of such transfers) remains a theoretical prediction and requires empirical evidence. As the integrative learning account of cognitive control proposes, generalization should be obtained depending on the extent of feature overlap (Abrahamse et al., 2016). For a conflict-triggered CSE, the most important overlap is the shared cognitive control mechanisms or conflict similarity (Braem et al., 2014). Notably, a previous study compared the CSEs across Stroop, Flanker, and Simon conflicts (Freitas & Clark, 2015) and provided some clues suggesting that conflict similarity modulates the CSE. The authors found a larger CSE across conflicts with greater similarity (i.e., between the Stroop-trajectory and flanker conflicts) than conflicts with less similarity (i.e., between the Stroop-trajectory and Simon conflicts) in the nature of information processing. However, because the experimental designs of the three conflicts differed in many aspects, the definition of similarity among the conflicts might be imprecise. In fact, it is impossible to know the exact similarity between different categories of conflicts. Without a precise definition of similarity, it is impossible to examine how similarity modulates the degree of CSE transfer. One approach to resolving this problem is to parametrically manipulate the overlap of the orthogonal conflict components.

The Present Study

The current study aimed to examine the impact of similarity on the transfer of the CSE. In the classic spatial Simon-Stroop task (Liu et al., 2004), the spatial Stroop conflict is induced by the incompatibility of a vertically oriented arrow and a top/bottom location, and the Simon conflict is induced by a left/right location and a horizontally arranged button response. We modified this task by adding a compound StroopSimon (StSm) conflict condition (e.g., an arrow off horizontal or vertical axes; Experiment 1). This manipulation took advantage of the orthogonality and dissociation of the spatial Stroop and Simon conflicts (Correa et al., 2010; Liu et al., 2010; Luo et al., 2011; Scerrati et al., 2017) and enabled the quantification of the similarity level based on how many overlapping components existed between the StSm conflict and the Stroop or Simon conflicts. For instance, when the StSm contains more vertical components (and fewer horizontal components), it is more similar to the Stroop conflict (and less similar to the Simon conflict). We hypothesized that no CSE would occur between the Simon and Stroop conflicts and that intermediate CSEs would be observed between the StSm and Stroop conflicts and between the StSm and Simon conflicts. We also expected that a full CSE could be detected within the same conflict type. Moreover, we manipulated the similarity level by changing the amount of the Simon/Stroop components through the polar angle (as defined by the directional angle of the stimulus location from the positive *x*-axis) of the arrow location in the StSm condition (Experiments 2a and 2b). We hypothesized that the magnitude of the CSE could be modulated by the level of similarity and that greater between-conflict similarity could generate a larger transfer of the CSE. To test the generalizability, we further manipulated the similarity level by stretching the Euclidian distance (as defined by the distance between the stimulus location and the screen center) of the arrow location along the horizontal (Experiment 3a) and vertical (Experiment 3b) axes while keeping the polar angle of the arrow in the compound conflicts the same as that in Experiment 1. We hypothesized that the magnitude of the CSE could also be modulated by the Euclidian distance.

Experiment 1

Method

Participants

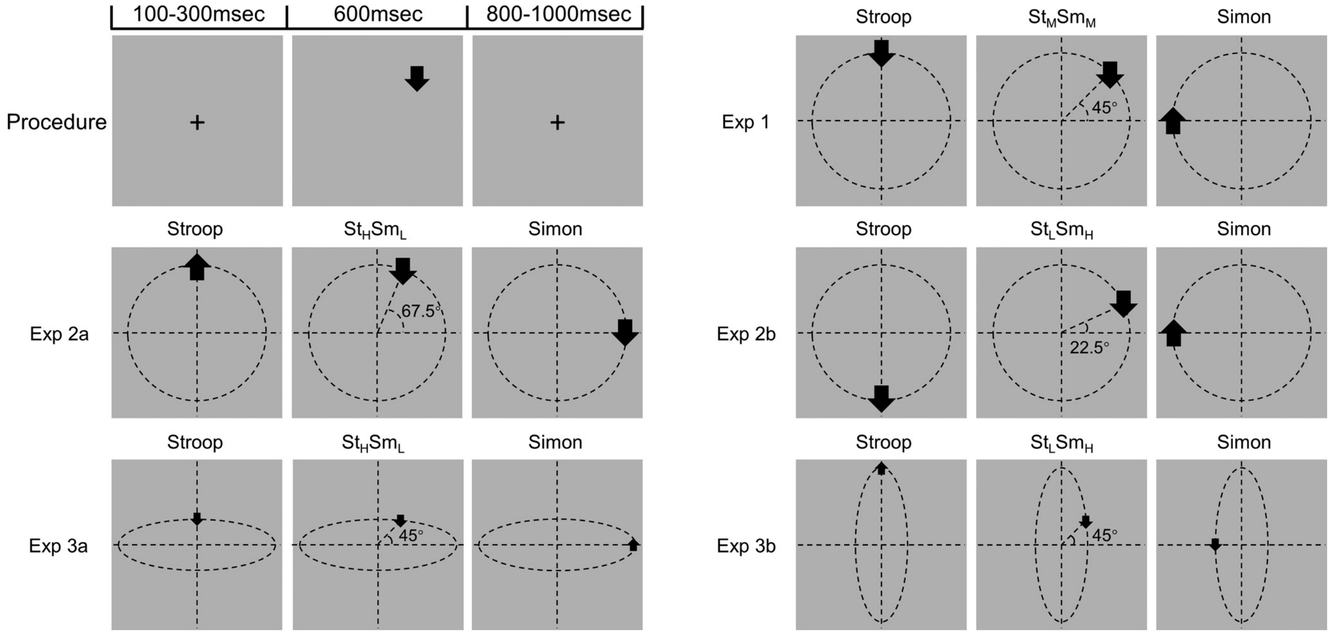
The sample size was estimated using G*Power 3.1 (Faul et al., 2007) with an α of .05 and the effect size (η_p^2) of .16 based on a previous similar study (Freitas & Clark, 2015). It was estimated that we needed 30 participants to achieve 90% power. Therefore, 30 adults participated in Experiment 1 (19−28 years old, average of 22.5 ± 2.4 years old; 13 male). All of the participants were healthy and right-handed, with normal or corrected-to-normal visual acuity, and they signed informed-consent forms before the experiments. The study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Science.

Apparatus, Stimuli, and Procedure

We adopted a modified spatial Stroop-Simon task (Liu et al., 2004) and added a mixed StSm condition (see Figure 1). The stimulus was an upward or downward arrow displayed on a 17-in. LCD monitor at a viewing distance of 57 cm. The arrow appeared in one of six locations inside a square with the same distance from the center, including two horizontal (left and right), two vertical (top and bottom), and two corner (top-right and bottom-left or top-left and bottom-right, depending on the stimulus-response mapping) locations. We excluded the combination of inconsistent congruencies between the Stroop and the Simon conditions (e.g., the $\text{Stroop}_{\text{Congruent}}\text{Simon}_{\text{Incongruent}}$ condition) because the CSEs between these conditions and other “pure” conflict conditions are difficult to interpret, and including these conditions could have increased the required trial numbers. Therefore, the polar angles of the arrows in the StSm condition were 45°-upward arrow/225°-downward arrow (but not 135°-

Figure 1

The Procedure and Stimuli of Experiments 1, 2a, 2b, 3a, and 3b



Note. Each experiment contained three types of conflicts (i.e., Stroop, StSm, and Simon). The stimuli of the Stroop and Simon conflicts were identical in Experiments 1, 2a, and 2b, but those of the StSm conflict differed in the vector angle of the arrow. The sizes of the arrows in Experiments 3a and 3b were the same as those in Experiments 1, 2a, and 2b, but the gray squares were enlarged to display the arrows with longer distances to the center. To fit the whole figure, they are zoomed out. The arrow pointed either upward or downward. Participants were asked to respond with the left button to the downward arrow and the right button to the upward arrow in the schematic conditions displayed here, and the stimulus-response mapping was counterbalanced across the subjects. Dashed lines are shown only to indicate the location of arrows and were not shown in the experiments. St = Stroop; Sm = Simon; M = medium; H = high; L = low.

upward arrow/315°-downward arrow) for half of the subjects, who were instructed to respond to the upward arrow with the right button and the downward arrow with the left button (see Figure 1). The polar angles were 135°-upward arrow/315°-downward arrow (but not 45°-upward arrow/225°-downward arrow) when the stimulus-response mapping was reversed. The arrow could appear in one of the six locations randomly and equiprobably. In addition, to avoid the influence of a priming effect, the arrow in two consecutive trials appeared in different locations. Based on the similarity level with the Simon and Stroop conditions, the StSm condition in Experiment 1 was termed St_MSm_M (where St, M, and Sm are abbreviations for Stroop, medium, and Simon, respectively). Hereafter, we use abbreviations for Stroop and Simon in the mixed condition and consecutive CSE conditions (e.g., Stroop_Simon is referred to as St_Sm).

