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Distinct Cognitive Control Mechanisms as Revealed by Modality-Specific Conflict Adaptation Effects

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Cognitive control is essential to resolve conflict in stimulus-response compatibility (SRC) tasks. The SRC effect in the current trial is reduced after an incongruent trial as compared with a congruent trial, a phenomenon being termed conflict adaptation (CA). The CA effect is found to be *domain-specific*, such that it occurs when adjacent trials contain the same type of conflict, but disappears when the conflicts are of different types. Similar patterns have been observed when tasks involve different modalities, but the *modality-specific* effect may have been confounded by task switching. In the current study, we investigated whether or not cognitive control could transfer across auditory and visual conflicts when task-switching was controlled. Participants were asked to respond to a visual or auditory (Experiments 1A/B) stimulus, with conflict coming from either the same or a different modality. CA effects showed modality-specific patterns. To account for potential confounding effects caused by differences in task-irrelevant properties, we specifically examined the influence of task-irrelevant properties on CA effects within the visual modality (Experiments 2A/B). Significant CA effects were observed across different conflicts from distinct task-irrelevant properties, ruling out that the lack of cross-modal CA effects in Experiments 1A/B resulted from differences in task-irrelevant information. Task-irrelevant properties were further matched in Experiments 3A/B to examine the pure effect of modality. Results replicated Experiments 1A/B showing robust modality-specific CA effects. Taken together, we provide supporting evidences that modality affects cognitive control in conflict resolution, which should be taken into account in theories of cognitive control.

Public Significance Statement

People need to recruit cognitive control to resolve conflicting information from different sources in order to make a goal-directed response. However, it is still unclear whether resolution of conflicts rising from different sensory modalities relies on the same mechanism or not. We took advantage of the conflict adaptation (CA) effect, a reduction of conflict effect following a previous incongruent trial, to examine whether cognitive control can transfer across trials to resolve a conflict rising from a different modality. We designed three sets of experiments involving both stimulus-stimulus and stimulus-response conflicts rising from the visual or auditory modality, whereas controlling for other potential confounds such as task switching and task-irrelevant attributes. We consistently found that CA effects appeared only for the within-modality condition but not for the cross-modality condition. These findings support that cognitive control acts in a modality-specific fashion.

Keywords: cognitive control, modality-specific, conflict adaptation, stimulus-stimulus, stimulus-response

The adaptive adjustment of cognitive control is important for a better response to a forthcoming event. In many stimulus-response compatibility (SRC) tasks, people typically perform more slowly and less accurately in incongruent condition than in congruent condition. Moreover, conflict adaptation (CA) effect occurs when a previous conflict event leads to a smaller SRC effect in the

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following trial (Gratton, Coles, & Donchin, 1992). For instance, in the Stroop task, if the previous trial is incongruent (e.g., "RED" written in the color blue), the SRC effect of the current trial would be smaller than if the previous condition is congruent (e.g., "RED" written in the color red). The CA effect reflects the adjustment of cognitive control, as proposed by the conflict-monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001). This theory proposes that the conflict-monitoring (CM) module is activated when a person is confronted with a conflict task, and the CM further conveys warning signals to the executive-control (EC) module, which in turn biases attention to the task-relevant information and facilitates conflict processing in the following trial.

Although conflict-monitoring theory provides a satisfactory interpretation of the CA effect, its domain-general framework faces challenges from empirical studies that have examined different types of conflict. Some studies revealed that the CA effect occurred across different tasks involving seemingly distinctive conflicts (Freitas, Bahar, Yang, & Banai, 2007; Kleiman, Hassin, & Trope, 2014), whereas many other studies showed that the CA effect was present in two successive trials with the same type of conflict (within-domain) but disappeared in trials with different types of conflict (cross-domain) (Akcay & Hazeltine, 2011; Egner, Delano, & Hirsch, 2007; Freitas & Clark, 2015; Funes, Lupianez, & Humphreys, 2010; Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005), supporting the domain-specific account (see review Egner, 2008).

Contradictory as they may appear, the above mentioned domain-general and domain-specific CA effect patterns can be accounted for under a unified framework of dimensional overlap (DO) (Kornblum, Hasbroucq, & Osman, 1990). The DO between the task-relevant stimulus (Sr), task-irrelevant stimulus (Si), or response (R) was originally introduced to categorize various conflicts (e.g., those found in the Stroop and Simon tasks) into different stimulus-response ensembles (Kornblum, 1994). According to the DO framework, both the Stroop-like and Eriksen flanker tasks contain the S-S conflict (overlap between Sr and Si), whereas the Simon task contains the S-R conflict (overlap between Si and R). In view of this taxonomy, the aforementioned studies that revealed cross-task CA effects in fact adopted different tasks involving the same S-S conflict, whereas studies that did not reveal cross-task CA effects used tasks containing different S-S and S-R conflicts. Therefore, cognitive control may only transfer within the same DO type but not across different DO types (Braem et al., 2014; Freitas & Clark, 2015). In other words, the DO type of conflict act as a *boundary* of cognitive control. This account is compatible with the mechanism-accessibility view (Freitas & Clark, 2015), which suggested that CA effects should appear between two tasks only when their mechanisms are the same.

Several studies found that cognitive control can transfer within DO types in the visual modality (Freitas et al., 2007; Kleiman et al., 2014; but see Mayr, Awh, & Laurey, 2003), but when the sensory modality was alternated, the transfer disappeared (Aisenberg, Salzer, Gotler, Mannheim, & Henik, 2011; Hazeltine, Lightman, Schwarb, & Schumacher, 2011). By using visual and auditory task-relevant stimuli, researchers found that the CA effect was only significant in the modality-repetition condition rather than in the modality-alteration condition (Hazeltine et al., 2011, Experiment 1). Similar modality-specific CA effects occurred in another study with tactile and visual stimuli (Aisenberg et al., 2011). However, the absence of cross-modality CA effects might be caused by a confounding variable of task-switching. In particular, the target property alternated from visual to auditory information in the former study and from a visual colored patch to tactile vibration in the latter study. Task-switching, in addition to the DO types, has been shown to be another boundary of cognitive control (Braem et al., 2014; Hazeltine et al., 2011; Notebaert & Verguts, 2008). Therefore, whether cognitive control is modality-specific or not has to be clarified.

To examine the impact of modality on CA effect, it is necessary to design a task that controls both the DO types and task-switching factors. The modality-general cognitive control account assumes that the same mechanism underlies the processing of conflicts from different modalities and predicts that cross-modality CA effects would occur. On the contrary, if cognitive control is modality-specific, no CA effect would be observed between conflicts across different modalities. To test the above hypothesis, we combined conflicts produced by task-irrelevant stimuli from either the visual or auditory modality in the same task, while keeping the task-relevant stimulus modality and DO types of conflict constant in Experiments 1A and 1B. To rule out the potential influence from differences in task-irrelevant properties, we designed Experiments 2A and 2B, in which we varied the task-irrelevant properties while keeping the same DO types of conflict within the visual modality. Moreover, we designed Experiments 3A and 3B to test the effect of modality when task-irrelevant properties were controlled.

