



Making a saccade enhances Stroop and Simon conflict control

Xiaoxiao Luo^{1,2} · Jiayan Gu³ · Yueyuan Zheng⁴ · Xiaolin Zhou^{1,2,3,5}

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Abstract

Cognitive control is an important ability instantiated in many situations such as conflict control (e.g., Stroop/Simon task) and the control of eye movements (e.g., saccades). However, it is unclear whether eye movement control shares a common cognitive control system with the conflict control. In Experiment 1, we asked participants to make a prosaccade or antisaccade and then to identify the color of a lateralized color word (i.e., a Stroop–Simon stimulus). The stimulus onset asynchrony (SOA) between the saccadic cue and the Stroop–Simon stimulus was manipulated to be either short (200 ms) or long (600 ms). Results showed that the Stroop effect at the response level and the (negative) Simon effect were smaller when the SOA was short than long, demonstrating a decline of response control over time after making a saccade. Moreover, this temporal change of the Simon effect was more pronounced in the antisaccade session than in the prosaccade session. Furthermore, individuals who had better performance in the antisaccade task performed better in the response control of Stroop interference. When the saccade task was removed in Experiment 2, the temporal declines of the response control observed in Experiment 1 were absent. Experiment 3 replicated the key results of Experiment 1 by replacing the Stroop–Simon task with a typical Simon task and separately testing the typical Stroop and Simon tasks. Overall, our findings suggest that a common system is shared between the control of eye movements and the conflict control at the response level.

Keywords Saccade · Conflict control · Stroop effect · Simon effect · Temporal dynamic

Introduction

Cognitive control is the ability to generate, maintain and adjust sets of goal-directed processing (Egner, 2008). One typical situation that requires cognitive control is when individuals face conflicts (i.e., conflict control)—they need to select task-relevant information for processing and responding but not get distracted by task-irrelevant information (Botvinick

et al., 2001; Posner & DiGirolamo, 1998; van Veen & Carter, 2006). Another situation that requires cognitive control is when individuals actively make saccades (i.e., the control of eye movements)—they need to control and direct their gaze to a goal location (Munoz & Everling, 2004; Ray et al., 2004), which is one of the most important methods to gather or search for information in daily life.

Cognitive control is often studied by using a broad range of tasks, such as the Stroop task (MacLeod, 1991; Stroop, 1935) and the Simon task (Hommel, 2011; Simon & Rudell, 1967) for investigating the conflict control, and the pro- or antisaccade task (Hallett, 1978; Munoz & Everling, 2004) for investigating the control of eye movements. The Stroop task requires individuals to respond to the ink color of a color word and ignore the word meaning. Individuals' performance is declined when the ink color and the word meaning are semantically incongruent (e.g., “red” in green ink) than when congruent (i.e., the Stroop effect). The Simon task requires individuals to respond to a lateralized stimulus and ignore the location of the stimulus. Individuals' performance is declined when the location of the stimulus is incongruent with the required response effector (e.g., the stimulus is presented at left but the correct response should be made by the right hand) than when congruent (i.e., the Simon effect). Smaller

✉ Xiaolin Zhou
xz104@pku.edu.cn

¹ Shanghai Key Laboratory of Mental Health and Psychological Crisis Intervention, School of Psychology and Cognitive Science, East China Normal University, Shanghai 200062, China

² Beijing Key Laboratory of Behavior and Mental Health, School of Psychological and Cognitive Sciences, Peking University, Beijing 100871, China

³ Institute of Linguistics, Shanghai International Studies University, Shanghai 201600, China

⁴ Department of Psychology, Faculty of Social Sciences, University of Hong Kong, Hong Kong, China

⁵ PKU-IDG/McGovern Institute for Brain Research, Peking University, Beijing 100871, China

Stroop or Simon effect often reflects more involvement of the control system. In the prosaccade task, participants need to direct their gaze toward the location of a peripheral cue (i.e., following a reflexive tendency), possibly requiring little cognitive control. In the antisaccade task, participants need to direct their gaze away from the location of a cue to its mirror position (i.e., inhibiting the reflexive tendency and complete a re-directed saccade), possibly recruiting more cognitive control compared with the prosaccade task.

Numerous studies have shown that the conflict control is possibly domain specific or noncentralized; that is, there are (partially) different cognitive control systems operate (in parallel) to deal with different types of conflict. This notion is evidenced by studies showing no interaction between the Stroop congruency and the Simon congruency in a combined Stroop–Simon task (Hommel, 1997; Kornblum, 1994; Simon & Berbaum, 1990; Wendt et al., 2006), and by studies showing no correlation between different types of conflict effects across participants (Hedge et al., 2018; Rey-Mermet et al., 2019; Rouder & Haaf, 2019). For the conflict adaptation effect, which refers to the phenomenon that the conflict effect would be smaller following an incongruent stimulus than following a congruent stimulus (Egner, 2007, 2008), it has been shown that the Stroop conflict could only affect the resolution of subsequent conflict in a Stroop stimulus but not the resolution of conflict in a Simon stimulus, and vice versa (Egner et al., 2007; Torres-Quesada et al., 2013), suggesting that separate, conflict-specific control mechanisms are involved in different conflicts for the adaptation of conflict control.

Although it is believed that there are domain-specific systems for different types of conflict, it is still an open question whether the control of eye movements recruits a (part of) system involved in conflict control. Previous studies showed that in a saccadic Stroop task in which a saccade was made to the location of a peripheral color patch which matched the ink-color of a centrally presented Stroop stimulus, saccadic performance would be affected by the congruency of the Stroop stimulus (Hermens & Walker, 2012; Hodgson et al., 2009; Singh & Mishra, 2013). Moreover, the typical Simon effect was absent when participants had to make a prosaccade toward the location of the stimulus beforehand (Buetti & Kerzel, 2010); and the magnitude of the Simon effect was reduced if participants were previously trained with an antisaccade task (Verghese et al., 2018). Furthermore, performance in conflict control tasks (e.g., Stroop task) correlated with the antisaccade performance (Redick et al., 2016; Unsworth & Spillers, 2010). By using latent variable models, researchers also had showed that the general executive/sustained attention measured by conflict control tasks could predict the antisaccade performance (Meier et al., 2018). Taken together, it seems that the control of eye movements may share a (partly) common cognitive control mechanism with the Stroop or Simon conflict.

Nevertheless, a study that directly combines the saccade task, the Stroop task, and the Simon task is needed to provide direct evidence for this proposal, which is the aim of the present study. If there is a (partly) common system behind the control of eye movements and the control of conflict, a saccade to a particular location may affect the subsequent response to the stimulus of conflict appearing at that location.

Experiment 1

In Experiment 1, we combined the Stroop task and the Simon task (i.e., a Stroop–Simon task; see also Egner et al., 2007; Hommel, 1997; Kornblum, 1994; Simon & Berbaum, 1990; Wendt et al., 2006) but asked participants to actively execute a prosaccade or antisaccade before responding to the Stroop–Simon stimulus. Importantly, we manipulated the stimulus onset asynchrony (SOA) between the cue for the pro- or antisaccade and the Stroop–Simon stimulus to be either short (200 ms) or long (600 ms).

This SOA manipulation would allow us to investigate the temporal dynamic of the impact of making a saccade upon the subsequent conflict control. Previous studies have shown that the conflict adaptation effect results from increased top-down control on the processing of the current stimulus, triggered by the occurrence of conflict at the preceding incongruent stimulus (Botvinick et al., 2001; Ullsperger et al., 2005). The magnitude of this conflict adaptation effect can dynamically decline as a function of the SOA between the presentations of the two stimuli, demonstrating a temporal decline of top-down control. For example, in a variation of the Stroop task, the conflict adaptation effect would be most pronounced at the shortest SOA, quickly decay in magnitude with the increasing SOA, and be absent at longer SOA (Egner et al., 2010). Similar patterns were also found for the conflict adaptation effect in the Simon task (Wühr & Ansorge, 2005). Therefore, in Experiment 1, if the control of eye movements shares a part of common cognitive control system with the Stroop or Simon conflict, the control of eye movements might trigger the conflict adaptation processes for the subsequent conflict control task. Accordingly, we predicted that the Stroop and/or Simon effect could be smaller after making a saccade when the SOA was short than long, and this impact of SOA might be more pronounced after an antisaccade (which requires more cognitive control) than after a prosaccade (which requires less cognitive control). In contrast, if the control of eye movements recruits an independent cognitive control system, making a saccade should not affect the subsequent resolution of conflict, regardless of the SOA. In addition, across individuals, if the control of eye movements shares a part of common cognitive control with the Stroop or Simon conflict, the performance in the saccade task might correlate with the performance in the Stroop–Simon task.

Moreover, in Experiment 1, we differentiated the Stroop effect at the perceptual level and at the perceptual-response level (see Methods for details; see also Chen et al., 2013; Chen et al., 2006; de Houwer, 2003; Schmidt & Cheesman, 2005) to explore how the control of eye movements would affect conflict control at different processing levels. The Dimensional Overlap (DO) model (Kornblum et al., 1990) defines different sources of the conflict effect according to the overlap of the processing level between task-relevant and task-irrelevant dimensions, such that the conflict could occur at the perceptual level, that is, stimulus–stimulus compatibility (SSC) and at the perceptual-response level, that is, stimulus–response compatibility (SRC). For example, the Stroop effect is produced by the combination of the conflict at SSC level and the conflict at SRC level (de Houwer, 2003; Schmidt & Cheesman, 2005; Zhang & Kornblum, 1998) whereas the Simon effect is produced by the conflict at SRC level (Egner, 2008; Egner et al., 2007; Liu et al., 2004). Therefore, if the control of eye movements shares a common control system with the Stroop or Simon conflict, it may affect the SRC level more than the SSC level, because that the control of eye movements is tightly coupled with other goal-directed motor movements (de Brouwer et al., 2021).

Method

Participants

The power analysis by G*power 3.1 (Faul et al., 2007) showed that 36 participants were needed to detect the effects in a design with at least four measures (e.g., a 2×2 within-participants design) given a medium effect size ($f = 0.25$), $\alpha = 0.05$, and $power = 0.95$. Thus, 48 university students took part in Experiment 1. Two participants were excluded due to low accuracy in the Stroop–Simon task (beyond three standard deviations below the mean accuracy), and three participants were excluded due to extensive trial exclusion (beyond three standard deviations above the mean proportion) based on their saccade data (trials with insufficient saccade were excluded; see Data Analysis for details). Thus, 43 participants were included (31 females, 18 to 26 years old, $M = 21.23$, $SD = 2.05$). All participants were right-handed and had normal or corrected-to-normal vision. None of them reported a history of neurological or psychiatric disorders. This study was performed in accordance with the Declaration of Helsinki and was approved by the Committee on Human Research Protection, East China Normal University, and by the Committee for Protecting Human and Animal Subjects, School of Psychological and Cognitive Sciences, Peking University. Informed consent was obtained from all participants who received monetary compensation for their participation (¥50 per hour).

Stimuli and procedure

All stimuli were presented on a ViewSonic LCD monitor with a gray background (display size: 44×33 cm, refresh rate: 100 Hz, resolution: $1,024 \times 768$ pixels) positioned 70 cm from the participant, connected to a Dell OptiPlex 9020 PC. Stimuli include a white fixation cross “+” ($1.7^\circ \times 1.7^\circ$) presented at the center of the screen, a white cue stimulus “=” ($1.7^\circ \times 1.0^\circ$) presented 13.4° left or right to the center of the screen, and target stimuli including four Chinese characters (“红”, “绿”, “黄”, and “蓝”, meaning “red”, “green”, “yellow”, and “blue”, respectively, $2.2^\circ \times 2.2^\circ$) with four possible colors (red, green, yellow, and blue) presented 13.4° left or right to the center of the screen. Stimulus presentation and response recording were controlled by Psychophysics Toolbox (<http://www.psychtoolbox.org/>, Brainard, 1997) with MATLAB. Each participant individually performed the experiment in a dimly lit room with the head position maintained on a chinrest. Eye-tracking was monitored based on the left eye of each participant using the EyeLink 1000 plus system (SR Research) at a sampling rate of 1000 Hz.