There were two training sessions to familiarize the participants with the task. The first training session aimed to familiarize the subjects with the stimulus-response correspondence, and during this session, the subjects were asked to respond to the direction of an arrow presented in the center of the screen. Then, another training session was conducted in which the participants were asked to respond to the direction of an arrow presented in one of six locations, which was the same as in the formal test. When 85% accuracy was achieved in both training sessions, the participants began the formal test session.

During the formal test, there were 11 blocks, each containing 109 trials. The trial sequences were pseudorandomly defined to ensure that each consecutive condition contained an equal number of trials (Yang et al., 2017), which also excluded the confounding effect of contingency learning (Schmidt, 2013). In each trial, a fixation was displayed for 100−300 ms; then, the target was presented for 600 ms, followed by another fixation for 800−1,000 ms (see Figure 1). The visual angle of the arrow from the center was approximately 3°. The participants were asked to respond to the direction of the arrow while ignoring its location. The mapping between the arrows and the response buttons was counterbalanced across participants. All of the data can be found at https://osf.io/7x2yp/.

Data Analysis

The RT and error rate (ER) were the major dependent variables. Because we were mainly interested in the CSEs between the St_MSm_M condition and the Stroop condition or Simon condition, the analyses and results of the SRC effects are not shown here but are provided in Part S1 of the online supplemental materials. For the RT, error trials (3.4%), trials with RTs beyond 3 *SD*s or shorter than 200 ms (1.3%), the first trial of each block (.9%), trials after an error (3.3%), and trials with repeated stimuli (49.6%) were excluded before the statistical analysis. For conditions in which the successive conflicts alternated, the number of remaining trials in each cross-conflict

CSE subcondition (CC, CI, IC, II) was between 20 and 40, with a mean of 30. For the conditions in which the successive conflicts were repeated, the number of remaining trials ranged between 33 and 57, with a mean of 44. In the ER analysis, trials with repeated stimuli (49.7%) were excluded. In our two-alternative forced choice (2-AFC) design, each stimulus corresponded to one response; thus, the exclusion of the stimulus-repetition trials also excluded the response-repetition trials. For the dataset with only repeated stimuli and the full dataset with stimulus-repetition, we also performed the same analyses as depicted below, and these results can be found in Parts S2 and S3 of the online supplemental materials.

We combined consecutive conditions with the same conflict pair but different orders (e.g., the St_Sm condition and the Sm_St condition were both termed the St_Sm condition) in the statistical analyses, and we list the CSEs of both orders in Table 1. To reveal the impact of conflict similarity on the CSE, we conducted three-way repeated-measures analyses of variance (ANOVAs) of Consecutive Conflict Type (Repetition [Rep] vs. St_St$_M$Sm$_M$ vs. St$_M$Sm$_M$_Sm vs. St_Sm) × Previous Congruency (Congruent vs. Incongruent) × Current Congruency (Congruent vs. Incongruent). If the three-way interaction was significant, a simple effect analysis was performed to compare the interaction between previous congruency and current congruency (i.e., the CSE) in different conditions (St_Sm vs. St_St$_M$Sm$_M$ vs. St$_M$Sm$_M$_Sm vs. Rep). To achieve this purpose, we conducted a one-way repeated-measures ANOVA of the consecutive conflict type, in which the CSE was calculated as (CI−CC) − (II−IC) (Nieuwenhuis et al., 2006).

Results

CSE

For the RT, we observed significant main effects of consecutive conflict type, $F(3, 87) = 20.94$, $p < .001$, $\eta_p^2 = .42$; previous congruency, $F(1, 29) = 76.87$, $p < .001$, $\eta_p^2 = .73$; and current congruency, $F(1, 29) = 222.25$, $p < .001$, $\eta_p^2 = .89$. We found significant interactions between previous congruency and current congruency, $F(1, 29) = 177.41$, $p < .001$, $\eta_p^2 = .86$, and between current congruency and consecutive conflict type, $F(3, 87) = 3.59$, $p = .017$, $\eta_p^2 = .11$, but not between previous congruency and conflict type, $F(3, 87) = 1.25$, $p = .298$, $\eta_p^2 = .04$. The interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 17.93$, $p < .001$, $\eta_p^2 = .38$. Simple effect analyses revealed significant CSEs in the St_St$_M$Sm$_M$ condition, $F(1, 29) = 37.78$, $p < .001$, $\eta_p^2 = .57$; the St$_M$Sm$_M$_Sm condition, $F(1, 29) = 52.59$, $p < .001$, $\eta_p^2 = .64$; and the repetition condition, $F(1, 29) = 135.96$, $p < .001$, $\eta_p^2 = .82$, but no significant CSE in the St_Sm condition, $F(1, 29) = 3.00$, $p = .094$, $\eta_p^2 = .09$.

For the ER, we observed significant main effects of current congruency, $F(1, 29) = 21.80$, $p < .001$, $\eta_p^2 = .43$, and consecutive conflict type, $F(3, 87) = 8.33$, $p < .001$, $\eta_p^2 = .22$, and significant interactions between previous congruency and current congruency, $F(1, 29) = 35.50$, $p < .001$, $\eta_p^2 = .55$, and previous congruency and consecutive conflict type, $F(3, 87) = 4.46$, $p = .006$, $\eta_p^2 = .13$. The interaction among consecutive conflict type, previous congruency, and current congruency was also significant, $F(3, 87) = 7.05$, $p < .001$, $\eta_p^2 = .20$. Simple effect analyses showed significant CSEs in

Table 1
Mean CSEs in the Reaction Time (ms) and the Error Rate (%) in Experiments 1–3

		Trial *n*					
		RT (ms)			ER (%)		
Experiment	Trial *n* − 1	St	St$_M$Sm$_M$	Sm	St	St$_M$Sm$_M$	Sm
Exp.1	St	43 (32)	31 (24)	0 (33)	8.4 (8.8)	2.2 (9.0)	−0.4 (8.8)
	St$_M$Sm$_M$	17 (32)	41 (33)	24 (22)	5 (7.8)	10.1 (14.8)	2.7 (9.1)
	Sm	12 (22)	24 (26)	40 (30)	1.9 (10.2)	1.1 (9.5)	5.6 (12.3)
		St	St$_H$Sm$_L$	Sm	St	St$_H$Sm$_L$	Sm
Exp.2a	St	37 (42)	37 (31)	−4 (32)	8.8 (12.8)	4.6 (13.1)	0.7 (10.5)
	St$_H$Sm$_L$	29 (36)	34 (35)	11 (32)	0.6 (9.8)	6 (10.8)	1.6 (9.1)
	Sm	3 (29)	16 (35)	49 (40)	0.1 (7.7)	−0.4 (7.0)	6.1 (9.5)
		St	St$_L$Sm$_H$	Sm	St	St$_L$Sm$_H$	Sm
Exp.2b	St	35 (41)	10 (42)	7 (31)	9.2 (11.1)	3.3 (9.2)	1.6 (10.5)
	St$_L$Sm$_H$	2 (37)	52 (40)	42 (30)	2.2 (10.2)	10.8 (11.2)	5.8 (8.8)
	Sm	5 (36)	34 (36)	61 (46)	2.2 (7.5)	9.5 (14.0)	13.8 (14.4)
		St	St$_H$Sm$_L$	Sm	St	St$_H$Sm$_L$	Sm
Exp.3a	St	29 (27)	22 (28)	1 (38)	6.2 (11.2)	0.3 (11.4)	1.6 (8.6)
	St$_H$Sm$_L$	19 (29)	27 (43)	15 (31)	3.5 (8.2)	7.3 (8.6)	4.6 (9.1)
	Sm	8 (32)	12 (26)	46 (39)	2.4 (7.4)	0.7 (9.5)	8 (10.2)
		St	St$_L$Sm$_H$	Sm	St	St$_L$Sm$_H$	Sm
Exp.3b	St	56 (44)	23 (40)	5 (39)	10.3 (14.3)	3.6 (8.8)	−3.4 (12.3)
	St$_L$Sm$_H$	25 (33)	35 (40)	28 (38)	5.4 (9.4)	12.6 (13.4)	2.7 (12.6)
	Sm	7 (37)	29 (38)	49 (42)	1.1 (7.1)	5.8 (12.5)	10.8 (17.8)

Note. St = Stroop; Sm = Simon; M = medium; H = high; L = low; CSE = congruency sequence effect. The standard error of the mean is shown in parentheses.

the repetition condition, $F(1, 29) = 33.40$, $p < .001$, $\eta_p^2 = .56$, and the St_St$_M$Sm$_M$ condition, $F(1, 29) = 11.36$, $p = .002$, $\eta_p^2 = .33$, but not in either the St$_M$Sm$_M$_Sm condition, $F(1, 29) = 1.39$, $p = .250$, $\eta_p^2 = .00$, or the St_Sm condition, $F(1, 29) = .74$, $p = .400$, $\eta_p^2 = .00$. No other main effects or interactions were observed.