Experiments 1A and 1B

In the following two experiments, we examined and compared conflicts from the visual or auditory modality while avoiding task-switching. To control the confounding influence of DO types, we mixed two S-S conflicts with visual and auditory distractors in Experiment 1A, and two S-R conflicts with visual and auditory distractors in Experiment 1B.

Method

Participants. Thirty volunteers participated in Experiment 1A (16 men and 14 women, aged between 18 and 27 years) and another 30 volunteers participated in Experiment 1B (15 men and 15 women, aged between 19 and 26 years). All participants were healthy, right-handed with normal hearing and normal or corrected-to-normal visual acuity. All participants signed informed consent before the experiments and completed a postexperiment inquiry. This study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

Apparatus, stimuli, and procedure. We used the Chinese characters "上" and "下" (meaning "up" and "down," respectively) (see also Li, Nan, Wang, & Liu, 2014) as visual stimuli and spoken words (i.e., "shàng" and "xià", the pronunciation of "上" and "下", respectively) as the auditory stimuli. The visual stimuli were displayed on a 17-inch LCD monitor with the viewing distance of approximately 60 cm. In addition, the spoken word was presented via a headphone.

In Experiment 1A, the visual word was displayed either on the top, center or bottom of a square box. Visual S-S (SS_V) conflict came from the overlap between the vertical location (up or down, 1.79° angle) and the meaning of the Chinese character ("上" or

"下"), whereas the auditory S-S (SS_A) conflict came from the semantic overlap between the spoken word ("shàng" or "xià") and the visual word. To avoid compound conflict involving both visual and auditory conflicts within a trial, we manipulated the congruency in one modality whereas keeping the task-irrelevant stimulus from the other modality neutral. That is, in the SS_V conditions, the auditory stimulus was a neutral spoken word ("zhōng", denoting center). In the SS_A conditions, the visual word was displayed in the center of the screen. Participants were instructed to make left/right key press as quickly and accurately as possible in response to the visual character, while ignoring its location or the spoken word. For instance, they responded to "上" with left index finger and to "下" with right index finger. The stimulus-response mapping was counterbalanced across participants (see Figure 1).

In Experiment 1B, the spoken word ("shàng" or "xià") was displayed mono-aurally or biaurally. The auditory S-R (SR_A) conflict originated from overlap between the mono-aural location (left or right ear) of the spoken word and left/right key press, whereas the visual S-R (SR_V) conflict came from overlap between the direction of a visually displayed arrow (pointing either leftward or rightward) presented on the center of the screen and left/right key press. To avoid compound conflict, in SR_A conditions, a cross instead of arrow was displayed visually; and in SR_V conditions, the spoken word was presented biaurally. Participants were asked to make left/right key press as quickly and accurately as possible in response to the auditory word, while ignoring its location or the arrow direction. For instance, participants were required to respond to "shàng" with left index finger and to "xià" with right index finger. The stimulus-response mapping was counterbalanced across subjects. In addition, they were instructed to watch the screen attentively to ensure the effectiveness of visual distractors (see Figure 1).

In both experiments, congruent (C) and incongruent (I) conditions and their sequential combinations were mixed pseudorandomly with equal probability (Akcay & Hazeltine, 2011; Egner et al., 2007). Distinct sequences were created in different blocks. To decrease the participants' expectations, stimulus was selected totally randomly with replacement. For both Experiments 1A and 1B, there were three training blocks (10 trials each) for the participants to familiarize themselves with the stimulus-response mapping. The formal testing contained eight blocks of 81 trials each. In each trial, a fixation was displayed for 200 ± 100 ms, after which the target word was presented for 600 ms, followed by another fixation for 1,700 ± 100 ms.

Data analysis. Data were analyzed with dependent variables of both reaction time (RT) and error rate (ER). We adopted the analysis approaches from previous studies (Funes et al., 2010; Hazeltine et al., 2011). Error trials and trials with RT beyond 3 *SD*s and shorter than 200 ms were excluded. Furthermore, we excluded the first trial of each block, trials after an error, and response-repetition trials before analyzing CA effects (Akcay & Hazeltine, 2008; Funes et al., 2010; Kerns et al., 2004; Ullsperger, Bylsma, & Botvinick, 2005). We conducted three-way repeated measures analyses of variance (ANOVAs) of Switch (2, modality alternation vs. repetition) × Previous Congruency (2, congruent vs. incongruent) × Current Congruency (2, congruent vs. incongruent).

To address the potential speed-accuracy trade-off, many studies applied "OR" logic such that the positive statistical results would be reported if either RT or ER yielded significant CA effects (e.g., Freitas & Clark, 2015; Notebaert & Verguts, 2008). However, "OR" logic may lead to more false positives. Consequently, we conducted the multivariate analyses of variance (MANOVAs) on RT and ER as well in all experiments.

Given our main interest was to test whether there were domain-specific CA effects, we mainly reported the main effect of Current Congruency (SRC effect), the interaction between Previous Congruency and Current Congruency (CA effect), as well as interaction among three factors (domain-specificity). Other significant effects were reported but not discussed further.

Results

Experiment 1A. For the RT, there was a significant main effect of Current Congruency (SRC effect), $F(1, 29) = 107.84$,

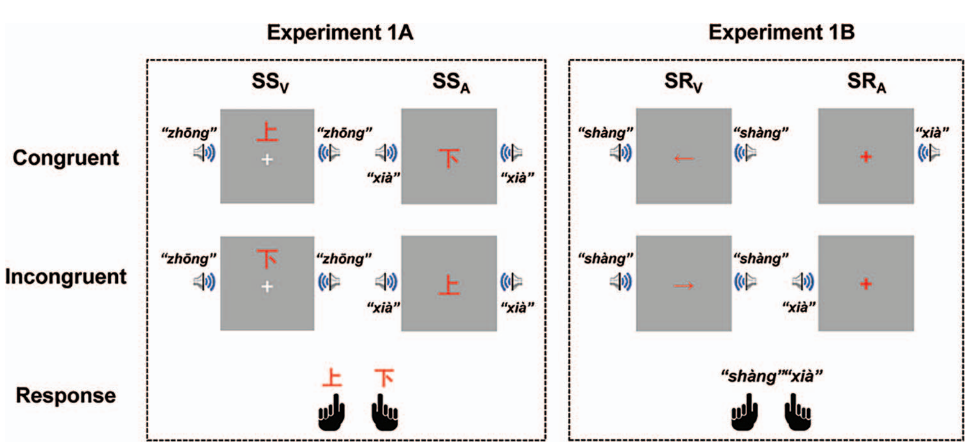

Figure 1. Examples of the different conditions in Experiments 1A and 1B. All possible trials (eight for each experiment) are randomly shown and counterbalanced across participants. Participants were asked to respond to the word displayed on the screen in Experiment 1A and respond to the voice presented by headphones in Experiment 1B. V = visual; A = auditory; SS = stimulus-stimulus overlap; SR = stimulus-response overlap. See the online article for the color version of this figure.

