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Volition motivates cognitive performance at the response-execution level by attenuating task-irrelevant motor activations

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ABSTRACT

Humans express volition by making voluntary choices which, relative to forced choices, can motivate cognitive performance in a variety of tasks. However, a task that requires the generation of motor responses on the basis of external sensory stimulation involves complex underlying cognitive processes, e.g., pre-response processing, response selection, and response execution. The present study investigated how these underlying processes are facilitated by voluntary choice-making. In five experiments, participants were free or forced to choose a task-irrelevant picture from two alternatives, and then completed a conflict task, i.e., Flanker, Stroop, Simon, Stroop-Simon, or Flanker-Simon task, where the conflict effect could occur at different processing levels. Results consistently showed that responses in all tasks were generally faster after voluntary (vs. forced) choices. Importantly, the conflict effect at the response-execution level (i.e., the Simon effect), but not the conflict effect at the pre-response and response-selection levels (i.e., the Flanker and Stroop effects), was reduced by the voluntary choice-making. Model fitting revealed that the peak amplitude of automatic motor activations in the response-execution conflict was smaller after voluntary (vs. forced) choices. These findings suggest that volition motivates subsequent cognitive performance at the response-execution level by attenuating task-irrelevant motor activations.

1. Introduction

Volition is the foundation of individual activity and human society. To express volition, we constantly make voluntary actions/choices in our lifetimes, which help us control the external environment to achieve wanted outcomes and/or to avoid unwanted outcomes (Leotti, Iyengar, & Ochsner, 2010), and to gain a sense of agency (Haggard, 2019). Humans have the necessity of making voluntary choices to exert control (Leotti et al., 2010); the satisfaction of this necessity can motivate behavioral performance (Patall, Cooper, & Robinson, 2008). After making a voluntary choice, relative to a forced choice, individuals' performance in a variety of cognitive tasks could be improved, including visual search (Luo et al., 2023; Luo, Wang, & Zhou, 2022), time estimation (Murayama et al., 2015), and declarative memory (Murty, DuBrow, & Davachi, 2015), even when the choice-making is irrelevant to these tasks. Moreover, the performance-enhancement effect is diminished when the outcome of the choice-making is believed to be uncontrollable (Luo, Wang, & Zhou, 2022). Similarly, individuals' motivation to perform is enhanced (with faster responses) when actions have trivial but constant perceptual effects compared with when actions have no effect (Eitam, Kennedy, & Higgins, 2013) or when the effect is temporally/spatially out of control (Karsh, Eitam, Mark, & Higgins, 2016). These convergent findings point to the motivational role of human volition.

Despite enhanced performance across different tasks, it is unclear how underlying cognitive processes are facilitated by the preceding voluntary choice-making. In a task that requires the generation of motor responses based on external sensory stimulation, the underlying

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cognitive processes can be divided into at least three levels (Donders, 1969; Töllner, Rangelov, & Müller, 2012): (1) pre-response processing, by which individuals complete the preattentive perception and the attentional engagement in the target, (2) response selection, by which individuals select an appropriate response according to the S-R mapping, and (3) response execution, by which individuals execute the motor response using their effectors. Although previous studies have revealed a general enhancement of response speed by the expression of volition (Eitam et al., 2013; Karsh et al., 2016; Luo et al., 2023; Luo, Wang, & Zhou, 2022), it is unknown upon which processing level(s) the voluntary choice-making could act to generate the facilitatory effect.