Comparison of CSEs

For the RT, the effect of consecutive conflict type was significant, $F(3, 87) = 17.93$, $p < .001$, $\eta_p^2 = .38$. Pairwise comparisons showed that the CSE of the repetition condition (42 ms) was significantly larger than the St_Sm (6 ms, $M_{diff} = 36.0$ ms, 95% CI [22.2, 49.8], Cohen's $d = 1.86$, $p < .001$), the St$_M$Sm$_M$_Sm (21 ms, $M_{diff} = 20.7$ ms, 95% CI [6.9, 34.6], Cohen's $d = 1.15$, $p < .001$), and the St_St$_M$Sm$_M$ (24 ms, $M_{diff} = 18.0$ ms, 95% CI [2.4, 33.5], Cohen's $d = .87$, $p = .017$) conditions. In addition, the CSE of the St_Sm condition (6 ms) was significantly smaller than the St_St$_M$Sm$_M$ (24 ms, $M_{diff} = -18.0$ ms, 95% CI [−32.2, −3.8], Cohen's $d = -.89$, $p = .007$), and the St$_M$Sm$_M$_Sm (21 ms, $M_{diff} = -15.2$ ms, 95% CI [−28.8, −1.7], Cohen's $d = -.87$, $p = .020$) conditions. More importantly, there was no significant difference in the CSE between the St_St$_M$Sm$_M$ condition (24 ms) and the St$_M$Sm$_M$_Sm condition (21 ms, $M_{diff} = 2.8$ ms, 95% CI [−9.9, 15.4], Cohen's $d = .15$, $p = 1.000$; see Figure 2).

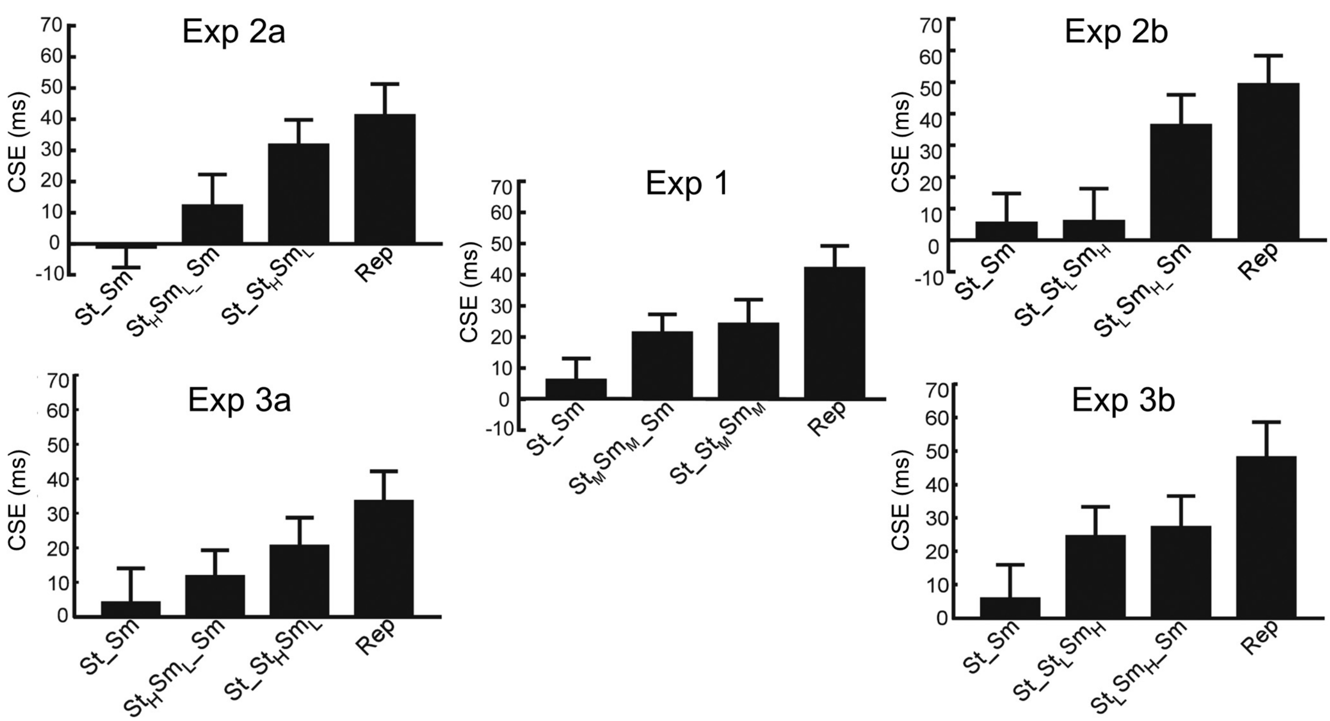
For the ER, the effect of consecutive conflict type was significant, $F(3, 87) = 7.05$, $p < .001$, $\eta_p^2 = .20$. Pairwise comparisons revealed that the CSE of the repetition condition (8.1%) was larger than the St$_M$Sm$_M$_Sm condition (1.5%, $M_{diff} = 6.6\%$, 95% CI [1.1%, 12.2%], Cohen's $d = .90$, $p = .013$), and the St_Sm condition (1.0%, $M_{diff} = 7.2\%$, 95% CI [2.1%, 12.3%], Cohen's $d = 1.04$, $p = .002$). No other significant differences were found.

Discussion

The results of Experiment 1 showed that the cross-conflict CSE appeared when there was an overlap between two conflicts, consistent with the integrative learning account of cognitive control, which predicts that similarity modulates the CSE. Specifically, we found that the CSE could transfer between the compound conflict (containing both the Stroop and Simon components) and the Stroop condition as well as between the compound conflict and the Simon condition. According to the dimensional overlap structure (Kornblum et al., 1990), the StSm condition here belongs to Type 8, which contains both S-S and S-R conflicts. Liu et al. (2010) found that the SRC effect of such a compound condition showed additive processing of S-S and S-R conflicts. Therefore, the bidirectional CSEs could be attributed to the shared components (or similarity) under the StSm condition and the Stroop or Simon condition. Importantly, the CSEs across these shared components should not be treated as the within-conflict CSEs because, during the experiment, no visible axes were shown, and the stimuli in the compound condition could only be represented as a holistic conflict, rather than dissociated combinations of the Stroop and Simon components. Moreover, the inclusion of orthogonal conflict components also introduced dissimilarity between the compound condition and the pure Stroop or Simon condition.

To better determine the parametrical modulation of similarity on the CSE, we conducted Experiments 2a and 2b, in which the polar angle of the arrow location was shifted 22.5° toward the Stroop or Simon condition, respectively.

Figure 2
Cross-Conflict CSEs in Experiments 1–3



Note. Error bars indicate 95% confidence intervals. St = Stroop; Sm = Simon; M = medium; H = high; L = low; Rep = repetition; CSE = congruency sequence effect.

Experiment 2a

Method

Participants

A new sample of 30 adults participated in Experiment 2a (19–28 years old, average of 22.3 ± 2.7 years old; 13 male). All of the participants were healthy and right-handed, with normal or corrected-to-normal visual acuity.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedure were the same as those in Experiment 1, except that the polar angles of the arrows in the StSm condition were 67.5°/247.5° or 112.5°/292.5°, according to the stimulus-response mapping (see Figure 1). Based on the similarity level with the Stroop and Simon conditions, the StSm condition in Experiment 2a was termed St_HSm_L (where H and L are abbreviations of high and low, respectively).

Data Analysis

The data analysis procedures were the same as those described in Experiment 1. Before the statistical analysis, error trials (3.6%), trials with an RT beyond three *SD*s or shorter than 200 ms (1.4%), the first trial of each block (.9%), trials after an error (3.2%), and trials with repeated responses (49.6%) were excluded. For conditions in which the successive conflicts alternated, the number of remaining trials in each cross-conflict CSE subcondition (CC, CI, IC, and II) ranged between 20 and 40, with a mean of 30. For conditions in which the successive conflicts repeated, the number of remaining trials ranged between 33 and 57, with a mean of 44.