The trial structure is shown in Fig. 1. There were two experimental sessions, the prosaccade session, and the antisaccade session. In each trial, the fixation cross was presented at the center of the screen for 300 to 700 ms. Then the cue would be presented at either the left or right side of the screen for 50 ms, followed by a blank screen for 50 ms, and followed by the second appearance of the cue for another 50 ms at the same location. Thus, the cue flashed on and off briefly to attract attention. Then a blank screen was presented for 50 ms or 450 ms. Thus, the SOA between the onset of the cue and the onset of the target could be either 200 ms or 600 ms. Then, the target stimulus appeared at the same position as the cue in the prosaccade session, or at the position opposite to the cue in the antisaccade session, until participants made a response or until 2,000 ms elapsed. Feedback (“Too slow!”) would be presented at the center of the screen for 500 ms if no response was given within the 2,000 ms. At last, a blank screen was presented for 500 ms as an intertrial interval.

In the prosaccade (antisaccade) session, participants were asked to perform a saccade toward (away from) the direction of the cue as quickly as possible after the appearance of the cue, then identify the color of the target stimulus as quickly and accurately as possible by pressing “Q” or “P” key on the keyboard using the index finger on the left hand and the index finger on the right hand (for half of participants, they were asked to press “Q” if the color was red or green, and press “P” if the color was yellow or blue; for another half of participants, the mapping between keys and colors was reversed). To ensure that the button “Q” and the button “P” had equal horizontal distance to the center of the screen, the position of the keyboard was fixed during the experiment.

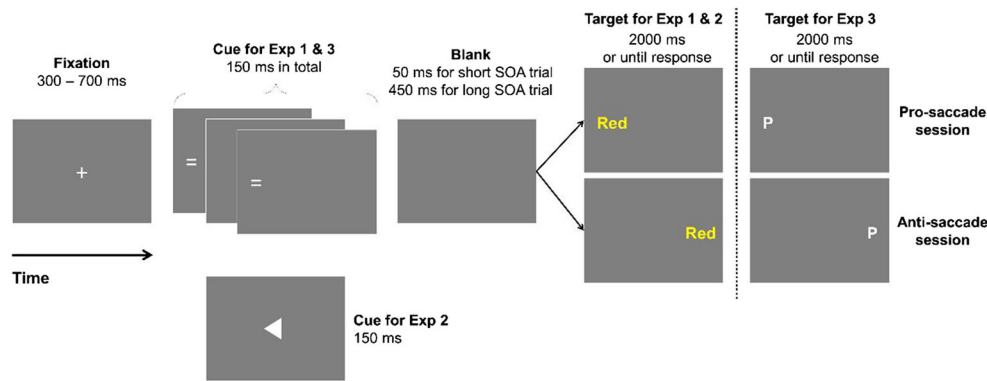


Fig. 1 The trial structure of the present study. In Experiment 1, a lateralized flashing cue was presented either left or right, and a lateralized color word was presented as the target at the same location as the cue (the prosaccade session) or at the opposite location to the cue (the antisaccade session). Participants were asked to make a pro- or antisaccade after the onset of the cue and then to identify the color of the target. In Experiment 2, the saccade task was removed, participants were asked to maintain their gaze at a central cue before the target was

presented. The central cue was a left or right arrow, and the lateralized target was presented at the same direction as the central arrow (the pro-arrow session) or at the opposite direction to the central arrow (the anti-arrow session). In Experiment 3, the lateralized color word in Experiment 1 was replaced with a lateralized letter (P or Q), and participants were asked to identify the letter after making a prosaccade or antisaccade. There was a 500-ms blank screen as the inter-trial-interval, not shown in this figure

For the Stroop congruency, there were three conditions (here we termed them as “S+R+”, “S–R+”, and “S–R–”). The S+R+ (congruent) condition: the word-meaning and the ink color were congruent, including “红” (“red”) in red ink, “绿” (“green”) in green ink, “黄” (“yellow”) in yellow ink, and “蓝” (“blue”) in blue ink. The S–R+ (semantically incongruent) condition: the word meaning and the ink color were semantically incongruent, but corresponding (potential) response keys were the same, including “红” (“red”) in green ink, “绿” (“green”) in red ink, “黄” (“yellow”) in blue ink, and “蓝” (“blue”) in yellow ink. The S–R– (double incongruent) condition: the word-meaning and the ink color were semantically incongruent, so the corresponding (potential) responses keys, including “红” (“red”) in blue or yellow ink, “绿” (“green”) in blue or yellow ink, “黄” (“yellow”) in red or green ink, and “蓝” (“blue”) in red or green ink.

For the Simon congruency, there were two conditions. The congruent condition: the correct response was “Q” (the left key) or “P” (the right key) when the target stimulus appeared at the *left* or *right* of the screen, respectively. The incongruent condition: the correct response was “Q” or “P” when the target stimulus appeared at the *right* or *left* of the screen, respectively.

Therefore, Experiment 1 had a 2 (Saccade type: prosaccade vs. antisaccade) \times 3 (Stroop congruency: S+R+, S–R+ vs. S–R–) \times 2 (Simon congruency: congruent vs. incongruent) \times 2 (SOA: 200 ms vs. 600 ms) within-participants design. There were 32 trials for each of the 24 conditions (16 blocks with 768 trials in total). In particular, there were eight blocks with 384 trials for each session (i.e., the pro- or antisaccade session). The sequence of the sessions was counterbalanced across participants. Trials for other experimental conditions were distributed with equal probability in each block, with trials for different conditions randomized for the test

sequence. Before each session, participants were asked to complete 48 practice trials, and they were required to repeat the practice trials if the accuracy was below 80%.

For monitoring eye movements, we performed nine-point calibration and verification with the eye tracker at the beginning of each session. Drift correction (and recalibrated if necessary) was performed at the beginning of each block. Participants were required to fixate at the fixation cross at the beginning of each trial before the flashing cue appeared. If participant’s fixation did not locate in the 1° area of the fixation cross within 5000 ms, drift correction would be performed again.

Data analysis

Saccade task The eye movement data was processed with the Edf2Mat MATLAB Toolbox (Etter & Biedermann, 2018; <https://www.github.com/uzh/edf-converter>). Figure 2 shows the relative distance (degree) of the gaze position from the screen center after the onset of the cue (i.e., the trajectory of gaze position), by which we could get the indexes of saccade performance for each trial. Specifically, Fig. 2a shows a typical saccade pattern in the prosaccade session. The onset of a saccade was defined as the time point when the trajectory of gaze position had changed over 1° within 10 ms (i.e., over 100%/s of saccade velocity). A correct saccade trial was defined as a trial in which the direction of the first saccade after the onset of the cue was target oriented, and the saccade latency was defined as the time interval between the onset of the cue and the onset of the first saccade in a correct saccade trial. Figure 2b shows a typical saccade pattern in the antisaccade session, and this was an incorrect saccade trial due to that the direction of the first saccade after the onset of the cue was opposite to the target position.

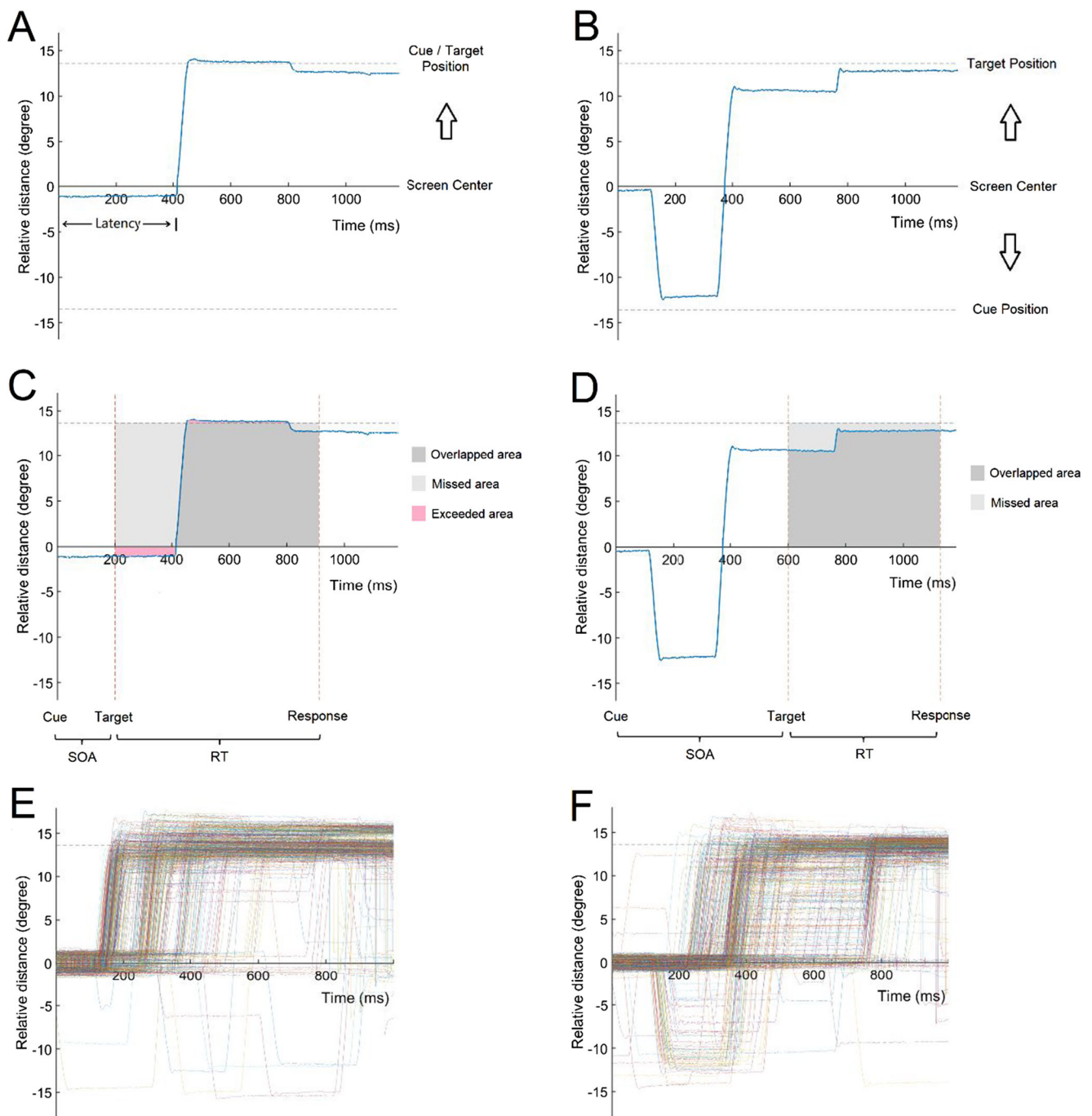


Fig. 2 The relative distance (degree) of the gaze position from the screen center after the onset of the cue (i.e., the trajectory of gaze position). The positive/negative value of the relative distance indicated that the gaze position was approaching/away from the target position (illustrated by the horizontal dotted line, 13.4° from the screen center). **a** A typical saccade pattern in the prosaccade session, that is, a successful prosaccade (trial #20 in the prosaccade session of participant #1). **b** A typical saccade pattern in the antisaccade session, that is, a failed antisaccade (trial #9 in

the antisaccade session of participant #1). **c** An example of calculating the proportion of overlapped areas in a prosaccade. The left and right vertical dotted lines represent for the onset of the target and the response, respectively. **d** An example of calculating the proportion of overlapped areas in an antisaccade. **e** The trajectories of gaze position of all trials in the prosaccade session for participant #1. **f** The trajectories of gaze position of all trials in the antisaccade session for participant #1. SOA = stimulus onset asynchrony between the onset of the cue and the onset of the target

The saccade accuracy in each session was calculated as the proportion of the correct saccade trial in all trials of that session, and the saccade error rate (SER) was calculated as “1—

saccade accuracy.” The mean saccade latency (SL) in each session was calculated as the mean latency of all correct saccade trials in that session. The paired *t* tests between the pro-

and antisaccades were conducted based on the SER and the SL to validate the success of the pro- and antisaccade manipulations.