$p < .001$, $\eta_p^2 = .79$. Participants responded more slowly in incongruent condition (485 ms) than in congruent condition (463 ms). Interaction between Previous Congruency and Current Congruency (CA effect) was significant, $F(1, 29) = 9.54$, $p < .01$, $\eta_p^2 = .25$, suggesting that the SRC effect (Incongruent vs. Congruent) was smaller after incongruent trials (484 vs. 468 ms) than after congruent trials (485 vs. 459 ms). Moreover, the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 18.93$, $p < .001$, $\eta_p^2 = .40$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (21 ms), $F(1, 29) = 21.36$, $p < .001$, but not in the modality-alternation condition, $F(1, 29) < 1$ (see Figure 2A). In addition, we observed significant main effects of Switch, $F(1, 29) = 22.60$, $p < .001$, $\eta_p^2 = .44$, and Previous Congruency, $F(1, 29) = 5.38$, $p < .05$, $\eta_p^2 = .16$. No other main effects or interactions were observed.

For the ER, there was a significant main effect of Current Congruency, $F(1, 29) = 12.09$, $p < .01$, $\eta_p^2 = .29$. Participants had a higher error rate in incongruent condition (4.4%) than in congruent condition (2.9%). There was a significant CA effect, $F(1, 29) = 13.17$, $p < .01$, $\eta_p^2 = .31$, suggesting that the SRC effect was smaller after incongruent trials (3.5% vs. 3.5%) than after congruent trials (5.3 vs. 2.4%). Moreover, the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 8.80$, $p < .01$, $\eta_p^2 = .23$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (4.8%), $F(1, 29) = 18.85$, $p < .001$, but not in the modality-alternation condition, $F(1, 29) = 1.07$, $p = .309$ (see Figure 2B). In addition, we observed a significant main effect of Switch, $F(1, 29) = 16.52$, $p < .001$, $\eta_p^2 = .36$. No other main effects or interactions were observed.

The MANOVA results indicated a significant interaction among Switch, Previous Congruency, and Current Congruency, $F(1, 29) = 10.28$, $p < .001$, $\eta_p^2 = .42$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition, $F(1, 29) = 15.94$, $p < .001$, but not in the modality-alternation condition, $F(1, 29) < 1$.

Experiment 1B. For the RT, there was a significant main effect of Current Congruency, $F(1, 29) = 127.79$, $p < .001$, $\eta_p^2 = .82$. Participants responded more slowly in incongruent condition (516 ms) than in congruent condition (472 ms). A significant CA effect was observed, $F(1, 29) = 13.20$, $p < .01$, $\eta_p^2 = .31$, suggesting that the SRC effect was smaller after incongruent trials (516 vs. 479 ms) than after congruent trials (516 vs. 466 ms). Moreover, the interaction among Switch, Previous Congruency, and Current Congruency was marginally significant, $F(1, 29) = 3.48$, $p = .072$, $\eta_p^2 = .11$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (23 ms), $F(1, 29) = 13.46$, $p < .01$, but not in the modality-alternation condition, $F(1, 29) < 1$ (see Figure 3A). In addition, there were significant main effects of Switch, $F(1, 29) = 18.81$, $p < .001$, $\eta_p^2 = .39$, and Previous Congruency, $F(1, 29) = 13.25$, $p < .01$, $\eta_p^2 = .31$. No other main effects or interactions were observed.

For the ER, there was a significant main effect of Current Congruency, $F(1, 29) = 68.65$, $p < .001$, $\eta_p^2 = .70$. Participants had a higher error rate in incongruent condition (4.9%) than in congruent condition (1.4%). A significant CA effect was observed, $F(1, 29) = 13.15$, $p < .01$, $\eta_p^2 = .31$, indicating that the SRC effect was smaller after incongruent trials (3.8% vs. 1.7%) than after congruent trials (5.9% vs. 1.2%). Moreover, the interaction among Switch, Previous Congruency, and Current Congruency was marginally significant, $F(1, 29) = 3.19$, $p = .085$, $\eta_p^2 = .10$. Simple effect analyses revealed that there was a significant CA effect in the modality-repetition condition (3.9%), $F(1, 29) = 10.33$, $p < .01$, and a marginally significant CA effect in the modality-alternation condition (1.5%), $F(1, 29) = 4.17$, $p = .050$ (see Figure 3B). In addition, there were a significant main effect of Switch, $F(1, 29) = 18.43$, $p < .001$, $\eta_p^2 = .39$, and a significant interaction between Switch and Current Congruency, $F(1, 29) = 23.74$, $p < .001$, $\eta_p^2 = .45$. No other main effects or interactions were observed.

The MANOVA results showed that the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 3.76$, $p < .05$, $\eta_p^2 = .21$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition, $F(1, 29) = 11.49$, $p < .001$, but not in the modality-alternation condition, $F(1, 29) = 2.04$, $p = .149$.

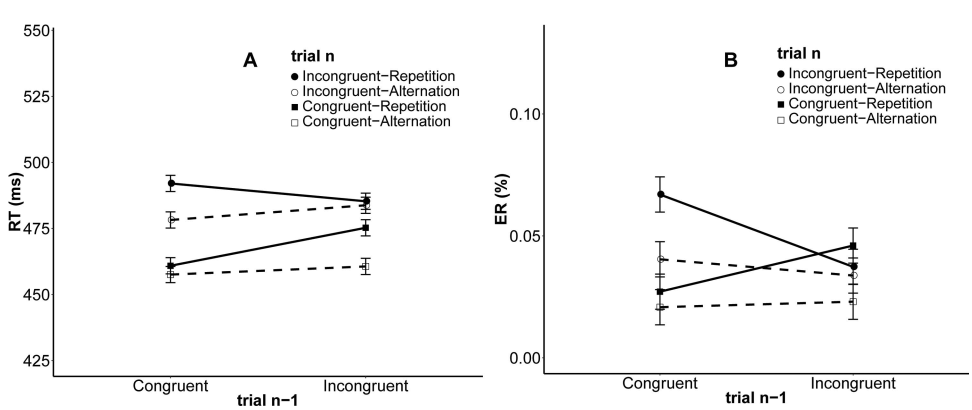

Figure 2. (A) Reaction time (RT) and (B) error rate (ER) of Experiment 1A as a function of congruent and incongruent conditions for both current and previous trials and their relationship (modality-repetition or alternation). The error bars show the 95% confidence intervals of the means.

Discussion

The consistent modality-specific CA effects in Experiments 1A and 1B supported the hypothesis that sensory modalities may affect the modularity of cognitive control. Specifically, a previously encountered conflict led to a smaller SRC effect in the current trial only in the modality-repetition conditions, similar to the patterns of domain-specific CA effects caused by different DO types of conflict (Akcay & Hazeltine, 2011; Egner et al., 2007; Li et al., 2015). Therefore, the lack of CA effects in modality-alteration conditions suggested that the modality of conflict may also act as a boundary for cognitive control.