Results

CSE

The RT results showed that there were significant main effects of consecutive conflict type, $F(3, 87) = 32.02$, $p < .001$, $\eta_p^2 = .53$; previous congruency, $F(1, 29) = 131.73$, $p < .001$, $\eta_p^2 = .82$; and current congruency, $F(1, 29) = 206.50$, $p < .001$, $\eta_p^2 = .88$, and a significant interaction between previous congruency and current congruency, $F(1, 29) = 70.36$, $p < .001$, $\eta_p^2 = .71$. In addition, the interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 21.30$, $p < .001$, $\eta_p^2 = .42$. Simple effect analyses revealed significant CSEs in the St_St_HSm_L condition, $F(1, 29) = 63.98$, $\eta_p^2 = .56$, $p < .001$, the St_HSm_L_Sm condition, $F(1, 29) = 5.88$, $p = .022$, $\eta_p^2 = .17$, and the repetition condition, $F(1, 29) = 67.82$, $p < .001$, $\eta_p^2 = .70$, suggesting that in these conditions, the SRC effect was smaller after incongruent trials than after congruent trials. There was no significant CSE in the St_Sm condition, $F(1, 29) = .10$, $p = .756$, $\eta_p^2 = .00$. No other interactions were observed.

For the ER, we observed significant main effects of consecutive conflict type, $F(3, 87) = 9.08$, $p < .001$, $\eta_p^2 = .24$, and current congruency, $F(1, 29) = 53.31$, $p < .001$, $\eta_p^2 = .65$, and an interaction between previous congruency and current congruency, $F(1, 29) = 11.62$, $p = .002$, $\eta_p^2 = .29$. In addition, the interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 8.55$, $p < .001$, $\eta_p^2 = .23$. Furthermore, simple effect analyses showed a significant CSE in the repetition condition, $F(1, 29) = 23.96$, $p < .001$, $\eta_p^2 = .44$, but not in other conditions (*ps* > .05). No other main effects or interactions were observed.

Comparison of CSEs

The RT results showed that the effect of consecutive conflict type was significant, $F(3, 87) = 21.30$, $p < .001$, $\eta_p^2 = .42$. Post hoc pairwise comparisons showed that the CSE of the repetition condition (41 ms) was significantly larger than the St_Sm (−1 ms, $M_{diff} = 42.1$ ms, 95% CI [23.4, 60.7], Cohen's $d = 1.83$, $p < .001$), and the St_HSm_L_Sm (12 ms, $M_{diff} = 29.0$ ms, 95% CI [11.8, 46.2], Cohen's $d = 1.06$, $p < .001$) conditions. Moreover, the CSE of the St_St_HSm_L condition (32 ms) was larger than the St_HSm_L_Sm condition (12 ms, $M_{diff} = 19.6$ ms, 95% CI [3.1, 36.0], Cohen's $d = .80$, $p = .013$), and the St_Sm (−1 ms, $M_{diff} = 32.7$ ms, 95% CI [20.1, 45.2], Cohen's $d = 1.65$, $p < .001$). No other significant effects were found (see Figure 2).

For the ER, the effect of consecutive conflict type was significant, $F(3, 87) = 8.56$, $p < .001$, $\eta_p^2 = .23$. Pairwise comparisons showed that the CSE of the repetition condition (7.3%) was significantly larger than the St_St_HSm_L condition (2.5%, $M_{diff} = 4.7\%$, 95% CI [.2%, 9.3%], Cohen's $d = .60$, $p = .039$); the St_HSm_L_Sm condition (.5%, $M_{diff} = 6.7\%$, 95% CI [1.9%, 11.6%], Cohen's $d = .97$, $p = .003$); and the St_Sm condition (.4%, $M_{diff} = 6.9\%$, 95% CI [2.2%, 11.6%], Cohen's $d = 1.01$, $p = .002$). No other differences were found.

Experiment 2b

Method

Participants

A new sample of 30 adults participated in Experiment 2b (19–28 years old, average of 21.6 ± 2.2 years old; 12 male). All of the participants were healthy and right-handed, with normal or corrected-to-normal visual acuity.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedures in this experiment were the same as those described in Experiments 1 and 2a, except that the polar angles of the arrows in the StSm condition were 22.5°/202.5° or 157.5°/337.5° according to the stimulus-response mapping (see Figure 1). Based on the similarity level in the Simon and Stroop conditions, the StSm condition in Experiment 2b was termed St_LSm_H (where H indicates high, and L indicates low).

Data Analysis

The data analysis procedures were the same as those described in Experiment 1. In the RT analysis, error trials (4.0%), trials with RTs beyond 3 *SD*s or shorter than 200 ms (1.3%), the first trial of each block (.9%), trials after an error (3.7%), and trials with repeated responses (49.6%) were excluded. For conditions in which the successive conflicts alternated, the number of remaining trials in each cross-conflict CSE subcondition (CC, CI, IC, and II) ranged between 20 and 40, with a mean of 30. For conditions in which the successive conflicts repeated, the number of remaining trials ranged between 29 and 58, with a mean of 45.

Results

CSE

For the RT, we observed significant main effects of consecutive conflict type, $F(3, 87) = 23.22$, $p < .001$, $\eta_p^2 = .45$; previous congruency, $F(1, 29) = 50.10$, $p < .001$, $\eta_p^2 = .63$; and current congruency, $F(1, 29) = 158.08$, $p < .001$, $\eta_p^2 = .85$; and a significant interaction between previous congruency and current congruency, $F(1, 29) = 80.78$, $p < .001$, $\eta_p^2 = .74$. In addition, the interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 23.57$, $p < .001$, $\eta_p^2 = .45$. Simple effect analyses revealed significant CSEs in the St_LSm_H_Sm condition, $F(1, 29) = 58.03$, $p < .001$, $\eta_p^2 = .67$, and the repetition condition, $F(1, 29) = 119.11$, $p < .001$, $\eta_p^2 = .80$, but no significant CSE in the St_St_LSm_H condition, $F(1, 29) = 1.27$, $p = .268$, $\eta_p^2 = .04$, or the St_Sm condition, $F(1, 29) = 1.27$, $p = .270$, $\eta_p^2 = .04$. No other interactions were observed.

The ER results showed that there were significant main effects of consecutive conflict type, $F(3, 87) = 10.97$, $p < .001$, $\eta_p^2 = .27$, and current congruency, $F(1, 29) = 42.54$, $p < .001$, $\eta_p^2 = .60$, and a significant interaction between previous congruency and current congruency, $F(1, 29) = 37.76$, $p < .001$, $\eta_p^2 = .57$. In addition, the interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 15.19$, $p < .001$, $\eta_p^2 = .34$. Simple effect analyses revealed significant CSEs in the repetition condition, $F(1, 29) = 48.05$, $p < .001$, $\eta_p^2 = .63$; the St_LSm_H_Sm condition, $F(1, 29) = 20.92$, $p < .001$, $\eta_p^2 = .44$; and the St_St_LSm_H condition, $F(1, 29) = 5.43$, $p = .027$, $\eta_p^2 = .25$, but no significant CSE in the St_Sm condition, $F(1, 29) = 3.70$, $p = .064$, $\eta_p^2 = .00$. No other main effects or interactions were observed.

Comparison of CSEs

The RT results showed that the effect of consecutive conflict type was significant, $F(3, 87) = 23.57$, $p < .001$, $\eta_p^2 = .45$. Pairwise comparisons showed that the CSE of the repetition condition (49 ms) was significantly larger than that of the St_Sm (5 ms, $M_{diff} = 43.9$ ms, 95% CI [26.9, 60.9], Cohen's $d = 1.75$, $p < .001$), and the St_St_LSm_H conditions (6 ms, $M_{diff} = 43.3$ ms, 95% CI [24.4, 62.3], Cohen's $d = 1.64$, $p < .001$). In addition, the CSE of the St_LSm_H_Sm condition (36 ms) was significantly larger than the St_St_LSm_H (6 ms, $M_{diff} = 30.5$ ms, 95% CI [12.9, 48.0], Cohen's $d = 1.12$), and the St_Sm (5 ms, $M_{diff} = 31.0$ ms, 95% CI [10.8, 51.3], Cohen's $d = 1.20$) conditions, $ps < .001$. There was no significant difference in the CSE between the repetition condition (49 ms) and the St_LSm_H_Sm condition (36 ms, $M_{diff} = 12.9$ ms, 95% CI [−2.0, 27.8], Cohen's $d = .51$, $p = .124$), or between the St_Sm (5 ms) condition and the St_St_LSm_H condition (6 ms, $M_{diff} = −.6$ ms, 95% CI −-20.7, 19.5], Cohen's $d = −.02$, $p = 1.000$; see Figure 2).