To differentiate levels of processing, we appealed to conflict control tasks in which individuals direct information processing in line with the current task goal and resolve competition between information from different sources (Egner, 2008). Conflict effects occur when the task-relevant and task-irrelevant information are incongruent, leading to impaired performance. Although the conflict may occur at all processing levels, the major locus of the conflict effect may differ between different tasks (Egner, 2008; Nee, Wager, & Jonides, 2007; Zhang & Kornblum, 1998). For instance, the Flanker task (Eriksen & Eriksen, 1974; Sanders & Lamers, 2002), where participants respond to a central target flanked by distractors, mainly involves conflicts at both the pre-response and response-selection levels (Chen, Tang, & Chen, 2013; Eriksen & Eriksen, 1974). When the central target is incongruent with flanking distractors, perceptual representations of the target and distractors are incongruent (i.e., the pre-response level); and the S-R mappings for the target and distractor are also incongruent (i.e., the response-selection level). Similarly, the Stroop task (MacLeod, 1991; Stroop, 1935), where participants respond to the ink color of a color word, also involves conflicts at both the pre-response and response-selection levels (de Houwer, 2003; Schmidt & Cheesman, 2005). However, the Simon task (Hommel, 2011; Simon & Rudell, 1967), where participants respond to a laterally presented stimulus, mainly involves a conflict at the response-execution level (Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002; Ridderinkhof, 2002). A laterally presented stimulus can automatically activate the motor response of the effector at the same side as the stimulus regardless of the learned S-R mapping (Burle et al., 2002; Ridderinkhof, 2002). This automatic motor activation is inappropriate when the required response effector is at the opposite side of the stimulus location, interfering with the execution of the required response. The response-related processing for the Simon effect is different from the processing for the Flanker or Stroop effect in a number of ways (Egner, 2008; Nee et al., 2007), including the pattern of RT distribution (De Jong, Liang, & Lauber, 1994; Pratte, Rouder, Morey, & Feng, 2010). Specifically, in the Flanker and Stroop tasks, the response processing that corresponds to the task-irrelevant dimension was crucially related to the meaning (e.g., direction in Flanker, sematic in Stroop) of the stimulus. By contrast in the Simon task, the response processing that corresponds to the task-irrelevant dimension (e.g., location) was not related to the meaning of the stimulus. In other words, although conflicts arise from the stimulus-response incompatibility in all three tasks, the conflict in the Simon task does not necessarily engage a conflict between the meaning of the stimulus and the response hand.

The main purpose of the current study was to investigate how voluntary choice-making modulates conflict control at different processing levels. The volition-motivated-performance (VMP) paradigm (Luo et al., 2023; Luo, Wang, & Zhou, 2022) was adopted. Participants chose a picture according to their own volition or according to the command of an external agent, and then completed a conflict task with the chosen picture as a task-irrelevant background. Based on previous studies (Luo et al., 2023, Luo, Wang, & Zhou, 2022), we expected the overall performance of the conflict task to be improved following a free (vs. forced) choice. Here Experiment 1 tested the effect of voluntary choice-making on the Flanker effect that involves conflicts mostly at both the pre-response and response-selection levels. In Experiment 2 where the Stroop task was used, conflicts at the pre-response and response-selection levels were dissociated (see Methods; see also de Houwer, 2003; Schmidt & Cheesman, 2005), and hence the potential impacts of voluntary choice-making on conflicts at these two levels could be examined separately. Experiment 3 (in which Experiment 3b was preregistered at https://osf.io/cvjqp) used the Simon task to investigate the influence of voluntary choice-making on the conflict at the response-execution level. Experiment 4 adopted a hybrid of the Stroop and Simon effects (i.e., a Stroop-Simon task where the Stroop stimulus is presented laterally; see also Hommel, 1997; Luo, Gu, Zheng, & Zhou, 2022) so that the impact of voluntary choice-making on the conflict at the pre-response, response-selection, and response-execution levels can be simultaneously assessed. Experiment 5 (preregistered at https://osf.io/vx8fe) used a hybrid of the Flanker and Simon effects (i.e., a Flanker-Simon task where the Flanker stimulus is presented laterally; see also Hommel, 1997; Wendt, Kluwe, & Peters, 2006) to replicate our findings. Taken together, the differentiation of processing levels across different tasks (Experiments 1–3) and in the same task (Experiments 4 and 5) would reveal upon which processing level(s) that the voluntary choice-making would act to facilitate performance. To decompose conflict tasks and further explore the facilitation of voluntary choice-making, the Diffusion Model for Conflict Tasks (DMC, Ulrich, Schröter, Leuthold, & Birngruber, 2015) was used to estimate and compare the same set of parameters between different conflict tasks.