Stroop–Simon task performance (uncorrected) Omissions, trials with incorrect response in the Stroop–Simon task were not included when the mean reaction time (RT) of each condition was calculated. Trials with RTs beyond three standard deviations above or below the mean RT in each condition were excluded (1.43% of total trials). The mean RT in each condition was then calculated based on the remaining trials. The accuracy in each condition was calculated as the proportion of the correct trials in all trials of that condition, and the error rate (ER) in each condition was calculated as “1—accuracy.” The 2 (Saccade type: prosaccade vs. antisaccade) \times 3 (Stroop congruency: S+R+, S–R vs. S–R–) \times 2 (Simon congruency: congruent vs. incongruent) \times 2 (SOA: 200 ms vs. 600 ms) repeated-measures ANOVA was performed on both RTs and ERs.

Stroop–Simon task performance (corrected) Considering that the eye fixation would not always locate on the target position after the onset of the target (especially in the 200 ms SOA condition) which may affect information processing for the target stimulus, we developed an index (P_T) to access the weight (proportion) of the cognitive processing for the target stimulus during the whole trial (i.e., from the onset of the cue to the response) and adjusted the RTs of the Stroop–Simon task (i.e., the time interval between the onset of the target and the response). Specifically, in Fig. 2c and d, the horizontal dotted line represents the target position (13.4° from the screen center), and the left and right vertical dotted lines respectively represent the onset of the target and the response in the current trial. These three dotted lines and the x -axis (i.e., the screen center) form a rectangle (all the gray areas) which demonstrates information processing of the target stimulus. If the gaze position always locates on the target position (i.e., all processes are assigned to the target after the onset of the target), the meaning of the area of this rectangle (i.e., RT \times the constant distance between screen center and the target location) is equivalent to the RT. However, the gaze position might not locate on the target position yet after the onset of the target, and the area between the trajectory of gaze position and the x -axis would be partly overlapped with the rectangle (i.e., overlapped area, S_O , the dark gray areas in Fig. 2c and d) which can be regarded as the cognitive processing for the target. In contrast, the remaining area in the rectangle (i.e., missed area, S_M , the light gray areas in Fig. 2c and d) can be regarded as the cognitive processing for the to-be-completed saccade. In addition, any other area, formed by the trajectory of gaze position, but exceeded the rectangle (i.e., exceeded area, S_E , the pink area in Fig. 2c) can be regarded as the processing which hinder the target processing, since the gaze

position in that trajectory goes far away from the target position. Based on all these areas, the proportion of the cognitive processing for the target during the whole trial can be calculated by using the formula: $P_T = (S_O - S_E) / (S_O + S_M)$.

Higher P_T indicates that more cognitive processing was assigned to the target stimulus (i.e., participants completed the saccade task earlier after the onset of the target stimulus). In contrast, lower P_T indicates that less cognitive processing was assigned to the target stimulus (i.e., the saccade task was still incomplete, or the saccade was insufficient after the onset of the target). Thus, the RT for the target stimulus in each trial can be corrected by using the formula: $RT_{corr} = RT \times P_T$.

It should be note that participants might identify the target stimulus by peripheral vision with an insufficient saccade (or even without a saccade), which was inconsistent with the task requirement (i.e., making a saccade). Thus, trials with insufficient saccade ($P_T < 50\%$) were excluded (9.34% of total trials) when the corrected RT was calculated. After the trial exclusion of omissions, trials with incorrect response, and trials with RTs beyond three standard deviations above or below the mean RT in each condition in the Stroop–Simon task, the mean corrected RTs of the Stroop–Simon task in each condition were calculated with the remaining trials. The same 2 \times 3 \times 2 \times 2 repeated-measures ANOVA on corrected RTs was conducted.

Correlation analysis To test whether the control of eye movement and the conflict control share a (part of) common mechanism with each other, we conducted correlation analyses based on the antisaccade latency and the Stroop or Simon effect, since the antisaccade performance is often used as an index of the recruitment of control in the eye movement (e.g., Kane et al., 2001; Meier et al., 2018; Redick et al., 2016).

Results

Saccade task performance

Figure 2e and f show an example of the trajectories of gaze position of all trials in the pro- and antisaccade sessions. It is clear that the saccade error rate (SER) was lower and the saccade latency (SL) was shorter in the prosaccade session than in the antisaccade session, SER: 4.33% vs. 23.09%, $t(42) = 9.49$, $p < .001$, $d = 1.45$; SL: 206 vs. 379 ms, $t(42) = 15.46$, $p < .001$, $d = 2.36$, which was consistent with the typical patterns of the pro- and antisaccade tasks.

Stroop–Simon task performance

The 2 (Saccade type: prosaccade vs. antisaccade) \times 3 (Stroop congruency: S+R+, S–R vs. S–R–) \times 2 (Simon congruency: congruent vs. incongruent) \times 2 (SOA: 200 ms vs. 600 ms) ANOVA was conducted on RTs, corrected RTs, and ERs of the

the Stroop–Simon task. To directly test our prediction and simplify the report of results, we focused on the Stroop and Simon effects and their interactions with other factors (full results can be found in the [Supplementary Information](#)).

Reaction times (uncorrected) The main effect of Stroop congruency was significant, $F(2, 84) = 122.65, p < .001, \eta_p^2 = .75$. Importantly, the interaction between Stroop congruency and SOA was significant, $F(2, 84) = 4.29, p = .017, \eta_p^2 = .10$ (Fig. 3a). Planned t tests on simple effects showed that under both the 200 ms SOA and the 600 ms SOA, the typical Stroop effects were observed at both the SSC level and the SRC level (all p s < .001). We further calculated the magnitude of Stroop effects (Fig. 3b) at both the SSC level (i.e., the RT in S–R+ condition minus the RT in S+R+ condition) and the SRC level (i.e., the RT in S–R– condition minus the RT in S–R+ condition), and found that the Stroop effect at the SSC level did not differ between the two SOA conditions (15 vs. 15 ms), $t < 1$; in contrast, the Stroop effect at the SRC level was smaller when

the SOA was 200 ms than when the SOA was 600 ms (47 vs. 60 ms), $t(42) = 2.53, p = .015, d = 0.39$.

The main effect of Simon congruency was also significant, $F(1, 42) = 9.21, p = .004, \eta_p^2 = .18$, with participants responded *slower* for the congruent condition (673 ms) than for the incongruent condition (663 ms), that is, a negative Simon effect. Moreover, the interaction between Simon congruency and SOA was significant, $F(1, 42) = 9.46, p = .004, \eta_p^2 = .18$. Importantly, the three-way interaction between Simon congruency, SOA, and Saccade type was significant, $F(1, 42) = 5.83, p = .020, \eta_p^2 = .12$ (Fig. 4a). In the prosaccade session, the 2 (SOA: 200 ms vs. 600 ms) \times 2 (Simon congruency: congruent vs. incongruent) ANOVA showed only a significant main effect of SOA, $F(1, 42) = 94.42, p < .001, \eta_p^2 = .69$; the main effect of Simon congruency, $F(1, 42) = 3.17, p = .082$, or the interaction, $F(1, 42) = 1.25, p = .270$, was not significant. However, in the antisaccade session, the same 2 \times 2 ANOVA showed not only a significant main effect of SOA, $F(1, 42) = 277.14, p < .001, \eta_p^2 = .87$, but also a