For the ER, the main effect of the consecutive conflict type was significant, $F(3, 87) = 15.19$, $p < .001$ $\eta_p^2 = .34$. Pairwise comparisons showed that the effect in the repetition condition (11.4%) was larger than the St_LSm_H_Sm condition (7.0%, $M_{diff} = 4.3\%$, 95% CI [.1%, 8.6%], Cohen's $d = .50$, $p = .041$); the St_St_LSm_H condition (2.6%, $M_{diff} = 8.8\%$, 95% CI [3.8%, 13.8%], Cohen's $d = 1.14$, $p < .001$); and the St_Sm condition (1.9%, $M_{diff} = 9.5\%$, 95% CI [4.7%, 14.3%], Cohen's $d = 1.28$, $p < .001$). In addition, the CSE of the St_LSm_H_Sm condition (7.0%) was larger than the St_Sm condition (1.9%, $M_{diff} = 5.1\%$, 95% CI [.3%, 10.0%], Cohen's $d = .73$, $p = .031$). No other differences were found.

Discussion of Experiments 2a and 2b

In Experiments 2a and 2b, we examined cross-conflict CSEs by manipulating two types of compound conflicts with different similarity levels to the Stroop and Simon conditions. The results replicated the findings in Experiment 1 and further support that the magnitude of the cross-conflict CSE is modulated by the similarity between conflicts (Abrahamse et al., 2016; Braem et al., 2011).

In Experiments 2a and 2b, the similarity was defined as the ratio of shared conflict components, computed as the projection of the StSm condition onto the vertical or horizontal axes, divided by the Stroop or Simon condition, respectively. In accordance with this idea, the similarity could also be adjusted by altering the Stroop or Simon condition (i.e., the denominator). Thus, the Euclidian distance from the screen center to the target arrows in the Simon or Stroop condition was manipulated in Experiments 3a and 3b, respectively, while the polar angles of the arrows in the compound conflicts remained the same as those in Experiment 1.

Experiment 3a

Method

Participants

A new sample of 30 adults participated in Experiment 3a (19−28 years old, average of 22.8 ± 2.2 years old; 16 male). All of the participants were healthy and right-handed, with normal or corrected-to-normal visual acuity.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedures were similar to those described in Experiment 1 with the following changes (see Figure 1). The Euclidian distance between the stimulus and the origin in the Simon condition was three times greater than that of the Simon condition in Experiment 1. Another slight difference was that the arrow in the StSm condition was located on an ellipse passing the location of the arrows in the Stroop and Simon conditions. Based on the ratio of component overlap, StSm was termed St_HSm_L, consistent with Experiment 2a.

Data Analysis

The data analysis procedures were the same as those described in Experiment 1. In the RT analysis, error trials (3.6%), trials with RTs beyond 3 *SD*s or shorter than 200 ms (1.8%), the first trial of each block (.9%), trials after an error (3.6%), and trials with repeated responses (49.6%) were excluded. For conditions in which the successive conflicts alternated, the number of remaining trials for each cross-conflict CSE subcondition (CC, CI, IC, and II) ranged between 17 and 40, with a mean of 30. For conditions in which the successive conflicts repeated, the number of remaining trials ranged between 27 and 58, with a mean of 45.

Results

CSE

The RT results showed that there were significant main effects of consecutive conflict type, $F(3, 87) = 27.23$, $p < .001$, $\eta_p^2 = .48$; previous congruency, $F(1, 29) = 142.80$, $p < .001$, $\eta_p^2 = .83$; and current congruency, $F(1, 29) = 221.15$, $p < .001$, $\eta_p^2 = .88$; and an interaction between previous congruency and current congruency, $F(1, 29) = 74.03$, $p < .001$, $\eta_p^2 = .72$. The interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 8.35$, $p < .001$, $\eta_p^2 = .22$. Similar to Experiment 2a, simple effect analyses revealed significant CSEs in the St_St_HSm_L condition, $F(1, 29) = 25.14$, $p < .001$, $\eta_p^2 = .46$; the St_HSm_L_Sm condition, $F(1, 29) = 9.67$, $p = .004$, $\eta_p^2 = .25$; and the repetition condition, $F(1, 29) = 60.59$, $p < .001$, $\eta_p^2 = .68$, but not in the St_Sm condition, $F(1, 29) = .65$, $p = .426$, $\eta_p^2 = .02$. No other interactions were observed.

The ER analyses showed that there were significant main effects of consecutive conflict type, $F(3, 87) = 6.87$, $p < .001$, $\eta_p^2 = .19$, and current congruency, $F(1, 29) = 36.90$, $p < .001$, $\eta_p^2 = .56$, and an interaction between previous congruency and current congruency, $F(1, 29) = 22.97$, $p < .001$, $\eta_p^2 = .44$. The interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 5.55$, $p = .002$, $\eta_p^2 = .16$. Simple effect analyses revealed significant CSEs in the repetition condition, $F(1, 29) = 32.29$, $p < .001$, $\eta_p^2 = .50$, and the St_HSm_L_Sm condition, $F(1, 29) = 4.20$, $p = .050$, $\eta_p^2 = .00$, but no significant CSE in the St_St_HSm_L condition, $F(1, 29) = 2.16$, $p = .153$, $\eta_p^2 = .00$, or the St_Sm condition, $F(1, 29) = 3.67$, $p = .065$, $\eta_p^2 = .00$. No other main effects or interactions were observed.

Comparison of CSEs

For the RT, the main effect of consecutive conflict type was significant, $F(3, 87) = 8.35$, $p < .001$, $\eta_p^2 = .22$. Pairwise comparisons showed that the CSE of the repetition condition (33 ms) was significantly larger than that of the St_Sm (4 ms, $M_{diff} = 29.4$ ms, 95% CI [9.7, 49.0], Cohen's $d = 1.16$, $p < .001$), and the St_HSm_L_Sm conditions (12 ms, $M_{diff} = 21.7$ ms, 95% CI [7.1, 36.4], Cohen's $d = .99$, $p < .001$). No other pairwise differences were found (see Figure 2).

For the ER, the main effect of consecutive conflict type was significant, $F(3, 87) = 5.55$, $p = .002$, $\eta_p^2 = .16$. Pairwise comparisons showed that the CSE of the repetition condition (7.3%) was larger than the CSEs of the St_HSm_L_Sm condition (2.5%, $M_{diff} = 4.8\%$, 95% CI [1.1%, 8.5%], Cohen's $d = .69$, $p = .006$); the St_St_HSm_L condition (1.8%, $M_{diff} = 5.6\%$, 95% CI [.7%, 10.5%], Cohen's $d = .82$, $p = .017$); and the St_Sm condition (2.1%, $M_{diff} = 5.3\%$, 95% CI [1.4%, 9.2%], Cohen's $d = .81$, $p = .003$). No other differences were found.

Experiment 3b

Method

Participants

A new sample of 30 adults participated in Experiment 3b (19−25 years old, average of 22.5 ± 1.9 years old; 12 male). All of the participants were healthy and right-handed, with normal or corrected-to-normal visual acuity.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedure were similar to those described in Experiment 1, with the following changes (see Figure 1). The major difference was that the Euclidian distance between the stimulus and the origin in the Stroop condition was three times greater than that of the Stroop condition in Experiment 1. Another slight difference was that the arrow of the StSm condition was located on an ellipse passing the location of the arrows in the Stroop and Simon conditions. Based on the ratio of component overlap, StSm was termed St_LSm_H, consistent with Experiment 2b.

Data Analysis

The data analysis procedures were the same as those described in Experiment 1. In the RT analysis, error trials (4.3%), trials with RTs beyond 3 *SD*s or shorter than 200 ms (1.5%), the first trial of each block (.9%), trials after an error (4.3%), and trials with repeated responses (49.6%) were excluded. For conditions in which the successive conflicts alternated, the number of remaining trials for each cross-conflict CSE subcondition (CC, CI, IC, and II) ranged between 17 and 40, with a mean of 30. For conditions in which the successive conflicts repeated, the number of remaining trials ranged between 27 and 57, with a mean of 44.

Results

CSE

For the RT, there were significant main effects of consecutive conflict type, $F(3, 87) = 47.98$, $p < .001$, $\eta_p^2 = .62$; previous congruency, $F(1, 29) = 58.15$, $p < .001$, $\eta_p^2 = .67$; and current congruency, $F(1, 29) = 98.53$, $p < .001$, $\eta_p^2 = .77$, and significant interactions between previous congruency and current congruency, $F(1, 29) = 118.46$, $p < .001$, $\eta_p^2 = .80$, and between current congruency and consecutive conflict type, $F(3, 87) = 5.20$, $p = .002$, $\eta_p^2 = .15$. In addition, the interaction among consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 12.74$, $p < .001$, $\eta_p^2 = .31$. Simple effect analyses revealed significant CSEs in the St_St_LSm_H condition, $F(1, 29) = 30.9$, $p < .001$, $\eta_p^2 = .52$; the St_LSm_H_Sm condition, $F(1, 29) = 33.79$, $p < .001$, $\eta_p^2 = .54$; and the repetition condition, $F(1, 29) = 83.71$, $p < .001$, $\eta_p^2 = .74$, but not in the St_Sm condition, $F(1, 29) = 1.24$, $p = .274$, $\eta_p^2 = .04$. No other interactions were observed.