Experiments 2A and 2B

In Experiments 1A and 1B, the alternation of modality also involved a difference in task-irrelevant properties. Hence, the lack of a CA effect in modality-alternation conditions might have resulted from the difference of property, rather than modality per se. Therefore, we designed Experiments 2A and 2B to examine this possibility when keeping both the DO type and the modality constant within each experiment. In Experiment 2A, we examined two S-S conflicts defined by distinct properties of task-irrelevant stimuli, both in visual modality. A similar design was implemented in Experiment 2B, in which two S-R conflicts were created with different task-irrelevant properties both coming from the same visual modality. Therefore, if we presumed that the modality-specific CA effects observed in Experiments 1A and 1B resulted from the differences in modality rather than in the task-irrelevant property, we would predict that both within- and cross-Condition CA effects be present in Experiments 2A and 2B.

Method

Participants. Thirty volunteers participated in Experiment 2A (16 men and 14 women, aged between 18 and 28 years) and another 30 volunteers participated in Experiment 2B (13 men and 17 women, aged between 20 and 26 years). All other information was the same as in Experiments 1A and 1B.

Apparatus, stimuli, and procedure. The stimuli, procedure, and response rules in Experiments 2A and 2B were similar to those in Experiments 1A and 1B, with the following changes. We used four white arrows (directing up, down, left, and right) and a rectangle placed at four locations (top, bottom, left, and right) to create S-S and S-R conflicts visually. This ensured that conflicts rising from the arrow directions and rectangle locations both similarly came from the spatial dimension.

In Experiment 2A, the conflict from vertical location (up or down) was termed Location S-S (SS_{Loc}), whereas the other conflict from vertically pointing arrow (upward or downward) was termed Arrow S-S (SS_{Arr}). In the SS_{Loc} condition, the target word was displayed within a rectangle, while in the SS_{Arr} condition, the target word and the arrow were displayed at the center of the screen (see Figure 4).

Similarly, in Experiment 2B, the Location S-R (SR_{Loc}) conflict originated from overlap between the horizontal location (left or right) and the left/right key press, whereas the Arrow S-R (SR_{Arr}) conflict came from overlap between the direction of the arrow (pointing toward left or right) and the left/right key press. In the SR_{Loc} condition, the target word was displayed within a rectangle, while in the SR_{Arr} condition, the target word and the arrow were displayed at the center of the screen (see Figure 4).

In Experiments 2A and 2B, the participants were instructed to make left/right key press as quickly and accurately as possible in response to the word ("上" or "下"), ignoring its location or the arrow direction. For instance, participants were required to respond to "上" with the left index finger and to "下" with the right index finger. The stimulus-response mapping was counterbalanced across participants. In addition, the procedures were similar to those of Experiments 1A and 1B.

Data analysis. The analysis approaches were similar to those of Experiments 1A and 1B. We conducted three-way ANOVAs of Switch (2, property- alternation vs. repetition) × Previous Congruency (2, congruent vs. incongruent) × Current Congruency (2, congruent vs. incongruent).

Results

Experiment 2A. For the RT, there was a significant main effect of Current Congruency, $F(1, 29) = 139.93$, $p < .001$, $\eta_p^2 = .83$. Participants responded more slowly in incongruent condition

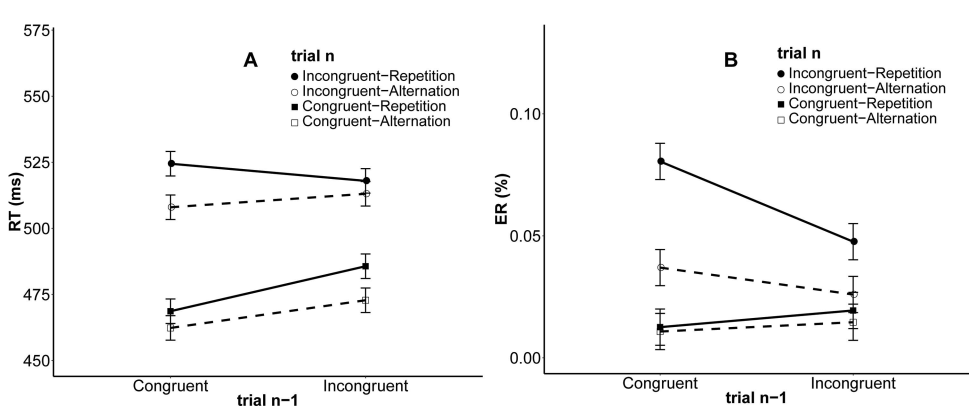

Figure 3. (A) Reaction time (RT) and (B) error rate (ER) of Experiment 1B as a function of congruent and incongruent conditions for both current and previous trials and their relationship (modality-repetition or alternation). The error bars show the 95% confidence intervals of the means.

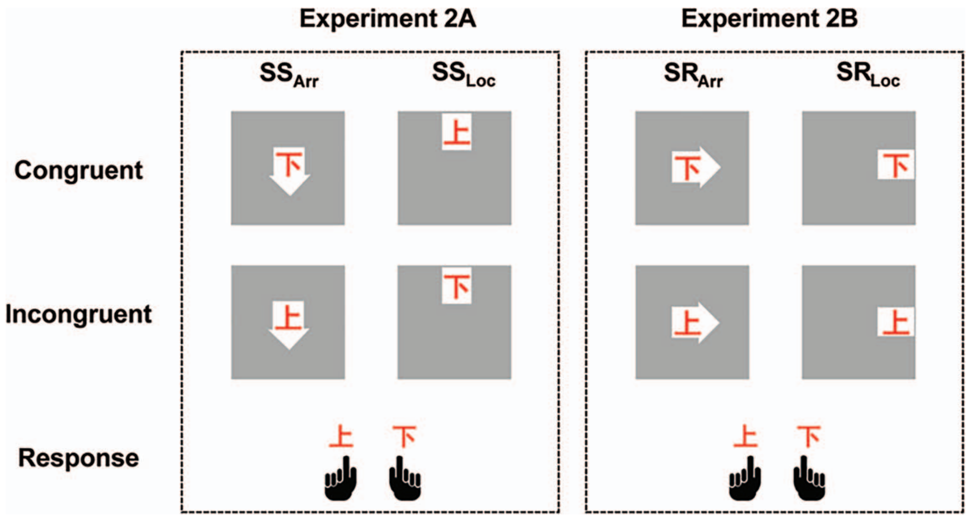

Figure 4. Examples of the different conditions in Experiments 2A and 2B. All possible trials (eight for each experiment) are randomly shown and counterbalanced across participants. Participants were asked to respond to the word in Experiment 2A and Experiment 2B. Arr = arrow; Loc = location; SS = stimulus-stimulus type; SR = stimulus-response type. See the online article for the color version of this figure.