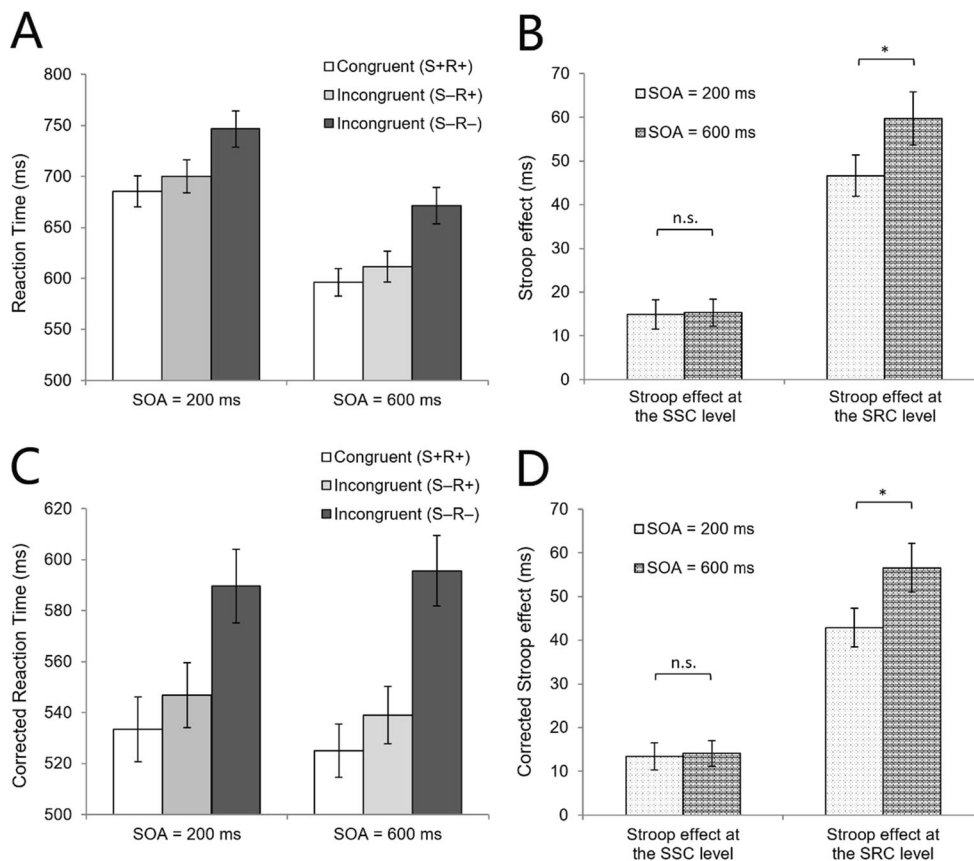
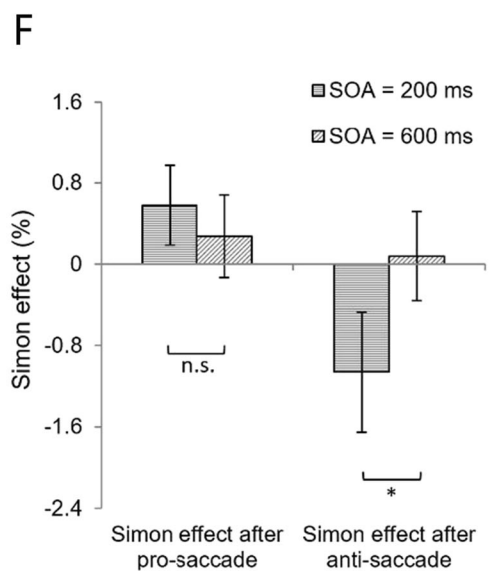
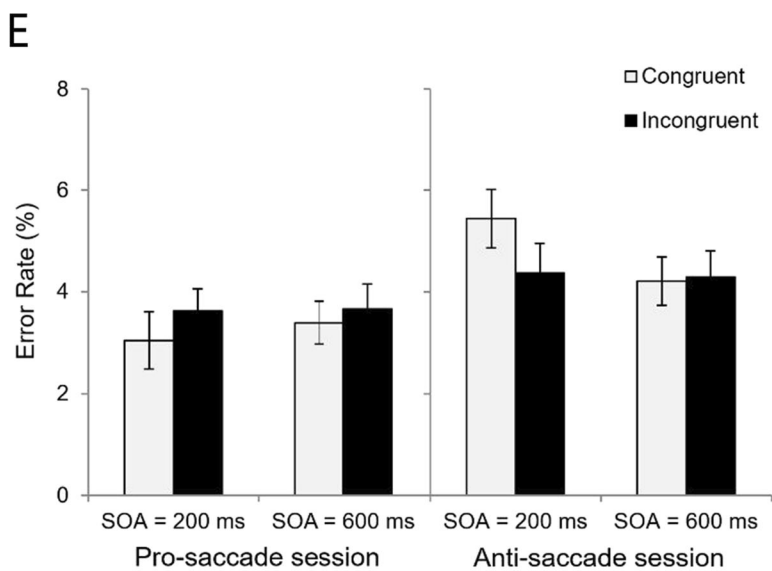
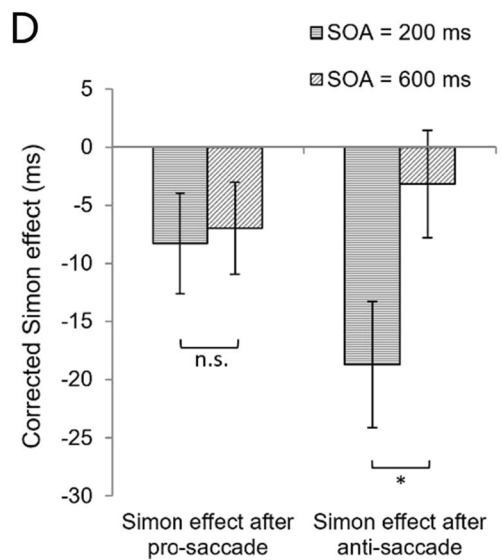
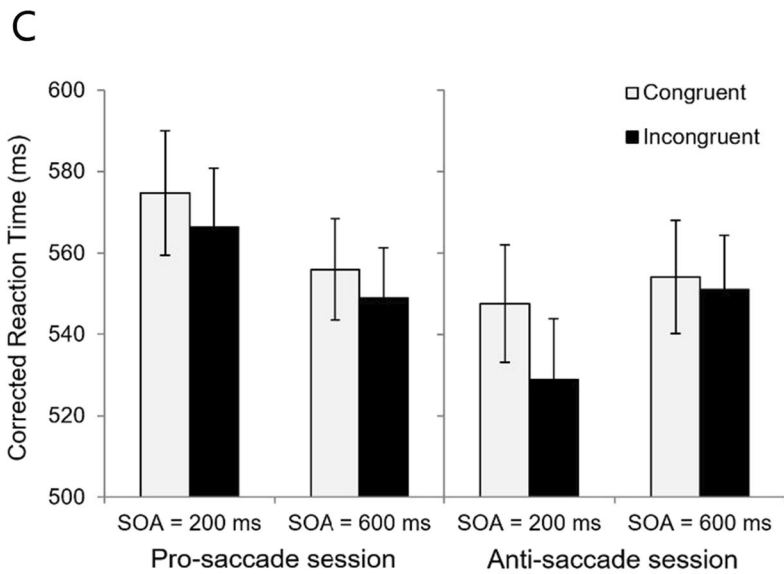
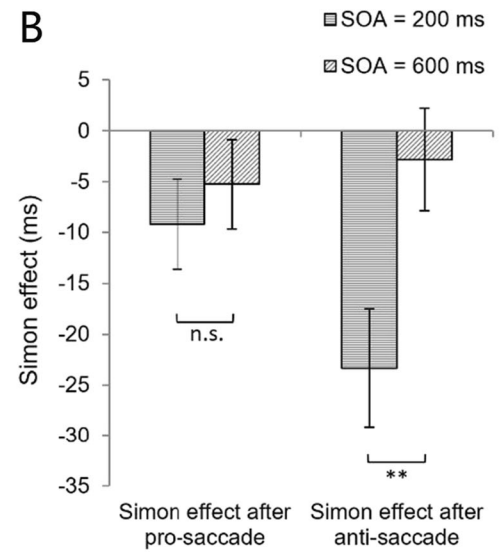
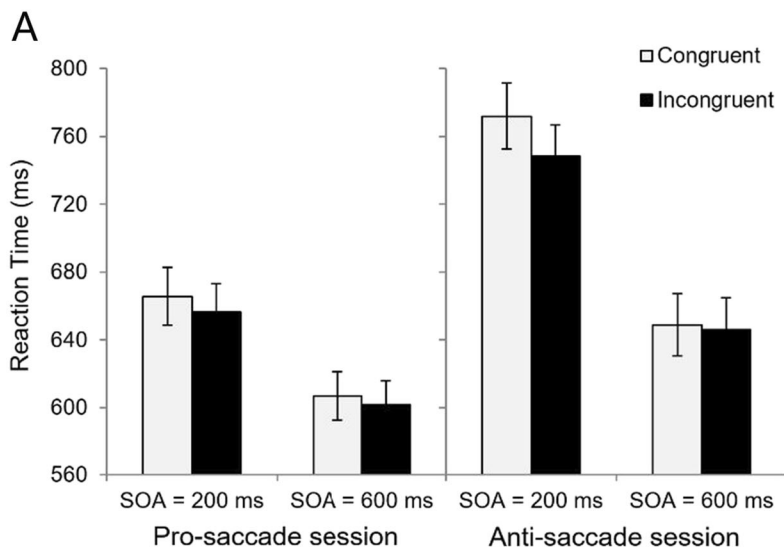


Fig. 3 The reaction time (RT) results on the interactions between Stroop congruency and SOA type in Experiment 1. **a** Uncorrected RTs as a function of SOA and Stroop congruency. **b** Uncorrected Stroop effects at the stimulus–stimulus compatibility (SSC) level and the stimulus–response compatibility (SRC) level for different SOAs. **c** Corrected RTs as a function of SOA and Stroop congruency. **d** Corrected Stroop effects at the SSC and SRC levels for different SOAs. Error bars denote *SEMs*. SOA = the stimulus onset asynchrony between the onset of the cue and

the onset of the target. S+R+ = Stroop stimulus which is semantically congruent. S–R+ = Stroop stimulus that is semantically incongruent, but corresponding (potential) responses are congruent. S–R– = Stroop stimulus which is incongruent in both semantics and corresponding (potential) responses. The Stroop effect at the SSC level equals to the RT in S–R+ condition minus the RT in S+R+ condition, and the Stroop effect at the SRC level equals to the RT in S–R– condition minus the RT in S–R+ condition. * $p < .05$



◀ **Fig. 4** The reaction time (RT) and error rate (ER) results on the interactions between Saccade type, SOA type, and Simon congruency in Experiment 1. **a** Uncorrected RTs as a function of Saccade type, SOA, and Simon congruency. **b** Uncorrected Simon effects for different SOAs in the pro- and antisaccade sessions. **c** Corrected RTs as a function of Saccade type, SOA, and Simon congruency. **d** Corrected Simon effects for different SOAs in the pro- and antisaccade sessions. **e** ERs as a function of Saccade type, SOA, and Simon congruency. **f** Simon effects on ERs for different SOAs in the pro- and antisaccade sessions. Error bars denote *SEMs*. SOA = the stimulus onset asynchrony between the onset of the cue and the onset of the target. The Simon effect is calculated by subtracting the RT (or ER) in the congruent condition from the RT (or ER) in the incongruent condition. * $p < .05$, ** $p < .01$

significant main effect of Simon congruency, $F(1, 42) = 8.86$, $p = .005$, $\eta_p^2 = .17$, and, more importantly, a significant interaction between Simon congruency and SOA, $F(1, 42) = 9.94$, $p = .003$, $\eta_p^2 = .19$. It is clear from Fig. 4a that while the difference between the RTs for the congruent and incongruent conditions did not reach significance when the SOA was 600 ms (649 vs. 646 ms), $t < 1$, this difference did when the SOA was 200 ms (772 vs. 749 ms), $t(42) = 4.00$, $p < .001$, $d = 0.61$. To simplify, we subtracted RTs for the congruent from RTs for the incongruent conditions (i.e., the Simon effects; Fig. 4b) and conducted *t* tests for the Simon effects between different SOAs. The Simon effect did not differ between the 200 ms and 600 ms SOAs in the prosaccade session (-9 vs. -5 ms), $t(42) = 1.12$, $p = .270$; in contrast, the Simon effect was smaller when the SOA was 200 ms than 600 ms in the antisaccade session (-23 vs. -3 ms), $t(42) = 3.15$, $p = .003$, $d = 0.48$.

Reaction times (corrected) All significant interactions based on uncorrected RTs were replicated in the results of corrected RTs (see [Supplementary Information](#) for full results). Figure 3c shows the interaction of Stroop congruency and SOA, $F(2, 84) = 6.01$, $p = .004$, $\eta_p^2 = .13$. Figure 4c shows the three-way interaction of Simon congruency, SOA, and Saccade type, $F(1, 42) = 4.01$, $p = .052$, $\eta_p^2 = .09$. Figure 3d, and Fig. 4d show further comparisons after calculating the Stroop or Simon effects.

Error rates The ER results replicated the three-way interaction between Simon congruency, SOA, and Saccade type as in the above analyses (Fig. 4e), $F(1, 42) = 4.51$, $p = .040$, $\eta_p^2 = .10$. Figure 4f illustrates the Simon effects in ERs for the pro- and antisaccade sessions.

Correlations

Although the correlation between the antisaccade latency (i.e., the SL in the antisaccade session) and the Stroop effect at the SRC level did not reach significance, $r = .263$, $p = .089$, participants who were in the top-half of the antisaccade

latency (i.e., long latency group, $n = 21$) showed significantly larger Stroop effect at the SRC level than participants who were in the bottom-half of the antisaccade latency (i.e., short latency group, $n = 22$), $t(41) = 2.22$, $p = .032$, $d = 0.56$ (Fig. 5). The correlation between the antisaccade latency and the Stroop effect at the SSC level, $r = .165$, $p = .290$, or the Simon effect, $r = .021$, $p = .892$, was not significant.

Discussion

In line with our predictions, the Stroop effect at the SRC level and the Simon effect (i.e., a conflict at the SRC level) after making a saccade were smaller when the time interval (between the saccade task and the Stroop–Simon task) was short than when the time interval was long, demonstrating that the top-down response control declined over time after making a saccade. Making a saccade could trigger a process similar to the process of conflict adaptation, facilitating the subsequent conflict resolution at the response level. Moreover, the temporal decline of the response control (i.e., a larger Simon effect when the SOA was long than short) was more pronounced after making an antisaccade than after making a prosaccade, suggesting that the conflict control at the response level is more affected by a saccade which requires more cognitive control. Furthermore, the Stroop effect at the SRC level in the Stroop–Simon task was smaller for participants who had short antisaccade latency than those who had longer antisaccade latency, indicating that individuals who have better control of eye movements could have better control of response conflict. Taken together, we suggest that the control of eye movements and the response conflict control may share a (part of) common cognitive control mechanism.