The ER results showed that there were significant main effects of consecutive conflict type, $F(3, 87) = 5.08$, $p = .003$, $\eta_p^2 = .15$, and current congruency, $F(1, 29) = 23.18$, $p < .001$, $\eta_p^2 = .44$, and significant interactions between previous congruency and current congruency, $F(1, 29) = 22.99$, $p < .001$, $\eta_p^2 = .44$, and between current congruency and consecutive conflict type, $F(3, 87) = 5.12$, $p = .003$, $\eta_p^2 = .15$. In addition, the interaction among Consecutive conflict type, previous congruency, and current congruency was significant, $F(3, 87) = 11.48$, $p < .001$, $\eta_p^2 = .28$. Simple effect analyses revealed significant CSEs in the repetition condition, $F(1, 29) = 27$, $p < .001$, $\eta_p^2 = .50$; the St_LSm_H_Sm condition, $F(1, 29) = 4.46$, $p = .043$, $\eta_p^2 = .13$; and the St_St_LSm_H condition, $F(1, 29) = 15.67$, $p < .001$, $\eta_p^2 = .25$, but not in the

St_Sm condition, $F(1, 29) = 1.08$, $p = .308$, $\eta_p^2 = .00$. No other main effects or interactions were observed.

Comparison of CSEs

For the RT, the effect of the consecutive conflict type was significant, $F(3, 87) = 12.74$, $p < .001$, $\eta_p^2 = .31$. Pairwise comparisons showed that the CSE of the repetition condition (48 ms) was significantly larger than the St_Sm condition (6 ms, $M_{diff} = 42.3$ ms, 95% CI [22.5, 62.0], Cohen's $d = 8.22$, $p < .001$); the St_LSm_H_Sm condition (27 ms, $M_{diff} = 20.9$ ms, 95% CI [1.0, 40.8], Cohen's $d = 4.22$, $p = .035$); and the St_St_LSm_H condition (24 ms, $M_{diff} = 24.0$ ms, 95% CI [5.8, 41.3], Cohen's $d = 4.87$, $p = .005$). In addition, the CSE of the St_LSm_H_Sm condition (27 ms) was significantly larger than the St_Sm condition (6 ms, $M_{diff} = 21.4$ ms, 95% CI [1.0, 41.8], Cohen's $d = 4.41$, $p = .036$). No other differences were found (see Figure 2).

Similar to the RT results, the ER results showed that the effect of the consecutive conflict type was significant, $F(3, 87) = 11.48$, $p < .001$, $\eta_p^2 = .28$. Pairwise comparisons showed that the CSE of the repetition condition (11.4%) was larger than the CSEs of the St_LSm_H_Sm condition (3.8%, $M_{diff} = 7.6\%$, 95% CI [2.0%, 13.2%], Cohen's $d = .69$, $p = .003$); the St_St_LSm_H condition (4.4%, $M_{diff} = 7.0\%$, 95% CI [.4%, 13.6%], Cohen's $d = .73$, $p = .032$); and the St_Sm condition (−1.3%, $M_{diff} = 12.7\%$, 95% CI [4.9%, 20.4%], Cohen's $d = 1.71$, $p < .001$). In addition, the CSE of the St_St_LSm_H condition (4.4%) was larger than the St_Sm condition (−1.3%, $M_{diff} = 5.7\%$, 95% CI [.8%, 10.6%], Cohen's $d = .89$, $p = .017$). No other differences were found.

Discussion of Experiments 3a and 3b

By manipulating the conflict similarity via the Euclidean distance in Experiment 3a, we observed results that were very similar to those observed in Experiment 2a, providing further evidence supporting the hypothesis that similarity modulates the degree of the cross-conflict CSE. In Experiment 3b, however, we unexpectedly observed that the larger eccentricity of the Stroop condition did not lead to a smaller CSE across the St_LSm_H and Stroop conditions than across the St_LSm_H and Simon conditions. Considering that similarity clearly modulated the CSE in the symmetrical design of Experiment 3a, we speculate that the difference between the two designs contributed to the inconsistent results. The perception of the arrow location in the vertical direction appeared to be condensed compared with that in the horizontal direction, consistent with the horizontal-vertical anisotropy phenomenon (Abrams et al., 2012). Previous studies have found that performance was usually better when the stimuli were presented on the horizontal axis than on the vertical axis of the visual field (Carrasco et al., 2004). Therefore, although the vertical location of the arrow was tripled in Experiment 3b, the perception of the conflict likely did not greatly change; thus, the mental similarity among the Stroop, St_LSm_H, and Simon conditions was not modulated exactly by the physical distance. Theoretically, it is possible to further modulate the similarity by introducing an even larger eccentricity. However, such a design is impractical since it produces more vertical eye movement and reduces the comparability among the Stroop and other conflict conditions.

Linear Mixed-Effect (LME) Modeling

We noted that the across-condition CSE comparisons were not sufficiently powerful to test the modulation effect of conflict similarity on the CSE. Considering Experiment 3a for instance, we did not observe a significant RT difference between the St_St_HSm_L and St_HSm_L_Sm conditions. However, we did observe a clear linear increase from St_Sm, St_HSm_L_Sm, and St_St_HSm_L to Rep conditions. One possibility is that the modulation effect on the CSE gradually accumulates. To test this assumption, we reanalyzed the data with LME modeling.

In addition, according to the integrative learning account of cognitive control (Egner, 2014), stimulus binding is a concrete perception compared with conflict control and thus might also influence the similarity level. To clarify the contribution of stimulus binding, LME was also performed using the data of the stimulus/response-repetition trials (i.e., the data excluded from the data analysis) and the full data without the stimulus/response-repetition trial exclusion (see Parts S2 and S4 in the online supplemental materials).

Method

To obtain a better overview of the similarity modulation on the cross-conflict CSE, we examined whether the similarity between two consecutive conflicts could predict their cross-conflict CSE using LME models. Notably, Braem et al. (2014) proposed a U-shaped nonlinear relationship between the CSE and conflict similarity. Given that we manipulated only the similarity level of the increasing part of the U-shape, whether the relationship was linear or nonlinear did not impact our major conclusions. To simplify the models, we only tested the results with linear functions.

The similarity was defined as the ratio of component overlap between the StSm condition and the Stroop or Simon condition, namely the projected length of the StSm condition onto the vertical or horizontal axes divided by the length of the Stroop or Simon condition, respectively. In Experiment 1, the shared component between StSm and Stroop was the length (i.e., the distance from the arrow to the origin) of the StSm condition multiplied by cosine (45°) and then divided by the length of the Stroop condition. Because the lengths of the two conditions were the same, their similarity was cosine (45°), approximately .71. In all of the experiments in this study, the similarity between St and Sm was 0, while the similarity between the same conditions (i.e., the repetition conditions) was 1. In Experiment 2a, the similarity between St and St_HSm_L was .92, while the similarity between St_HSm_L and Sm was .38. In Experiment 2b, the similarity between St and St_LSm_H was .38, and the similarity between St_LSm_H and Sm was .92. In Experiment 3a, the similarity between St and St_HSm_L was .67, while the similarity between St_HSm_L and Sm was .22. In Experiment 3b, the similarity between St and St_LSm_H was .22, while the similarity between St_LSm_H and Sm was .67.

The LME model was built with the lmerTest package (Kuznetsova et al., 2017) in the R open source programming environment, following the modeling steps suggested by Bates et al. (2015). Specifically, the modeling always began with the maximal model ($Model_{max}$), in which the similarity was entered to model fixed effects, and both the random slope and random intercept of each subject were included to model random effects. For both RTs and ERs, the CSEs of all consecutive-order combinations of all subjects (i.e., nine data points for each of the 30 subjects, yielding 270 points) were entered as the predicted variable. If Model_{max} caused overfitting to the data or could not converge, we simplified the model and tested the zero-correlation-parameter (ZCP) model (Model_{zcp}), which assumes a zero correlation among random effects. If Model_{zcp} caused overfitting or could not converge, principal component analysis was performed to further simplify Model_{zcp}. The alternative models could be Model_{slp} (where "slp" denotes "slope"), retaining only the random slope of the subject, or Model_{int} (where "int" denotes "intercept"), retaining only the random intercept of the subject. A model comparison was then performed to ensure that the best fitting model did not show a difference from Model_{max} in the goodness of fit. Before conducting the LME modeling, we examined the normal distribution of the residuals by Q-Q plots, and the results showed that all of the experiments met the normal distribution of residuals.