(526 ms) than in congruent condition (497 ms). The CA effect was significant, $F(1, 29) = 12.28$, $p < .01$, $\eta_p^2 = .30$, suggesting that the SRC effect was smaller after incongruent trials (527 vs. 503 ms) than after congruent trials (526 vs. 492 ms). The interaction among Switch, Previous Congruency, and Current Congruency was not significant, $F(1, 29) = 1.39$, $p = .249$, $\eta_p^2 = .05$ (see Figure 5A). In addition, we observed significant main effects of Switch, $F(1, 29) = 26.32$, $p < .001$, $\eta_p^2 = .48$, and Previous Congruency, $F(1, 29) = 23.47$, $p < .01$, $\eta_p^2 = .45$. No other main effects or interactions were observed.

For the ER, there was a significant main effect of Current Congruency, $F(1, 29) = 4.70$, $p < .05$, $\eta_p^2 = .14$. Participants had a higher error rate in incongruent condition (5.1%) than in congruent condition (3.6%). A significant CA effect was observed, $F(1, 29) = 8.13$, $p < .01$, $\eta_p^2 = .22$, suggesting that the SRC effect was smaller after incongruent trials (4.3% vs. 3.9%) than after congruent trials (5.9% vs. 3.2%). The interaction among Switch, Previous Congruency, and Current Congruency was marginally significant, $F(1, 29) = 3.34$, $p = .078$, $\eta_p^2 = .10$. Simple effect analyses revealed that there was a significant CA effect only in the property-repetition condition (3.7%), $F(1, 29) = 7.89$, $p < .01$, but not in the modality-alternation condition, $F(1, 29) < 1$ (see Figure 5B). In addition, there was a significant main effect of Switch, $F(1, 29) = 6.52$, $p < .05$, $\eta_p^2 = .18$. No other main effects or interactions were observed.

The MANOVA results showed that there was a significant CA effect, $F(1, 29) = 13.26$, $p < .001$, $\eta_p^2 = .49$, but the interaction among Switch, Previous Congruency, and Current Congruency was not significant, $F(1, 29) = 2.29$, $p = .12$, $\eta_p^2 = .14$.

Experiment 2B. For the RT, the main effect of Current Congruency was significant, $F(1, 29) = 25.55$, $p < .001$, $\eta_p^2 = .47$. Participants responded more slowly in incongruent condition (509

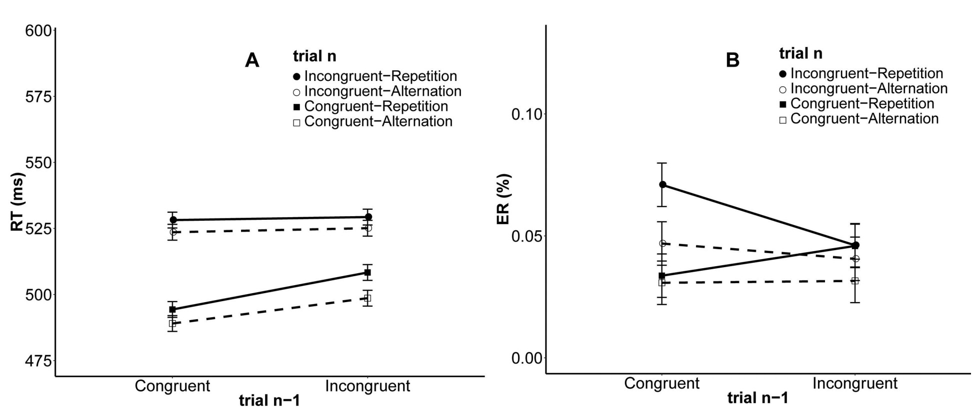

Figure 5. (A) Reaction time (RT) and (B) error rate (ER) of Experiment 2A as a function of congruent and incongruent conditions for both current and previous trials and their relationship (property- repetition or alternation). The error bars show the 95% confidence intervals of the means.

ms) than in congruent condition (493 ms). A significant CA effect was observed, $F(1, 29) = 23.04$, $p < .001$, $\eta_p^2 = .44$, suggesting that the SRC effect was smaller after incongruent trials (510 vs. 499 ms) than after congruent trials (509 vs. 486 ms). The interaction among Switch, Previous Congruency, and Current Congruency was not significant, $F(1, 29) = 1.46$, $p = .236$, $\eta_p^2 = .05$ (see Figure 6A). In addition, there were significant main effects of Switch, $F(1, 29) = 10.43$, $p < .01$, $\eta_p^2 = .27$, and Previous Congruency, $F(1, 29) = 23.27$, $p < .001$, $\eta_p^2 = .45$. No other main effects or interactions were observed.

For the ER, the main effect of Current Congruency was significant, $F(1, 29) = 13.09$, $p < .01$, $\eta_p^2 = .31$. Participants had a higher error rate in incongruent condition (7.7%) than in congruent condition (4.7%). There was a significant CA effect, $F(1, 29) = 21.21$, $p < .001$, $\eta_p^2 = .42$, suggesting that the SRC effect was smaller after incongruent trials (5.8% vs. 5.7%) than after congruent trials (9.7% vs. 3.5%). Moreover, the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 8.26$, $p < .01$, $\eta_p^2 = .22$. However, simple effect analyses revealed that there were significant CA effects in both property-repetition condition (9.4%), $F(1, 29) = 18.83$, $p < .001$, and property-alternation condition (3.1%), $F(1, 29) = 7.25$, $p < .05$ (see Figure 6B). In addition, there was a significant main effect of Switch, $F(1, 29) = 27.49$, $p < .001$, $\eta_p^2 = .49$. No other main effects or interactions were observed.

The MANOVA results showed that the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 4.47$, $p < .05$, $\eta_p^2 = .24$. However, simple effect analyses revealed that there were significant CA effects in both property-repetition condition, $F(1, 29) = 18.63$, $p < .001$, and property-alternation condition, $F(1, 29) = 5.28$, $p < .05$.

Discussion

Consistent with our hypothesis, besides observing the CA effect in property-repetition condition, we also found CA effect in property-alternation condition in Experiments 2A and 2B. These results are in agreement with recent studies, which found significant CA effect across S-S conflicts (e.g., Stroop-trajectory and flanker tasks; see Freitas & Clark, 2015), as well as across S-R conflicts (e.g., color Simon and shape Simon tasks; see Kim, Lee, & Cho, 2015). However, in these studies the task-irrelevant properties were of the same domain. For instance, the task-irrelevant stimuli of Stroop-trajectory and flanker tasks shared direction domain in the study of Freitas and Clark (2015). It is of importance to note this, because the contextual salient features are supposed to be critical factors determining transfer of CA effects (Braem et al., 2014). Our studies showed that task-irrelevant properties should not be salient enough as to contribute to the disappeared CA effects in Experiments 1A and 1B.

Experiments 3A and 3B

Although in Experiments 1A and 1B we found modality-specific CA effects, which suggest that conflicts rising from different modalities may involve distinct processes of cognitive control, the evidence was weakened by the potential confounding influence of task-irrelevant properties. To rule out the effect of task-irrelevant property differences on modality-specific CA effects, we then tested whether the task-irrelevant properties contributed to the domain-specific CA effects in Experiments 2A and 2B. While we found that changes in task-irrelevant property did not cause difference in CA effect in Experiment 2A, it did reduce, although not eliminate, the CA effect in Experiment 2B. These results suggest that task-irrelevant property may indeed affect the transfer of cognitive control, even though it may not fully account for the modality-specific CA effect observed in Experiments 1A and 1B. Therefore, we designed Experiments 3A and 3B to explore whether similar patterns as Experiments 1A and 1B would be replicated when task-irrelevant properties were controlled.