Experiment 2

We conducted Experiment 2 to verify the importance of making a saccade in the significant interactions found in Experiment 1 by removing the demand of eye movements before the Stroop–Simon task.

In Experiment 1, the cue served not only to indicate the direction of saccade but also to indicate the location of the upcoming Stroop–Simon stimulus. This may lead to an alternative account for the results. The activation-suppression model (Ridderinkhof, 2002) argues that the position of a stimulus can automatically activate the ipsilateral motor response, but this motor activation has to be subsequently suppressed. This suppression occurs because the automatic motor activation is elicited by a task-irrelevant information (i.e., position of the stimulus) which is irrelevant to the goal of the current task (i.e., identifying the stimulus itself) but need to be ignored. This idea of activation-suppression processing at response level is supported by the observed electroencephalogram

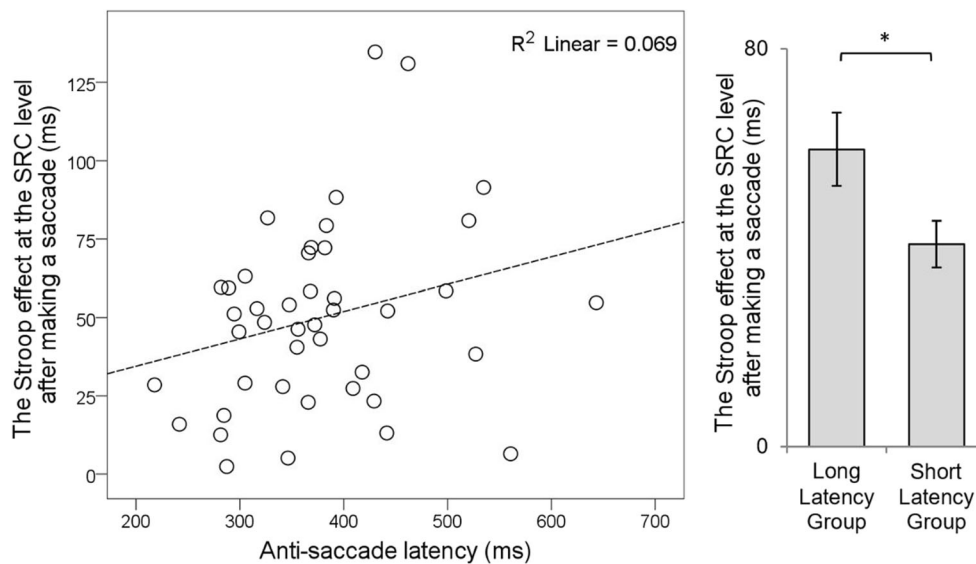


Fig. 5 The correlation between the antisaccade latency and the Stroop effect at the stimulus–response compatibility (SRC) level in Experiment 1. The bar-plot shows the Stroop effect at the SRC level for the

participants from the top-half (i.e., long latency group) and bottom-half (i.e., short latency group) of distribution of the antisaccade latency. Error bars denote *SEMs*. * $p < .05$

(EEG) signals (Eimer, 1995, 1999; Eimer & Schlaghecken, 1998; Wang et al., 2019) and the electromyogram (EMG) signals (Burle et al., 2002; Wang et al., 2021). It is also supported by the decreased or even negative Simon effect produced by a lateralized cue (Burle et al., 2005; Stoffer & Yakin, 1994; van der Lubbe et al., 1996) or a centrally presented arrow cue (Abrahamse & van der Lubbe, 2008; Eimer, 1995; Stoffer & Yakin, 1994) indicating the location of the upcoming target. The spatial code and motor response initially activated by the cue are inhibited or suppressed by the time the subsequent target is presented, which may lead to slower activation of the spatial code for the ipsilateral target and slower response to the ipsilateral target.

Therefore, in Experiment 1, the temporal decline of top-down response control may be due to the preprocessing of the target location which may elicit activation-suppression processes at the motor response level, rather than due to the control of eye movements. To exclude this explanation, Experiment 2 was designed to replace the peripheral cue with a new, central cue to indicate the location of the target. Participants were told that they should not move their eyes before the Stroop–Simon stimulus was presented. If the activation-suppression account is applicable to the patterns of results in Experiment 1, we should observe the same pattern in Experiment 2 given that the peripheral cue and a centrally presented cue would elicit the same activation-suppression processes before the presence of the target (Burle et al., 2005; Eimer, 1995, 1999; Eimer & Schlaghecken, 1998; Stoffer & Yakin, 1994; van der Lubbe et al., 1996). If, however, making a saccade is important for the presence of the interactions in Experiment 1, Experiment 2 should show a

different pattern of results when the control of eye movements in Experiment 1 is no longer required.

Method

Participants

A new group of forty-eight university students took part in Experiment 2. Two participants were excluded due to low accuracy in the Stroop–Simon task (beyond three standard deviations below the mean accuracy). Thus, 46 participants were included in the data analysis (35 females, 18 to 29 years old, $M = 21.98$, $SD = 1.79$). Other criteria were the same as Experiment 1.

Stimuli and procedure

All the stimuli and procedure in Experiment 2 were the same as in Experiment 1, with the following exceptions (Fig. 1). The cue appeared before the target stimulus was now a white triangle arrow ($2.1^\circ \times 2.1^\circ$) centrally presented for 150 ms. The lateralized target was presented at the same direction as the cue in the pro-arrow session, or at the opposite direction to the cue in the anti-arrow session. Participants were told that they should not move their eyes before the target stimulus was presented. In this way, participants were informed of the location of the target without the control of eye movements. The key difference between Experiments 1 and 2 was whether participants had actively made a saccade before the target stimulus presented. Eye-tracking was not performed in Experiment 2.

Data analysis

As in Experiment 1, omissions, trials with incorrect response were not included in the RT analysis. Trials with RTs beyond three standard deviations above or below the mean RT in each condition were excluded from data analysis (1.35% of total trials). The 2 (Cue type: pro-arrow vs. anti-arrow) \times 3 (Stroop congruency: S+R+, S-R+ vs. S-R-) \times 2 (Simon congruency: congruent vs. incongruent) \times 2 (SOA: 200 ms vs. 600 ms) repeated-measures ANOVA was performed on both RTs and ERs.

To further compare the key interactions in Experiment 1 with the same interaction in Experiment 2, we conducted cross-experiment comparison of effects by treating the Experiment (Exp. 1 vs. Exp. 2) as a between-participant variable.

Results

Figure 6 illustrates the results of Experiment 2 in the same way as the illustration for Experiment 1. We focused on the interaction between Stroop congruency and SOA, and the three-way interaction between Simon congruency, SOA and Cue type in Experiment 2 (full results can be found in the [Supplementary Information](#)).

Reaction times The main effect of Stroop congruency was significant, $F(2, 90) = 69.21, p < .001, \eta_p^2 = .61$, but this effect did not interact with SOA (Fig. 6a and b), $F(2, 90) = 1.14, p = .326$. The main effect of Simon congruency was not significant, $F(1, 45) = 1.59, p = .214$, nor its interaction with SOA, $F(1, 45) = 1.72, p = .197$, or with SOA and Cue type (Fig. 6c and d), $F < 1$.

Error rates None of the interactions reached significance (all $ps > .250$), including the three-way interaction between Simon congruency, SOA, and Cue type (Fig. 6e and f), $F(1, 45) = 1.24, p = .272$.

Between-experiment comparisons The between-experiment comparison on RTs showed that the interaction between Stroop congruency, SOA, and Experiment (Exp. 1 vs. Exp. 2) was significant, $F(2, 174) = 3.13, p = .046, \eta_p^2 = .04$, suggesting a reliable difference on the RT pattern of the Stroop Congruency \times SOA interaction between Experiments 1 and 2 (Fig. 3a vs. Fig. 6a; Fig. 3b vs. Fig. 6b), although the interaction between Simon congruency, SOA, and Experiments was not significant, $F(1, 87) = 1.20, p = .276$, nor the interaction between Simon congruency, SOA, Saccade/Cue type, and Experiments, $F(1, 87) = 2.86, p = .095, \eta_p^2 = .03$ (Fig. 4a vs. Fig. 6c; Fig. 4b vs. Fig. 6d).

The between-experiment comparison on ERs showed that the interaction between Simon congruency, SOA, Saccade/

Cue type, and Experiment (Exp. 1 vs. Exp. 2) was significant, $F(1, 87) = 4.63, p = .034, \eta_p^2 = .05$, suggesting a reliable difference on the ER pattern of the three-way interaction (Simon Congruency \times SOA \times Saccade/Cue type) between Experiments 1 and 2 (Fig. 4e vs. Fig. 6e; Fig. 4f vs. Fig. 6f).