Results

Figure 3 shows the mixed effect modeling results based on the RTs, with scatters representing the cross-conflict CSEs of each similarity level of each subject. The best fitting line and the standard error ribbon were added for each experiment. In addition to the RTs, we performed the same analysis with the ER data. For all experiments, the best fitting model showed no difference with the corresponding maximal model on the goodness of fit, *p*s $>$ .05.

Experiment 1

For both the RT and ER, the best fitting model was Model_{slp}, in which the random effects only included the random slope of the subject. The RT results showed a positive association between the similarity and cross-conflict CSE, R^2 = .16, $F(1, 213.44)$ = 49.07, $p < .001$, with slope b = 33.57, $t(213.44)$ = 7.01, $p < .001$. The ER results were similar to the RT results. A positive association was observed between the similarity and cross-conflict CSE, R^2 = .05, $F(1, 189.24)$ = 14.50, $p < .001$, with slope b = .07, $t(189.23)$ = 3.81, $p < .001$.

Experiment 2a

Similar to Experiment 1, for the RT and ER of the CSE, the best fitting model was Model_{slp}. The RT results showed a positive association between the similarity and cross-conflict CSE, R^2 = .17, $F(1, 110.79)$ = 47.60, $p < .001$, with slope b = 39.24, $t(110.79)$ = 6.90, $p < .001$. The ER results also revealed a positive association between the similarity and cross-conflict CSE, R^2 = .05, $F(1, 102.25)$ = 11.42, p = .001, with slope b = .06, $t(102.25)$ = 3.38, p = .001.

Experiment 2b

Similar to Experiment 1, for both the RT and ER, the best-fitting model was Model_{slp}. The RT results showed a positive association between the similarity and CSE, R^2 = .19, $F(1, 137.40)$ = 56.46, $p < .001$, with slope b = 45.78, $t(137.40)$ = 7.51, $p < .001$. The ER results also revealed a positive association between the similarity and CSE, R^2 = .10, $F(1, 82.86)$ = 22.86, $p < .001$, with slope b = .09, $t(82.86)$ = 4.78, $p < .001$.

Experiment 3a

For the RT, the best fitting model was Model_{max}. The results showed a positive association between the similarity and CSE, R^2 = .10, $F(1, 29)$ = 17.22, $p < .001$, with slope b = 28.14, $t(28.14)$ = 4.15, $p < .001$. For the ER, the best-fitting model was Model_{zcp}. The results showed a positive association between the similarity and CSE, R^2 = .04, $F(1, 54.04)$ = 10.68, p = .002, with slope b = .05, $t(54.04)$ = 3.27, p = .002.

Experiment 3b

Similar to Experiment 1, for both the RT and ER, the best fitting model was Model_{slp}. For the RT, the results showed a positive association between the similarity and CSE, R^2 = .12, $F(1, 117.23)$ = 32.81, $p < .001$, with slope b = 35.79, $t(117.23)$ = 5.73, $p < .001$. For the ER, the results showed a positive association between the similarity and CSE, R^2 = .10, $F(1, 57.17)$ = 18.18, $p < .001$, with slope b = .10, $t(57.17)$ = 4.26, $p < .001$.

Discussion of LME Modeling

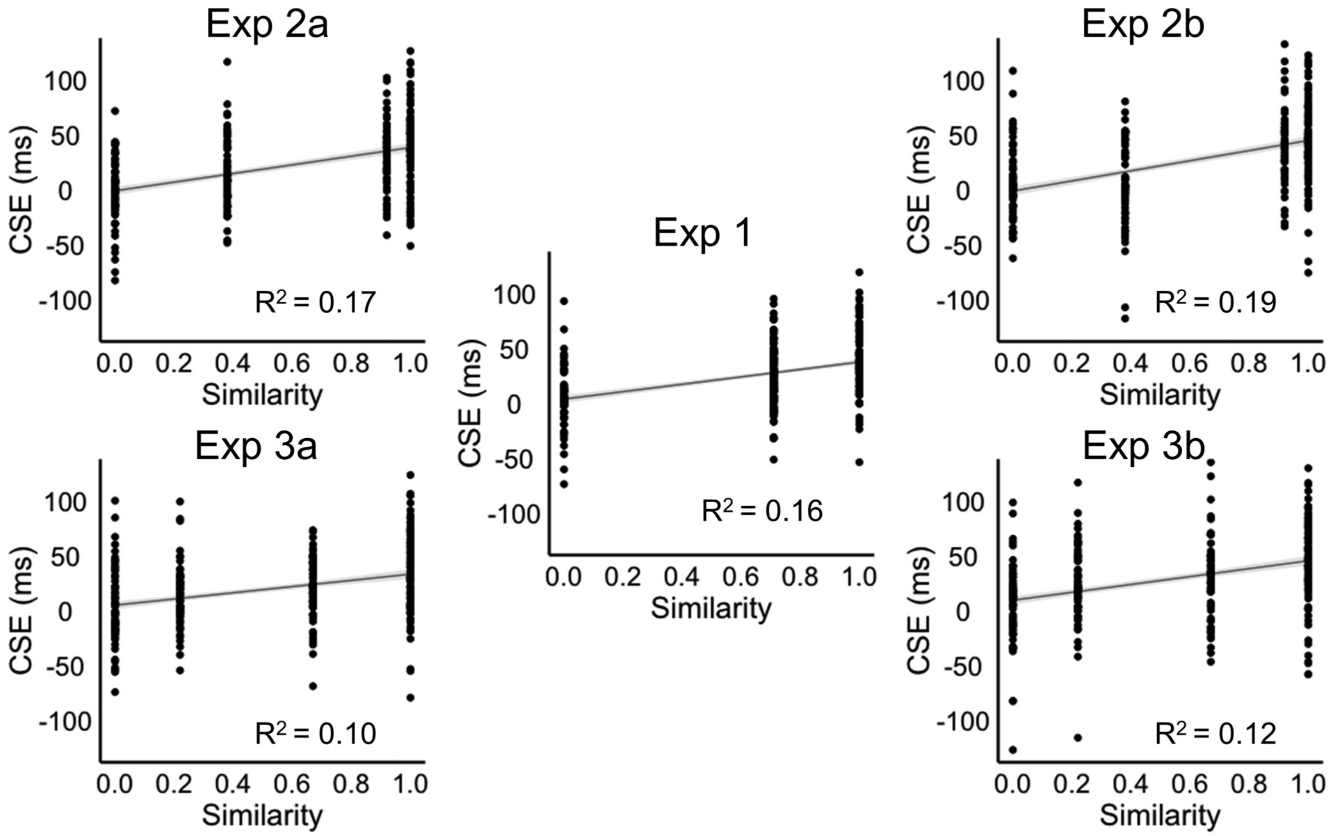
As hypothesized, we observed that conflict similarity could predict the cross-conflict CSEs linearly in all five experiments. The larger that the similarity was, the larger that the CSEs were. Future studies could adopt the spatial Stroop-Simon paradigm to test more fine-grained modulation with more similarity levels.

General Discussion

The current study provides empirical evidence supporting the hypothesis that the magnitude of cross-conflict CSE is parametrically modulated by the similarity between conflicts, favoring the integrative learning account of cognitive control (Abrahamse et al., 2016; Egner, 2014). Using the ratio of shared components to manipulate conflict similarity, we found that the cross-conflict CSE was absent between the Stroop and Simon conditions and gradually increased as the conflicts became more similar.

Our results replicated those of previous studies that found that the CSE occurred when consecutive conflicts were of the same conflict type but did not transfer across spatial Stroop and Simon conflicts (Lee & Cho, 2013; Verbruggen et al., 2005). This phenomenon has been demonstrated as a boundary condition (Braem et al., 2014). Beyond this finding, in Experiment 1, we found moderate CSEs across a compound conflict (i.e., St_MSm_M) and two spatial conflicts (i.e., spatial Stroop and Simon). This study provides the first evidence of cross-conflict CSEs across one intermediate conflict condition and two types of conflicts (i.e., Stroop and Simon) at the same time, although the resolution of the latter two conflicts expectedly relied on domain-specific control mechanisms (Egner, 2008; Liu et al., 2010). According to the dimensional overlap structure proposed by Kornblum et al. (1990), the conflict with both the Stroop and Simon components belongs to a different conflict type (i.e., Type 8) than the spatial Stroop (Type 4) and Simon (Type 3). Therefore, these findings renewed our understanding that the cross-conflict CSE could occur across conflicts that might not be of the same type qualitatively.

Figure 3
Linear Regression Results Based On the RT Data



Note. The similarity was defined as the ratio of component overlap between different conditions. The best fitting lines and the standard error ribbons were shown. CSE = congruency sequence effect; RT = reaction time.