Method

Participants. Thirty volunteers participated in Experiment 3A (15 men and 15 women, aged between 18 and 26 years) and another 30 volunteers participated in Experiment 3B (14 men and 16 women, aged between 19 and 27 years). All other information was the same as in Experiments 1A and 1B.

Apparatus, stimuli, and procedure. The stimuli and procedure in Experiments 3A and 3B were similar to those in Experi-

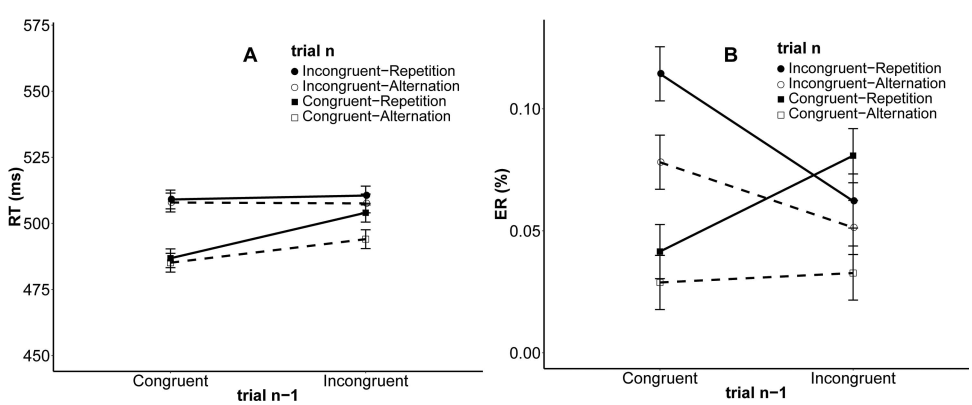

Figure 6. (A) Reaction time (RT) and (B) error rate (ER) of Experiment 2B as a function of congruent and incongruent conditions for both current and previous trials and their relationship (property- repetition or alternation). The error bars show the 95% confidence intervals of the means.

ments 1A and 1B, with the following changes. In Experiment 3A (compared with Experiment 1A), the SS_V conflict came from the background word instead of stimulus location, which matched the SS_A conflict semantically. However, this change might cause the SS_V conflict more difficult, because both the task-relevant and task-irrelevant stimuli were words. Therefore, we used an arrow as the task-relevant stimulus in place of a word. In detail, an arrow directing up or down was displayed at the center of a gray box, and a Chinese word "上" or "下" was displayed on the background in SS_V condition, while a neutral word (i.e., "立", denoting nonspatial information) was used in SS_A condition. Participants were instructed to make left/right key press as quickly and accurately as possible in response to the central arrow, ignoring the word shown in the background or the spoken word (see Figure 7). In Experiment 3B (compared with Experiment 1B), we replaced the arrow with a round dot appearing on the left/right side, to make sure both visual and auditory conflicts coming from the location. Thus, a red dot was shown on the left or right side of the gray box in SR_V condition, while a red dot was shown in the center in SR_A condition. Participants were instructed to watch the screen attentively and make left/right key press as quickly and accurately as possible in response to the spoken word, ignoring its spatial source (the left and/or right ear) or the location of the red dot (see Figure 7).

Data analysis. The analysis approaches were the same as those of Experiments 1A and 1B.

Results

Experiment 3A. For the RT, there was a significant main effect of Current Congruency, $F(1, 29) = 133.79$, $p < .001$, $\eta_p^2 = .82$. Participants responded more slowly in the incongruent condition (525 ms) than in the congruent condition (503 ms). The interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 8.69$, $p < .01$, $\eta_p^2 = .23$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (12 ms), $F(1, 29) = 5.55$, $p < .05$, but not in the modality-alternation condition, $F(1, 29) < 1$ (see Figure 8A). In addition, the main effect of Previous Congruency was significant, $F(1, 29) = 8.85$, $p < .01$, $\eta_p^2 = .23$. No other main effects or interactions were observed.

For the ER, there was a significant main effect of Current Congruency, $F(1, 29) = 7.64$, $p < .05$, $\eta_p^2 = .21$. Participants had a higher error rate in the incongruent condition (4.0%) than in the congruent condition (2.9%). The interaction among Switch, Previous Congruency, and Current Congruency was not significant, $F(1, 29) = 2.26$, $p = .143$, $\eta_p^2 = .07$ (see Figure 8B). In addition, the main effect of Switch was significant, $F(1, 29) = 29.35$, $p < .001$, $\eta_p^2 = .50$. No other main effects or interactions were observed.

The MANOVA results showed that the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 4.73$, $p < .05$, $\eta_p^2 = .25$. Simple effect analyses revealed that there was a marginally significant CA effect in the modality-repetition condition, $F(1, 29) = 3.01$, $p = .065$, but not in the modality-alternation condition, $F(1, 29) < 1$.

Given that the three-way interaction for the ER was not conclusive and we failed to obtain a CA effect for the within-modality condition, we conducted power analysis to estimate the current power and sample size needed to achieve 0.8 power for the within-modality CA effect. Based on data from 30 participants, the power for the ER was 0.53. It would require 52 participants to obtain a power of 0.8 for the ER. Therefore, we collected data from another 30 participants and replicated the above results, with a power of 0.85 for the ER for 60 participants.

For the RT, there was a significant main effect of Current Congruency, $F(1, 59) = 181.43$, $p < .001$, $\eta_p^2 = .76$. Participants responded more slowly in the incongruent condition (520 ms) than in the congruent condition (500 ms). The interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 59) = 6.51$, $p < .01$, $\eta_p^2 = .10$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (10 ms), $F(1, 59) = 8.20$, $p < .01$,

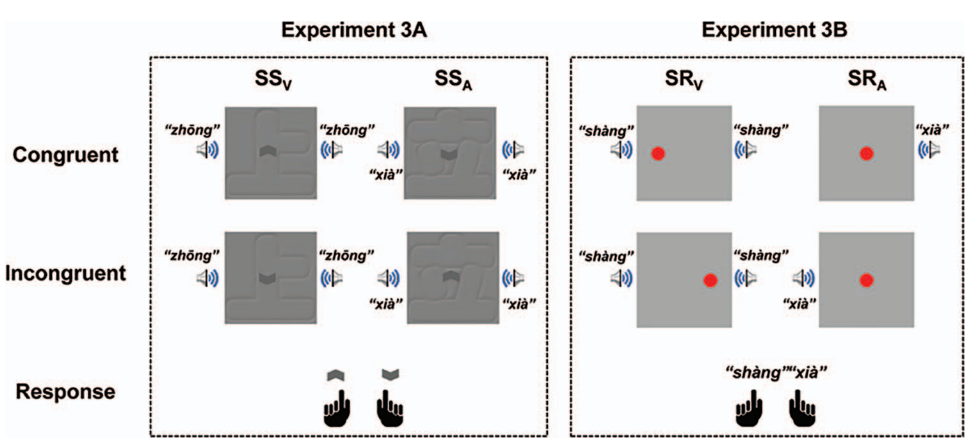

Figure 7. Examples of the different conditions in Experiments 3A and 3B. All possible trials (eight for each experiment) are randomly shown and counterbalanced across participants. Participants were asked to respond to the arrow displayed on the screen in Experiment 3A and respond to the voice presented by headphones in Experiment 3B. V = visual; A = auditory; SS = stimulus-stimulus overlap; SR = stimulus-response overlap. See the online article for the color version of this figure.