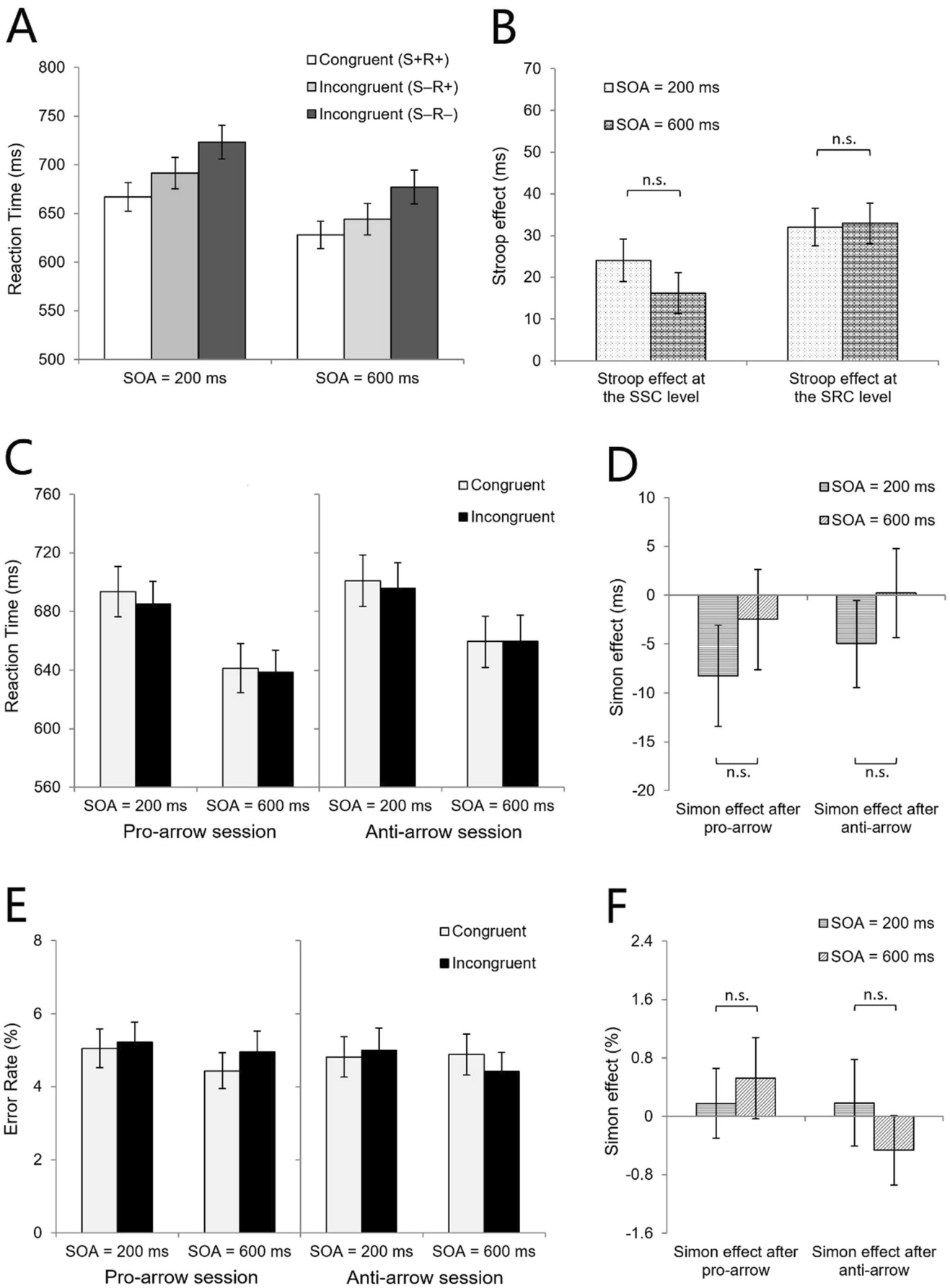
Discussion

The key interactions found in Experiment 1 (i.e., Stroop/Simon Congruency \times SOA, and Simon Congruency \times SOA \times Saccade/Cue type) were absent in Experiment 2. Between-experiment comparisons showed reliable difference on (parts of) RT and ER patterns. Thus, it is clear that removing the requirement of making a saccade before the presence of a Stroop–Simon target can indeed abolish the temporal decline of top-down response control. Conversely, the key interactions found in Experiment 1 was likely due to the control of eye movements before responding to the Stroop–Simon target, rather than due to the activation-suppression processing at the motor response level elicited by the pretarget cue indicating the location of the target.

Experiment 3

Experiments 1 did not show a typical Simon effect (i.e., faster RT in the congruent than in the incongruent condition), but showed a negative Simon effect (i.e., slower RT in the congruent than in the incongruent condition) after making a saccade, especially when the SOA between the saccadic cue and the Stroop–Simon stimulus was short in the antisaccade session. We have interpreted the negative Simon effect in the same way as the typical Simon effect; that is, the smaller (i.e., the more negative) the Simon effect was, the greater the cognitive control was recruited. However, it is possible that for the negative Simon effect, individuals had adopted a strategy that anticipates the opposite response to the stimulus location. Thus, the more optimal control might be a near-zero Simon effect. In this way, the more negative the Simon effect is, the less cognitive control is recruited.

Experiment 3 aimed to replicate the key findings of Experiment 1 and, more importantly, to test whether the (negative) Simon effect found in the current paradigm can be interpreted in the same way as the typical Simon effect. Here we simplified the design and replaced the Stroop–Simon stimuli in Experiment 1 with the conventional Simon stimuli. Importantly, we added an additional section in which participants were asked to complete a simple Simon task and a simple Stroop task without the preceding saccade. We predicted that the typical (positive) Simon effect should be observed in the simple Simon task. Crucially, if the numerically smaller Simon effect in the current paradigm could be regarded as an indication of more recruitment of cognitive control, the Simon



◀ **Fig. 6** The main reaction times (RTs) and error rates (ERs) results of Experiment 2. **a** RTs as a function of Stroop congruency and SOA. The interaction effect was NOT significant. S+R+ = Stroop stimulus which is semantically congruent. S-R+ = Stroop stimulus that is semantically incongruent, but corresponding (potential) responses are congruent. S-R- = Stroop stimulus which is incongruent in both semantics and corresponding (potential) responses. **b** Stroop effects at the stimulus–stimulus compatibility (SSC) level and the stimulus–response compatibility (SRC) level for different SOAs. The Stroop effect at the SSC level equals to the RT in S-R+ condition minus the RT in S+R+ condition, and the Stroop effect at the SRC level equals to the RT in S-R- condition minus the RT in S-R+ condition. **c** RTs as a function of Simon congruency, SOA, and Cue type. The three-way interaction was NOT significant. **d** The Simon effect on RTs after the pro- or anti-arrow for different SOAs. The Simon effect is calculated by subtracting the RT/ER in the congruent condition from the RT/ER in the incongruent condition. **e** ERs as a function of Cue type, SOA, and Simon congruency. The three-way interaction was NOT significant. **f** The Simon effect on ERs after the pro- or anti-arrow for different SOAs. SOA = the stimulus onset asynchrony between the onset of the cue and the onset of the target. Error bars denote SEMs

effect after making a saccade should positively correlate with the typical Simon effect in the simple Simon task over individuals. In contrast, this correlation should be negative if the numerically smaller Simon effect in the current paradigm reflects less recruitment of cognitive control.

Method

Participants

A new group of forty-eight university students took part in Experiment 3 (37 females, 18 to 26 years old, $M = 20.73$, $SD = 1.87$). Other criteria were the same as those in Experiment 1.

Stimuli and procedure

Experiment 3 had a main section and an additional section (the sequence of these two sections was counterbalanced across participants). The main section of Experiment 3 was the same as Experiment 1 with the following exceptions. The Stroop–Simon stimuli were replaced with the Simon stimuli (i.e., white letter “Q” and “P”, $2.2^\circ \times 2.2^\circ$) presented 13.4° left or right to the center of the screen (Fig. 1). Participants were asked to identify the letter and pressing the “Q” key on the keyboard using the left hand (if the target was “Q”) or the “P” key using the right hand (if the target was “P”). Thus, the main section of Experiment 3 had a 2 (Saccade type: prosaccade vs. antisaccade) \times 2 (Simon congruency: congruent vs. incongruent) \times 2 (SOA: 200 ms vs. 600 ms) within-participants design. There were 240 trials distributed in five blocks for either the pro- or antisaccade session (i.e., 10 blocks with 480 trials in total). The sequence of the pro- and antisaccade sessions was counterbalanced across participants. There were 16 practice

trials before each session. Eye-tracking was performed for the main section of Experiment 3.

In the additional section of Experiment 3, participants were asked to complete a simple Stroop task and a simple Simon task, with the sequence of these two tasks counterbalanced across participants. Eye-tracking was not performed for this section. In the simple Stroop task, the “Cue” and the “Blank” in the trial structure of Experiment 1 (see Fig. 1) were removed, and the target color word was presented at the center of the screen. Participants were asked to identify the color of the color word. The setting of the color-key mapping and other properties of target stimuli were the same as Experiment 1. Thus, the simple Stroop task had a one factor (Stroop congruency: S+R+, S-R+ vs. S-R-) within-participants design. There were 288 trials (96 trials for each condition) equally distributed in six blocks, and 24 practice trials before the formal task.

In the simple Simon task, the “Cue” and the “Blank” in the trial structure of the main section of Experiment 3 (see Fig. 1) were removed. Participants were asked to identify the lateralized letter directly. The setting of the letter-key mapping and other properties of stimuli were the same as the main section of Experiment 3 described above. Thus, the simple Simon task had a one factor (Simon congruency: congruent vs. incongruent) within-participants design. There were 192 trials (96 trials for each condition) equally distributed in six blocks, and 16 practice trials before the formal task.

Data analysis

Main section The analyses for the saccade task were the same as in Experiment 1. The saccade error rate (SER) and saccade latency (SL) in each session were calculated, and paired t tests between the pro- and antisaccades were conducted based on the SER and the SL to validate the success of the pro- and antisaccade manipulations.

The analyses for the Simon task after saccades were similar to Experiment 1. RT analysis was performed for both RT and corrected RT. Specifically, omissions, trials with incorrect response were not included in the RT analysis. Trials with RTs beyond three standard deviations above or below the mean RT in each condition were also excluded (1.54% of total trials), and uncorrected RTs were calculated based on the remaining trials. For the corrected RTs (equals to uncorrected $RT \times P_T$ as described in Experiment 1), trials with insufficient saccade ($P_T < 50\%$) were further excluded (13.97% of total trials). Error rates (ERs) were calculated as in Experiment 1. The 2 (Saccade type: prosaccade vs. antisaccade) \times 2 (Simon congruency: congruent vs. incongruent) \times 2 (SOA: 200 ms vs. 600 ms) repeated-measures ANOVA was performed on RTs, corrected RTs, and ERs.

Additional section For the simple Stroop and Simon tasks, omissions, trials with incorrect response were excluded from the RT analysis. Trials with RTs beyond three standard deviations above or below the mean RT in each condition were excluded (1.59% and 1.27% of total trials for the Stroop task and Simon task, respectively). The one factor (Stroop congruency: S+R+, S–R+ vs. S–R–) repeated-measures ANOVA on RTs and ERs for the simple Stroop task, and the paired *t* test (congruent vs. incongruent) on RTs and ERs for the simple Simon task were conducted.

Correlation analysis To examine whether the Simon effect after making a saccade could reflect conflict control processing similar to the processing for typical Simon effect, we conducted correlation analyses between the Simon effects in the two situations. In addition, to replicate the results in Experiment 1 and test whether the control of eye movement and the conflict control share a (part of) common mechanism, we conducted correlation analyses between the antisaccade performance and the performance in the simple Stroop task and the simple Simon task.

Results

Main section: Saccade task performance

The SER was lower (3.28% vs. 19.33%) and the SL was shorter (186 vs. 399 ms) in the prosaccade session than in the antisaccade session, SER: $t(47) = 9.37, p < .001, d = 1.35$; SL: $t(47) = 16.65, p < .001, d = 2.40$, consistent with the typical pattern observed for the pro- and antisaccade tasks.

Main section: Simon task performance

The 2 (Saccade type: prosaccade vs. antisaccade) \times 2 (Simon congruency: congruent vs. incongruent) \times 2 (SOA: 200 ms vs. 600 ms) ANOVA was conducted on RTs, corrected RTs, and ERs of the Simon task. To directly test our prediction and simplify the report of results, we focused on the Simon effect and its interaction with other factors (full results can be found in the [Supplementary Information](#)).

Reaction times (uncorrected) Similar to Experiment 1, the interaction between Simon congruency and SOA was significant, $F(1, 47) = 5.06, p = .029, \eta_p^2 = .10$, although the main effect of Simon congruency was not, $F < 1$. Importantly, the three-way interaction between Simon congruency, SOA, and Saccade type was significant, $F(1, 47) = 4.49, p = .039, \eta_p^2 = .09$, which showed a pattern similar to Experiment 1 (Fig. 7 vs. Fig. 4). It is clear from Fig. 7a and b that the Simon effect did not differ between the 200 ms and 600 ms SOAs in the prosaccade session (3 vs. 6 ms), $t < 1$; in contrast, the Simon effect was smaller when the SOA was 200 ms than 600 ms in

the antisaccade session (–10 vs. 7 ms), $t(47) = 2.70, p = .010, d = 0.39$.

Reaction times (corrected) The analysis of corrected RTs replicated the pattern above (Fig. 7c and d), with a significant interaction between Simon congruency and SOA, $F(1, 47) = 8.13, p = .006, \eta_p^2 = .15$, a significant three-way interaction between Simon congruency, SOA, and Saccade type, $F(1, 47) = 4.11, p = .048, \eta_p^2 = .08$, and a nonsignificant main effect of Simon congruency, $F < 1$.