Importantly, by manipulating different ratios of shared components, we observed a linear modulation of the CSE by conflict similarity. Specifically, the St_HSm_L condition was more similar to the Stroop condition and more distinct from the Simon condition; therefore, the CSE between the St_HSm_L condition and the Stroop condition was larger than that between the St_HSm_L condition and the Simon condition, and vice versa for the St_LSm_H condition. These results suggest that the cross-conflict CSE is determined by the similarity between two conflicts. Because the results reported here excluded the stimulus/response-repetition trials and the target locations were designed to be never repeated trial-by-trial, the CSE transfer results could not be explained by the bottom-up associative perspective. In addition, the domain-general or domain-specific control-based perspective (Egner, 2008) is unable to explain the potentially countless levels of conflict similarity that influence the cross-conflict CSE. Instead, these results provide strong evidence supporting the integrative learning account of cognitive control, which clearly predicts the modulation of conflict type overlap (i.e., similarity) on CSE transfer (Abrahamse et al., 2016). For the spatial Stroop, Simon, and compound StSm conditions, their conflict similarity served as an abstract cue of control states in determining the CSE transfer among them (Egner, 2017).

Notably, the similarity levels that we manipulated were particularly associated with the similarity between mental conflict representations rather than the similarity between physical stimuli. Regarding the data reported in our study, the task-relevant stimulus (i.e., the orientation of the arrow) always changed from trial to trial, and the stimulus similarity between the consecutive conflict trials was constant for each condition. Therefore, stimulus similarity did not contribute to the diverse levels of CSE transfer. Nevertheless, because our study only has two levels of stimulus similarity (i.e., stimulus-repeat and stimulus-nonrepeat), our study does not refute the possibility that properly manipulating stimulus similarity alone could also modulate the CSE, similar to conflict similarity. We are open to this possibility because the data of the stimulus/response-repetition trials (i.e., the data excluded from the data analysis) showed that concrete stimulus similarity appeared to interact with control-based conflict similarity. Specifically, when the stimulus/response was repeated, the linear modulation by conflict similarity was sharpened, with $R^2 \geq .27$ in all five experiments (see Figure S2), greater than that when there was no stimulus/response repetition (all $R^2 \leq .19$, see Figure 3). This finding is consistent with Weissman et al. (2016) study, which reported that concrete feature binding and abstract control learning interacted in an overadditive pattern. The interaction might suggest that they share similar learning mechanisms, although they differ in abstract levels (Egner, 2014). The exact role of concrete stimulus similarity in CSE transfer still requires further exploration.

Several previous studies (Hazeltine et al., 2011; Kan et al., 2013; Kleiman et al., 2014) have reported the transfer of the CSE across very dissimilar conflicts. The normal interpretation of such findings is that these two conflicts could be maintained simultaneously in working memory without interference, which is another type of "overlap" (Abrahamse et al., 2016; Braem et al., 2014). Because our study did not include any conflicts that are "very different," we cannot directly test whether such an interpretation is accurate. However, we suspect that the CSE transfer across these "very different" conflicts could be partly attributed to their similarities. The paradigms adopted by (Hazeltine et al., 2011) and (Kleiman et al., 2014) were based on variants of the same paradigms (prime-target task in (Hazeltine et al., 2011) and the flanker task in (Kleiman et al., 2014), thus, similarity could also explain the CSE transfer. In Experiment 1 of Kan et al.'s (2013) study, the authors observed CSE transfer across syntactic ambiguity and the nonsyntactic Stroop conflict, which are two processes that appear very different. However, because both processes are verbal in nature (as discussed in their paper), they inevitably share some similarity. In Experiments 2 and 3 of Kan et al.'s (2013) study, the perceptual Necker cube ambiguity and Stroop conflict indeed have limited similarity; thus, it is difficult to interpret the results based on similarity. However, a recent replication study (Aczel et al., 2021) with much larger sample sizes did not find a significant CSE transfer between Necker cube ambiguity and Stroop. Aczel et al. (2021) explained that the Necker cube ambiguity might not induce a negative affective effect like the Stroop conflict does, which reflects a lack of similarity in our view.

Our study also emphasizes the quantitative features of the CSE. Previously, the cross-conflict CSE was generally regarded as a dichotomic index indicating whether the processing of two conflicts shared cognitive control mechanisms (Egner, 2008). However, the results of our five experiments consistently indicated that the magnitude of the CSE relies on the degree of conflict similarity. Obviously, the cross-conflict CSE is not as dichotomous as it was previously regarded to be; instead, it involves a quantitative feature (see also Freitas & Clark, 2015; Kunde & Wuhr, 2006; Yang et al., 2017). Practically, it is beneficial to treat the continuous CSE size as a quantifiable variable to avoid dilemmatic conditions, such as when the *p*-value of the cross-conflict CSE falls within a marginal range (i.e., .05–.10). Moreover, it is possible to interpret the reverse CSE based on this quantitative view. Previous studies (Braem et al., 2011; Notebaert & Verguts, 2008) have reported CSEs that were less than zero across different task sets, which was regarded as evidence of local control. In accordance with our findings, the reverse CSE could be interpreted as reflecting even more dissimilar mechanisms (Notebaert & Verguts, 2008) because the adjustment of previous incongruent conditions from a different conflict task could worsen performance in the next trial.

The findings of our study have important implications for understanding the organization of cognitive control. Over the last decade, with evidence of the cross-conflict CSE (Akcay & Hazeltine, 2011; Freitas et al., 2007; Freitas & Clark, 2015; Kan et al., 2013; Kim et al., 2012; Kleiman et al., 2014), there has been controversy regarding whether cognitive control is domain-general or domain-specific. Several recent studies have suggested that cognitive control underlies both domain-general and domain-specific mechanisms (Jiang & Egner, 2014; Li et al., 2017). However, our results suggest that cognitive control might show different degrees of learned generalization depending on the conflict similarity. Therefore, instead of a dichotomic framework such as domain-general versus domain-specific (Egner, 2008), the scope of cognitive control generalization is better regarded as a continuum. Enlightened by the similarity modulation of the CSE, we propose that cognitive control processing is likely represented via certain brain patterns (Kragel et al., 2018) that would show greater similarities across more similar conflict types. This idea is in line with the finding that the similarity of task states is mirrored by the similarity among the functional connectivity patterns of the frontoparietal network (Cole et al., 2013). Future studies using brain imaging methods, such as representational similarity analysis (Kriegeskorte et al., 2008), might be useful for examining the neural mechanisms underlying the relationship between conflict similarity and the scope of cognitive control.

One might wonder whether the congruency effect could influence the size of the CSE. Theoretically, the congruency effect is calculated by I − C (i.e., $1/2 \times [\{II + CI\} - \{IC + CC\}]$), and the CSE is calculated by (CI − CC) − (II − IC), where I and C represent incongruent and congruent, respectively. The two effects share a small component, that is, $1/2 \times ([CI - II] + [IC - CC])$, but due to the unshared components, it is difficult for them to covary. To examine whether this theoretical prediction was valid in our study, we analyzed the correlation between the congruency effect and the within-conflict CSE, and the results showed only one significant correlation among 15 analyses (see Table S1 in the online supplemental materials). This finding is consistent with a previous study showing that the CSE and the congruency effect are not reliably correlated (Weissman et al., 2014). Furthermore, the CSE transfer was not influenced by the difference between the congruency effects of the consecutive trials, because no correlation was observed between the congruency effect difference and the CSE in any experiments; $ps > .24$. To remove the potential influence of the congruency effect, we also conducted a linear regression by dividing the CSE score by the congruency effect of the current trial condition, and the results replicated our major findings in general (see Part S4 in online supplemental materials).

Caveats

Regarding the data analysis, although we excluded the stimulus/response-repetition trials, the 2-AFC design could not entirely exclude the confounder of feature binding (Braem et al., 2019). However, this limitation does not influence our conclusion for two reasons. First, partial repetition remained only in the IC and CI trials of the conflict-repetition (i.e., repetition) conditions but was absent in the conflict-switch (e.g., $St\_St_HSm_L$) conditions and thus, could not affect the CSEs across the different conflict types, from which our major conclusion was drawn. Second, a recent study found very similar conflict-specific results between Stroop and Simon conflicts regardless of whether feature binding confounders were removed (Weissman, 2020), indicating that the feature-binding factors might not influence the scope of cognitive control. Consistent with this finding, both the full data and the stimulus/response-repetition data revealed very similar results patterns to those in the data that we reported in the main text (see Figures S1–S4). Future studies could adopt well-controlled 4-AFC designs (e.g., Weissman, 2020; for a review, see Braem et al., 2019) to test the similarity modulation of pure control-based CSEs.

Conclusion

In conclusion, we observed varied levels of CSEs depending on the similarity between the conflicts, and we provided strong evidence supporting the integrative learning account of cognitive control. The current study also emphasizes the need to take advantage of the quantitative aspects of the CSE—instead of regarding the CSE as a dichotomous index in future research.

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