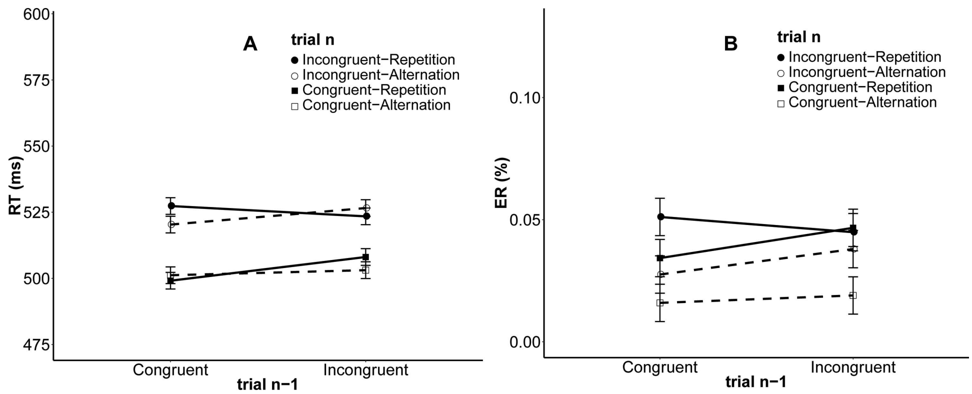

Figure 8. (A) Reaction time (RT) and (B) error rate (ER) of Experiment 3A as a function of congruent and incongruent conditions for both current and previous trials and their relationship (modality-repetition or alternation). The error bars show the 95% confidence intervals of the means.

but not in the modality-alternation condition, $F(1, 59) < 1$. In addition, the main effects of Switch, $F(1, 59) = 5.09$, $p < .05$, $\eta_p^2 = .08$, and Previous Congruency, $F(1, 59) = 5.24$, $p < .05$, $\eta_p^2 = .08$, were significant. No other main effects or interactions were observed.

For the ER, there was a significant main effect of Current Congruency, $F(1, 59) = 12.45$, $p < .01$, $\eta_p^2 = .17$. Participants had a higher error rate in the incongruent condition (4.9%) than in the congruent condition (3.3%). The interaction among Switch, Previous Congruency, and Current Congruency was marginally significant, $F(1, 59) = 3.76$, $p = .057$, $\eta_p^2 = .06$. Nevertheless, simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (2.0%), $F(1, 59) = 4.14$, $p < .05$, but not in the modality-alternation condition, $F(1, 59) < 1$. In addition, the main effect of Switch was significant, $F(1, 59) = 47.17$, $p < .001$, $\eta_p^2 = .44$. No other main effects or interactions were observed.

The MANOVA results showed that the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 59) = 4.80$, $p < .05$, $\eta_p^2 = .14$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition, $F(1, 59) = 5.36$, $p < .01$, but not in the modality-alternation condition, $F(1, 59) < 1$.

Experiment 3B. For the RT, there was a significant main effect of Current Congruency, $F(1, 29) = 52.19$, $p < .001$, $\eta_p^2 = .64$. Participants responded more slowly in the incongruent condition (537 ms) than in the congruent condition (511 ms). The interaction among Switch, Previous Congruency, and Current Congruency was not significant, $F(1, 29) = 1.81$, $p = .189$, $\eta_p^2 = .06$ (see Figure 9A). In addition, there were significant main effects of Switch, $F(1, 29) = 40.08$, $p < .001$, $\eta_p^2 = .58$, and Previous Congruency, $F(1, 29) = 8.16$, $p < .01$, $\eta_p^2 = .22$. No other main effects or interactions were observed.

For the ER, there was a significant main effect of Current Congruency, $F(1, 29) = 11.47$, $p < .01$, $\eta_p^2 = .28$. Participants had a higher error rate in the incongruent condition (4.7%) than in the congruent condition (2.9%). Moreover, the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 6.62$, $p < .05$, $\eta_p^2 = .19$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (3.2%), $F(1, 29) = 7.44$, $p < .05$, but not in the modality-alternation condition, $F(1, 29) < 1$ (see Figure

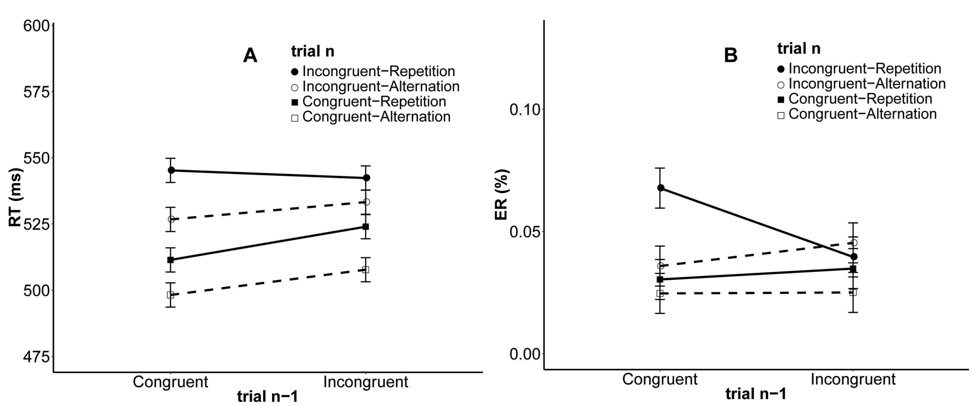

Figure 9. (A) Reaction time (RT) and (B) error rate (ER) of Experiment 3B as a function of congruent and incongruent conditions for both current and previous trials and their relationship (modality-repetition or alternation). The error bars show the 95% confidence intervals of the means.

9B). In addition, there was a significant main effect of Switch, $F(1, 29) = 5.94$, $p < .05$, $\eta_p^2 = .17$. No other main effects or interactions were observed.

The MANOVA results showed that the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 29) = 3.57$, $p < .05$, $\eta_p^2 = .20$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition, $F(1, 29) = 4.00$, $p < .05$, but not in the modality-alternation condition, $F(1, 29) < 1$.

Given the RT did not show a significant three-way interaction and we failed to obtain a CA effect for the within-modality condition, we conducted power analysis to estimate the current power and sample size needed to achieve 0.8 power for the within-modality CA effect. Based on data from 30 participants, the power for the RT were 0.79. It would require 31 participants to obtain a power of 0.8 for the RT. We collected data from another 30 participants along with Experiment 3A replication.