Error rates The analysis of ERs partly replicated the patterns of RTs, showing a significant interaction between Simon congruency and SOA (Fig. 7e), $F(1, 47) = 6.34, p = .015, \eta_p^2 = .12$. Planned *t* tests showed that the ER in the incongruent condition was higher than in the congruent condition (3.61% vs. 1.53%) when the SOA was 600 ms, $t(47) = 5.31, p < .001, d = 0.77$. This comparison did not reach significance when the SOA was 200 ms (3.22% vs. 2.35%), $t(47) = 1.78, p = .081, d = 0.26$. A further check (Fig. 7f) showed that the Simon effect on ERs was smaller when the SOA was 200 ms than when the SOA was 600 ms, (0.88% vs. 2.08%), $t(47) = 2.49, p = .016, d = 0.36$.

The main effect of Simon congruency was significant, $F(1, 47) = 15.56, p < .001, \eta_p^2 = .25$, with higher ERs in the incongruent condition than in the congruent condition (3.42% vs. 1.94%), demonstrating a typical Simon effect on ERs. The three-way interaction was not significant, $F < 1$.

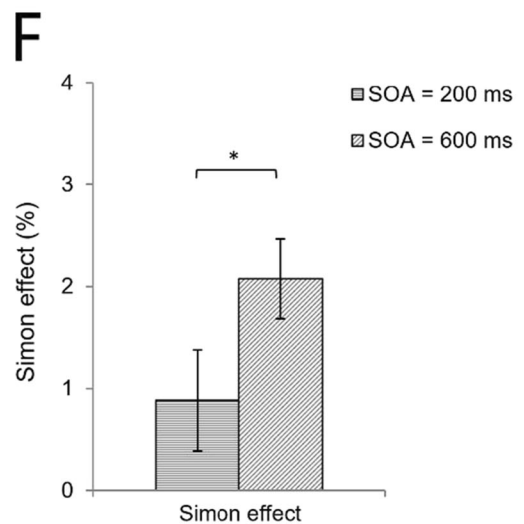
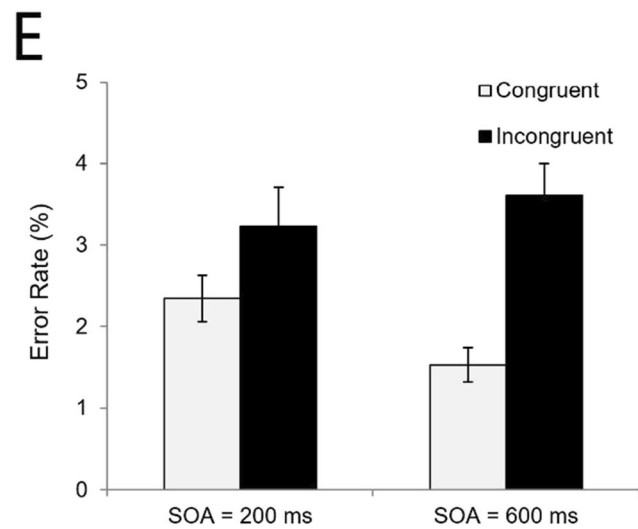
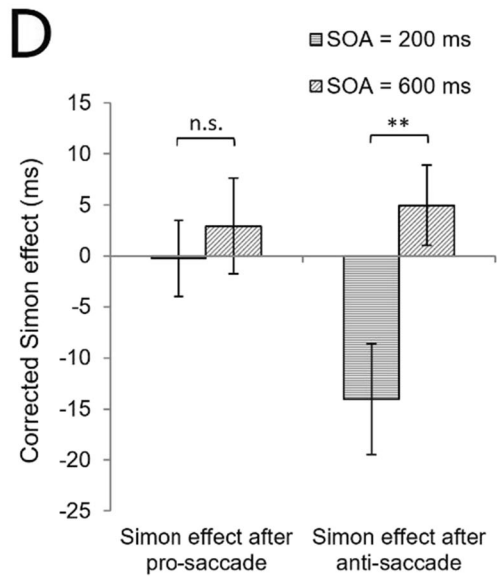
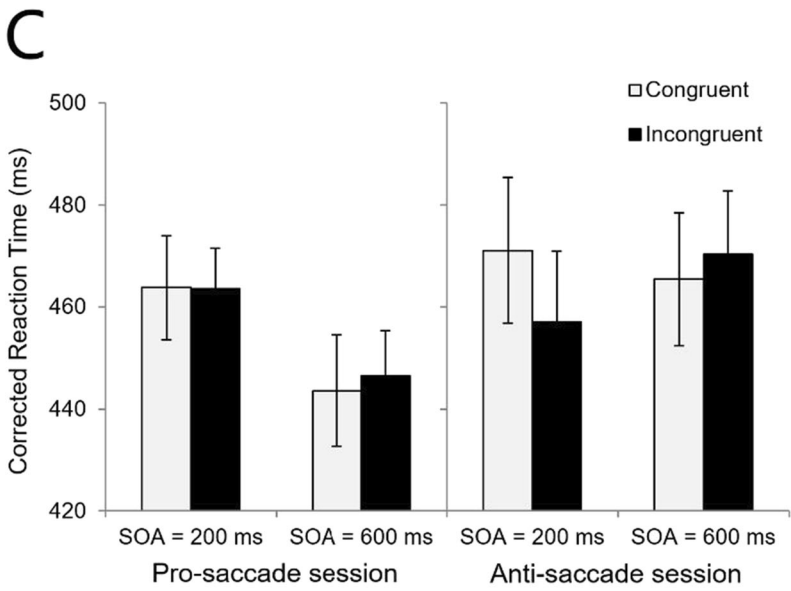
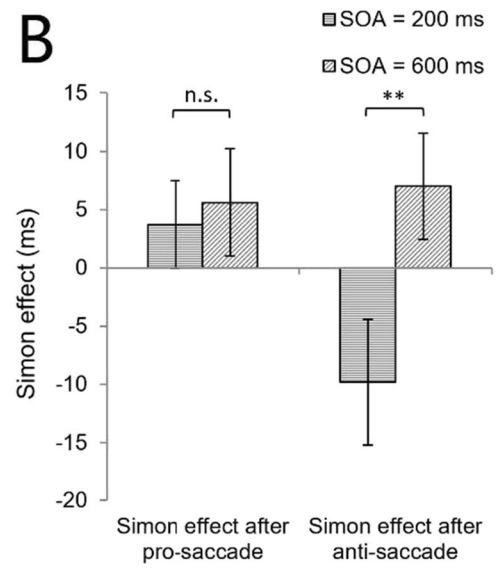
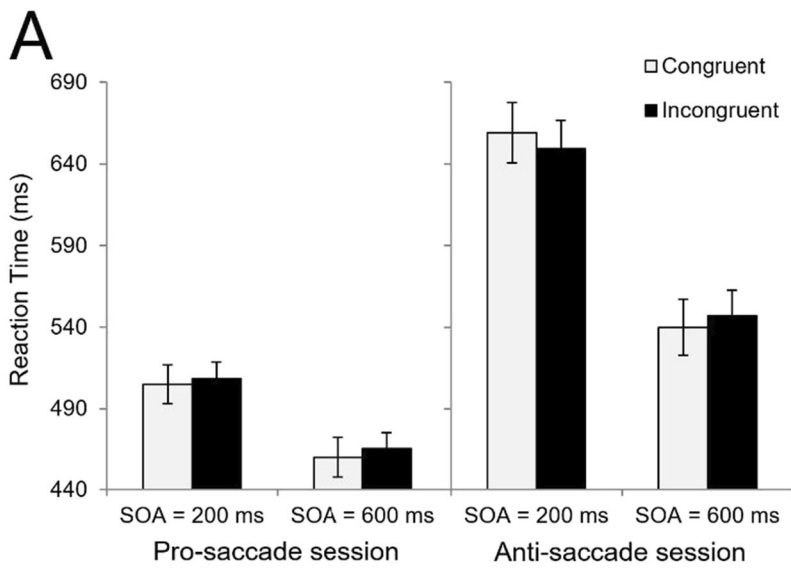
Additional section: Simple Simon task performance

Participants responded slower and had higher error rate in the incongruent condition than in the congruent condition, 526 vs. 507 ms, $t(47) = 5.43, p < .001, d = 0.78$; 5.47% vs. 2.92%, $t(47) = 4.26, p < .001, d = 0.62$, demonstrating the typical Simon effect.

Additional section: Simple Stroop task performance

The main effect of Stroop congruency was significant, for RTs: $F(1, 47) = 79.45, p < .001, \eta_p^2 = .63$; for ERs, $F(1, 47) = 34.16, p < .001, \eta_p^2 = .42$. Further pair-wise comparisons

Fig. 7 The main results of reaction time (RT) and error rate (ER) in Experiment 3. **a** Uncorrected RTs as a function of Saccade type, SOA, and Simon congruency. **b** Uncorrected Simon effects for different SOAs in the pro- and antisaccade sessions. **c** Corrected RTs as a function of Saccade type, SOA, and Simon congruency. **d** Corrected Simon effects for different SOAs in the pro- and antisaccade sessions. **e** ERs as a function of SOA and Simon congruency. **f** Simon effects on ERs for different SOAs. Error bars denote *SEMs*. SOA = the stimulus onset asynchrony between the onset of the cue and the onset of the target. The Simon effect is calculated by subtracting the RT in the congruent condition from the RT in the incongruent condition. * $p < .05$, ** $p < .01$



(with Bonferroni correction) for RTs showed that participants responded slower to the S–R– targets (637 ms) than to the S–R+ targets (586 ms) or the S+R+ targets (568 ms), and also slower to the S–R+ targets than to the S+R+ targets (all p s < .001). Pair-wise comparisons for ERs showed that participants had higher error rate for the S–R– targets (8.12%) than for the S–R+ targets (2.96%) or the S+R+ targets (3.86%) (all p s < .001). The difference between the S–R+ targets and the S+R+ targets was not significant ($p = .085$). These results demonstrated the typical pattern of Stroop effects at both the SSC level (on RTs) and the SRC level (on both RTs and ERs).

Correlations

After calculating the Simon effect (RT in the incongruent condition minus RT in the congruent condition), we conducted the correlation analysis for the Simon effect in the simple Simon task and the Simon effect after making a saccade in the main section (Fig. 8a): $r = .478$, $p = .001$ for the uncorrected RT, and $r = .518$, $p < .001$ for the corrected RT.

Similar to Experiment 1, although the correlation between the antisaccade latency (i.e., the SL in the antisaccade session) and the Stroop effect at the SRC level in the simple Stroop task did not reach significance, $r = .256$, $p = .079$, participants who were slow in making the antisaccade (i.e., the top-half, long latency group, $n = 24$) showed a significantly larger Stroop effect at the SRC level in the simple Stroop task than participants who were fast in making the antisaccade (i.e., the bottom-half, short latency group, $n = 24$), $t(46) = 2.47$, $p = .017$, $d = 0.64$ (Fig. 8b). The correlations between the antisaccade latency and the Stroop effect at the SSC level in the simple Stroop task or the Simon effect in the simple Simon task were not significant, $r = -.201$, $p = .171$, and $r = -.204$, $p = .165$, respectively.