For the RT, there was a significant main effect of Current Congruency, $F(1, 59) = 185.25$, $p < .001$, $\eta_p^2 = .76$. Participants responded more slowly in the incongruent condition (534 ms) than in the congruent condition (503 ms). Interaction between Previous Congruency and Current Congruency (CA effect) was significant, $F(1, 59) = 12.82$, $p < .01$, $\eta_p^2 = .18$, suggesting that the SRC effect (Incongruent vs. Congruent) was smaller after incongruent trials (533 vs. 497 ms) than after congruent trials (535 vs. 510 ms). The interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 59) = 6.76$, $p < .05$, $\eta_p^2 = .10$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (20 ms), $F(1, 59) = 15.30$, $p < .001$, but not in the modality-alternation condition, $F(1, 59) = 1.03$, $p = .311$. In addition, the main effects of Switch, $F(1, 59) = 81.19$, $p < .001$, $\eta_p^2 = .58$, and Previous Congruency, $F(1, 59) = 31.47$, $p < .001$, $\eta_p^2 = .35$, were significant. No other main effects or interactions were observed.

For the ER, there was a significant main effect of Current Congruency, $F(1, 59) = 44.08$, $p < .001$, $\eta_p^2 = .43$. Participants had a higher error rate in the incongruent condition (4.5%) than in the congruent condition (2.4%). The interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 59) = 17.78$, $p < .001$, $\eta_p^2 = .23$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition (2.5%), $F(1, 59) = 11.31$, $p < .01$, but not in the modality-alternation condition, $F(1, 59) = 2.81$, $p = .10$. In addition, the main effect of Switch was significant, $F(1, 59) = 22.87$, $p < .001$, $\eta_p^2 = .28$. The interaction between Switch and Current Congruency was also significant, $F(1, 59) = 4.10$, $p < .05$, $\eta_p^2 = .07$. No other main effects or interactions were observed.

The MANOVA results showed that the interaction among Switch, Previous Congruency, and Current Congruency was significant, $F(1, 59) = 11.23$, $p < .01$, $\eta_p^2 = .28$. Simple effect analyses revealed that there was a significant CA effect only in the modality-repetition condition, $F(1, 59) = 9.69$, $p < .01$, but not in the modality-alternation condition, $F(1, 59) = 1.69$, $p = .19$.

Discussion

After matching the properties of task-irrelevant stimuli in Experiments 3A and 3B, we replicated modality-specific CA effects as observed in Experiments 1A and 1B, respectively. In comparison with Experiments 2A and 2B, these two experiments indicated that modality difference generated clear-cut domain-specific patterns. Therefore, the domain-specific effects caused by modality were robust, and should not be attributed solely to the distinction between task-irrelevant stimulus properties. This argument concur with the recent review, suggesting that task-irrelevant modality is one of the salient features that determine the across-conflict CA effect (Braem et al., 2014).

General Discussion

In the present study, we aimed to address the issue of whether the resolution of conflicts rising from different modalities relies on common or distinct control mechanisms. The modality-specific CA effects observed in Experiments 1A and 1B suggest that cognitive control cannot be generalized across conflicts from visual and auditory modalities. Moreover, the potential confounding effects of task-irrelevant stimuli in Experiments 1A and 1B were examined in Experiments 2–3, which ruled out the alternative interpretation that the absence of cross-modality CA effects in Experiments 1A and 1B was caused by the differences in task-irrelevant properties. Thus, our results lend support to the hypothesis that cognitive control is modality-specific. These findings are consistent with results also obtained by Hazeltine et al. (2011, Experiment 1), in which the modality-specific CA effect might have been caused by task-switching.

Our findings accord with the distractor-deactivation account (Frings & Wuhr, 2014; Kim et al., 2015; Mozolic et al., 2008) and are against the target-amplification account (Egner & Hirsch, 2005) of conflict-resolution mechanism. If the conflict were resolved by focusing attentional resources on the task-relevant stimulus property, conflict adaptation should be also observed in modality-alternation conditions in Experiments 1A and 1B because task-relevant stimuli were kept constant. However, this was not the case. The modality-specific conflict adaptation suggests that conflict resolution relies more on suppressing the processing of distractors and cognitive control on conflict resolution does not transfer across modality. This account is consistent with previous studies that found that the allocation of attentional resources is modality-specific (Arrighi, Lunardi, & Burr, 2011; Keitel, Maess, Schroger, & Muller, 2013).

Moreover, we observed significant CA effects across the SS_{Arr} and SS_{Loc} conditions in Experiment 2A as well as across SR_{Arr} and SR_{Loc} conditions in Experiment 2B. These findings are consistent with previous studies. For example, CA effect occurred across color Simon and shape Simon tasks (Kim et al., 2015). Other studies have reported CA effects across two S-S tasks, such as Stroop-trajectory and flanker manipulations (Freitas & Clark, 2015), Stroop and flanker manipulations (Freitas et al., 2007), and classic flanker and gender flanker manipulations (Kleiman et al., 2014). Nevertheless another study observed significant CA effect in a vocal Stroop-like task when the task-irrelevant voice gender was repeated, but not when the gender was alternated (Spape & Hommel, 2008). Possible interpretation is that the task-irrelevant stimulus property indeed exerts influence on the transfer of cognitive control (Braem et al., 2014). However, sometimes it may not be salient enough to cause significant difference.

Yet, several limitations remained in our study. Although feature integration was excluded in context-alternation conditions, we could not entirely rule out the confounding factor of feature integration in context-repetition conditions. In the context-alternation conditions, by excluding the trials with repeated responses, we removed the contribution of the bottom-up stimulus/response priming to the CA effects (Ullsperger et al., 2005); therefore, the CA effects only reflected the transfer of cognitive control. However, after excluding trials with response repetition in context-repetition conditions, half of the remaining trials (i.e., the iC and cI trials) were still partially overlapped, sharing the same task-irrelevant stimulus dimension. Thus feature integration also contributed to the CA effects in the context-repetition conditions in our two-choice design. Furthermore, the negative priming was not controlled for two reasons: (a) Because there are the same number of negative priming situations for within- and cross- modality conditions, it should have influenced them similarly. Therefore, when we compared the two conditions, the reversal effect in conflict adaptation if any (Bugg, 2008), should be cancelled out; (b) It would be impossible to analyze the CA effect without these negative priming trials after priming trials being removed as we did, because removing the negative priming trials would have eliminated all II and IC trials. To clearly partial out these factors, recent studies have adopted SRC tasks that involve more than two response options (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014).

In conclusion, we observed distinct CA effects across modality-repetition and alternation conditions, similar to the domain-specific patterns caused by different DO types. In addition, the impact of task-irrelevant stimuli on the CA effect was discounted, as cognitive control could transfer across conflicts with distinct task-irrelevant stimuli. Moreover, our designs eliminated the task-switching influence (Egner, 2008) occurring in the previous studies. Therefore, the results of the current study clearly support that the modality should be considered as a boundary of cognitive control.

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