Discussion

Experiment 3 replicated the key findings on the Simon effect in Experiment 1: The Simon effect after making a saccade was smaller (even becoming negative) when the SOA between the saccade task and the Simon stimuli was short than when the

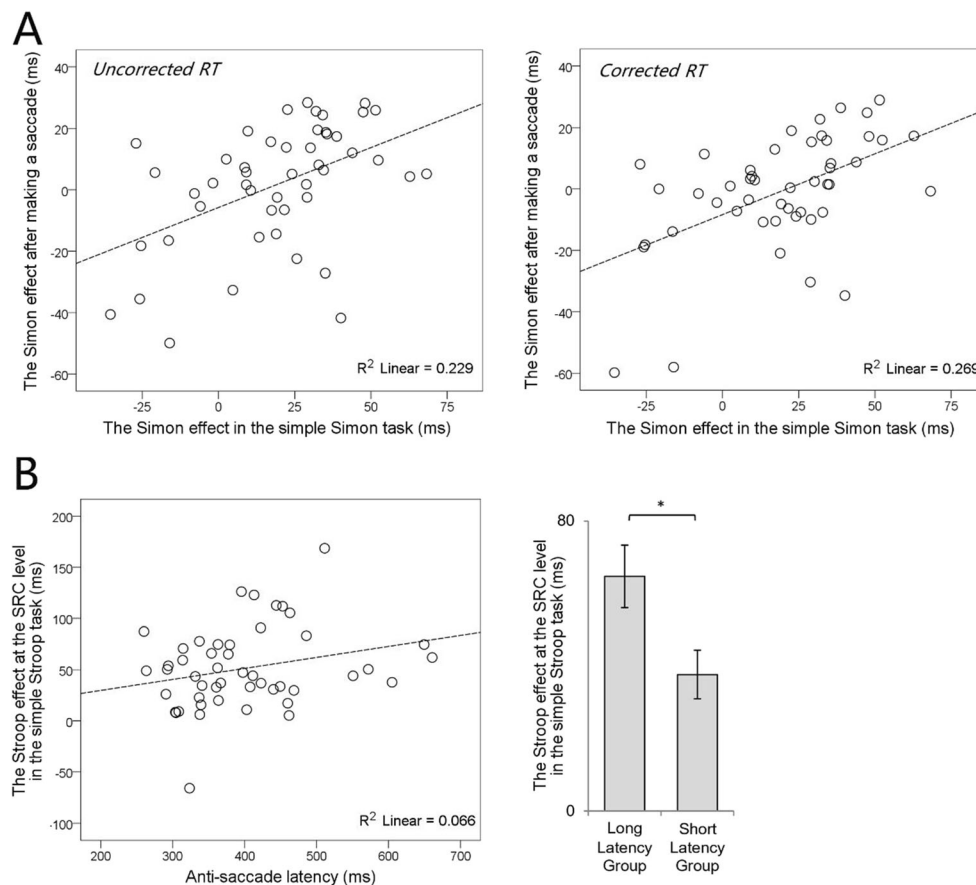


Fig. 8 Results of correlation analyses in Experiment 3. **a** The Simon effect in the simple Simon task positively correlated with the Simon effect after making a saccade. The left and right panels show the uncorrected and corrected RT results, respectively. **b** The correlation between the antisaccade latency and the Stroop effect at the stimulus–

response compatibility (SRC) level. The bar-plot shows the Stroop effect at the SRC level in the simple Stroop task for the participants in the top-half (i.e., long latency group) and bottom-half (i.e., short latency group) of the distribution of the antisaccade latency. Error bars denote *SEMs*. * $p < .05$

SOA was long, and this effect was more pronounced after making an antisaccade than after making a prosaccade. Importantly, the additional simple Simon task showed a typical (positive) Simon effect, which positively correlated with the Simon effect after making a saccade over participants. Moreover, the Simon effect on error rates after making a saccade showed a typical (positive) pattern, which was also smaller when the SOA was short than when it was long. Taken together, we tend to interpret the Simon effect after making a saccade in a similar way as the typical Simon effect (although correlation is not a demonstration of causality); that is, the conflict control was stronger when the Simon effect was numerically small. Individuals may adopt a strategy that anticipates a response opposite to the stimulus location in the negative (or absent) Simon effect, but they still have to overcome the automatic activation of the ipsilateral hand elicited by the lateralized target (Hommel, 2011; Ridderinkhof, 2002), which may reflect the recruitment of cognitive control.

General discussion

In the current study, we investigated whether the control of eye movements shares a common control system with the conflict control. Participants were asked to actively make a saccade before a Stroop–Simon task (Experiment 1) or before a Simon task (Experiment 3). We found that the Stroop effect at the SRC level became smaller when the SOA between the saccadic cue and the Stroop–Simon stimulus was short compared with when the SOA was long (Experiment 1), suggesting a decline of the top-down response control over time. Moreover, the same pattern was observed for the Simon manipulation, and the effects appeared mostly in the antisaccade session, not in the prosaccade session (Experiments 1 and 3). Furthermore, participants who had short antisaccade latency showed smaller Stroop effect at the SRC level than those who had long antisaccade latency (Experiments 1 and 3). Importantly, when the demand on the control of eye movements was removed (Experiment 2), interaction effects (i.e., $SOA \times$ Stroop/Simon Congruency, and $SOA \times$ Simon congruency \times Saccade/Cue type) disappeared, suggesting that executing the control of eye movements is a prerequisite for the appearance of these interactions.

We argue that these interactions and between-group differences reveal a common cognitive control system underlying the control of eye movements and the conflict control subserved by goal-directed motor response processes. We have differentiated the SSC and the SRC conflict in the Stroop stimuli (Chen et al., 2013, 2006; de Houwer, 2003; Schmidt & Cheesman, 2005) and found that the size of the Stroop effect increased over SOA at the SRC level, but not at the SSC level. The (negative) Simon effect has also been suggested to occur at the SRC level (Egner, 2008; Egner

et al., 2007; Liu et al., 2004). When eye movements are demanded by the prosaccade and especially the antisaccade task, the general control system is temporarily activated, rendering it ready for facing and resolving subsequent conflicts at the response level. However, this preactivation elicited by making a saccade may dissipate over time and the resolution of response conflict may need extra effort when it is not or less benefited from the pre-activation of the control system. This temporal dynamic pattern is reminiscent of the conflict adaptation effect (Botvinick et al., 2001; Egner, 2007, 2008), which shows an increased top-down control triggered by a previous incongruent trial (vs. a congruent trial; i.e., activating the control system associated with conflict resolution), and reminiscent of the decrease of the conflict adaptation effect over time (Egner et al., 2010; Wühr & Ansorge, 2005).

Moreover, the current findings may have broad implications for theories of cognitive control, which generally differentiate two stages of processing: a conflict monitoring stage in which conflicts between the task-relevant and task-irrelevant dimensions at different levels of processing are registered by the system, and a conflict resolution stage in which the conflicts are resolved towards the goal of the current task (Botvinick et al., 2001; Egner, 2008; Liu et al., 2010). However, these theories differ in whether the two stages of processing have domain-general or domain-specific neurocognitive substrates. Botvinick and colleagues (Botvinick et al., 2001) proposed that both the conflict monitoring and resolution processes are domain general, and deal with all types of conflicts. Egner and colleagues (Egner, 2008; Egner et al., 2007) proposed that the conflict monitoring possesses and the resolution processes are all domain specific for different types of conflict and they could operate in parallel. Liu and colleagues (Liu et al., 2004, 2010) proposed an integrated model in which the conflict monitoring possesses are domain-specific whereas the resolution processes are domain-free. Our results suggest that there is a common system subserving the control of eye movements and the response conflict resolution whereas the control of eye movements seems to have no obvious effect on the resolution of Stroop incongruence at the SSC level. This pattern of results is more consistent with Liu et al. (2004, 2010) rather than with the two former proposals.

Furthermore, the current findings may have implications for understanding neural activations of cognitive control. It has been repeatedly shown that the dorsolateral prefrontal cortex (dlPFC) is involved in a large number of tasks involving cognitive control (Cieslik et al., 2013; Gratton et al., 2018; Miller & Cohen, 2001), including the Stroop and Simon tasks (Liu et al., 2004; Nee et al., 2007; Ye & Zhou, 2009) and the control of eye movements (Everling & Fischer, 1998; Funahashi, 2014). The current findings suggest that the control of eye movements shares a common system with the resolution of response conflict, perhaps at the dlPFC.

It is noteworthy that the decline of response control over time after making a saccade was observed for both the Stroop effect at the SRC level and the Simon effect, but this temporal decline was further modulated by Saccade type only for the Simon effect. It seems that the response conflict involved in the Stroop effect and in the Simon effect are somewhat different, which is reminiscent of the evidence that no interaction or correlation was found between the Stroop and the Simon effect (e.g., Hedge et al., 2018; Hommel, 1997; Kornblum, 1994; Rouder & Haaf, 2019). For the Stroop effect, the task-irrelevant stimulus dimension (i.e., the word meaning) is associated with a stimulus–response mapping, and the response conflict occurs when a response needs to be selected based on stimulus–response mappings. For the Simon effect, the task-irrelevant stimulus dimension (i.e., the location of the stimulus) can elicit an automatic response activation at the ipsilateral effector (Hommel, 2011; Ridderinkhof, 2002) regardless of the stimulus–response mapping, and the response conflict occurs when a different response needs to be executed. Thus, the response conflict could be further divided as the conflict at the response-selection level (e.g., the Stroop effect at the SRC level), and the conflict at the response-execution level (e.g., the Simon effect). The latter may be related to the control of eye movements closer than the former.

Although we have excluded the contribution of the activation-suppression model in explaining the temporal decline of the top-down response control, a notable finding in the present study, that is, the negative Simon effect in Experiment 1 and the absence of Simon effect in Experiments 2 and 3, is possibly related to the activation-suppression processing. We argue that both the pre-processing of the target location and the control of eye movements may have contributed to the subsequent response control, resulting in the negative (or absence of) Simon effect.

For the contribution of the pre-processing of the target location, previous studies have shown that the Simon effect is declined or even becomes negative when there is a task-irrelevant cue indicating the location of the upcoming target (Burle et al., 2005; Eimer, 1995; Stoffer & Yakin, 1994; van der Lubbe et al., 1996). The cue could elicit the activation of the spatially corresponding response effector, but this activation is subsequently suppressed because the cue is not a target to respond to. This suppression would interfere with response activation for the Simon congruent target, leading to the decline of the Simon effect (even becoming negative) (Ridderinkhof, 2002; Stoffer & Yakin, 1994; van der Lubbe et al., 1996).

For the contribution of the control of eye movements, it has been shown that the typical Simon effect is absent when participants have to make a saccade towards the location of the stimulus before the target appears (Buetti & Kerzel, 2010). This saccade may activate the response effector at the target location due to eye–hand interaction (de Brouwer et al., 2021),

but this activation has to be suppressed, slowing down the hand response to the subsequent target. The antisaccade training reduces the Simon effect (Verghese et al., 2018), suggesting a transfer of inhibition learning across motor systems. It is possible that individuals are likely to adopt a general antiresponse strategy due to a bias to responding in the opposite direction to a stimulus in the current paradigm. Nevertheless, the negative (or absence of) Simon effect in the current paradigm might still reflect a recruitment of cognitive control similar to the typical Simon effect (as indicated by the correlation results in Experiment 3), since the automatic activation of motor response elicited by the lateralized target always needs to be overcome.

In summary, we combined the saccade task and the Stroop–Simon task to investigate whether the control of eye movements recruit a common cognitive control system with the conflict control. We found a decline of the top-down response control over time after making a saccade, and this temporal decline was more pronounced after antisaccades than prosaccades. These effects were absent when the demand on eye movements was removed and were replicated when the Stroop–Simon task was replaced with a Simon task. Moreover, individuals who had better performance in the control of eye movements also performed better in the response conflict control. We interpret our findings as evidence for a (part of) shared common cognitive control system between the control of eye movements and the control of goal-directed motor responses.

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Author contributions Xiaoxiao Luo: Conceptualization, Methodology, Software, Formal analysis, Writing—original draft. Jiayan Gu.: Investigation, Writing—original draft. Yueyuan Zheng.: Investigation, Writing—original draft. Xiaolin Zhou: Supervision, Conceptualization, Methodology, Writing—review & editing.

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