Note that all data, codes, and materials of the present study can be accessed at https://osf.io/6k72r/

2. Methods

2.1. Participants

A total of 188 university students took part in the present study. Three groups of 36 participants took part in Experiments 1, 2, and 3, respectively. Two groups of 40 participants took part in Experiments 4 and 5. The sample size in each experiment was determined by G*power 3.1.9.2 software (Faul, Erdfelder, Lang, & Buchner, 2007), given the test family = F tests, the statistical test = ANOVA: Repeated measures, within factors, $f = 0.25$ (a medium effect size), $\alpha = 0.05$, power = 0.95, number of groups = 1 (within-participants design), number of measurements = 4 (2×2 factorial design), corr among rep measures = 0.5, and nonsphericity correction = 1. The calculation showed that 36 participants were required. We recruited slightly more participants in Experiments 4 and 5 because there were fewer trials for each condition in these experiments than in other experiments. One participant in Experiment 3, one participant in Experiment 4, and one participant in Experiment 5 were excluded from data analysis because their response accuracies were beyond 3SD of the mean accuracy. Another participant in Experiment 4 was excluded because she reported that, to focus on the Stroop-Simon task, she ignored the choice phase (see below) and randomly pressed the buttons to make choices. The remaining participants had the following characteristics. Experiment 1: 24 females, 18–30 years old, $M = 21.19$, $SD = 2.84$; Experiment 2: 24 females, 18–30 years old, $M = 21.36$, $SD = 2.52$; Experiment 3: 22 females, 18–27 years old, $M = 21.71$, $SD = 2.02$; Experiment 4: 27 females, 18–30 years old, $M = 21.53$, $SD = 2.55$; Experiment 5: 30 females, 18–29 years old, $M = 22.26$, $SD = 2.65$.

All participants were right-handed and had normal or corrected-to-normal vision and normal color 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. Informed consent was obtained from all participants who received monetary compensation for their participation.

2.2. Stimuli and procedure

Stimuli were presented on a grey screen (44 × 33 cm, refresh rate:

100 Hz, resolution: 1024 × 768 pixels) connected to a PC. The eye-to-monitor distance was 70 cm. Head position was maintained using a chinrest. Each participant individually performed the experiment in a dimly lit laboratory room and responded via a key press on a standard American keyboard. Psychophysics Toolbox (Brainard, 1997, http://www.psychtoolbox.org/) with MATLAB was used to control the stimulus presentation and response recording. The sequence of events in a trial is illustrated in Fig. 1. Each trial consisted of three successive phases: the cue phase, the choice phase, and the task phase.

2.2.1. Experiment 1

In the cue phase, a white dot (0.7° × 0.7°) was first presented as the central fixation for 0.8–1.2 s. Then a cyan or yellow dot (1.6° × 1.6°) indicating the choice condition of the current trial (i.e., voluntary vs. forced) was presented at the center of the screen for 1 s. The association between color and choice condition was counterbalanced across participants.

In the choice phase, after a central fixation presented for 0.5–0.8 s, two pictures (5.3° × 5.3° each) were presented at 4.9° left and right to the center of the screen. Participants could choose a picture by pressing "D" (the picture on the left) or "F" (the picture on the right) using the middle and index fingers of the left hand. In the voluntary-choice condition, participants freely chose a picture from the two options via button press. In the forced-choice condition, the two pictures were first presented for a pre-defined time interval, $T_{interval}$, until one of the two pictures was randomly marked with the frame, and participants had to choose the marked picture via button press. The inclusion of the $T_{interval}$ in the forced-choice trials was to control the exposure times of the optional pictures between choice conditions (see *Supplementary Materials*, pp. 2–3, for details). After the button press, in either condition, the two pictures together with the frame that marked the chosen picture were presented for another 1 s.

In the task phase (Fig. 1a), after a central fixation presented for 0.5–0.8 s, the chosen picture was presented at the center of the screen as the background picture (11.4° × 11.4°) for 1 s. Then participants were asked to complete a Flanker task (Eriksen & Eriksen, 1974; Sanders & Lamers, 2002), in which a row of five white arrows ("<" or ">", 1.6° × 1.6° each) was embedded inside a grey rectangle (1.8° × 9.0°) and presented on top of the background picture. Participants were asked to judge the direction (left vs. right) of the middle arrow as quickly and accurately as possible by pressing "J" (if the direction was left) or "K" (if the direction was right) using the index and middle fingers of the right hand while ignoring the other arrows. The task stimulus and the background picture remained on the screen until a button press was given or

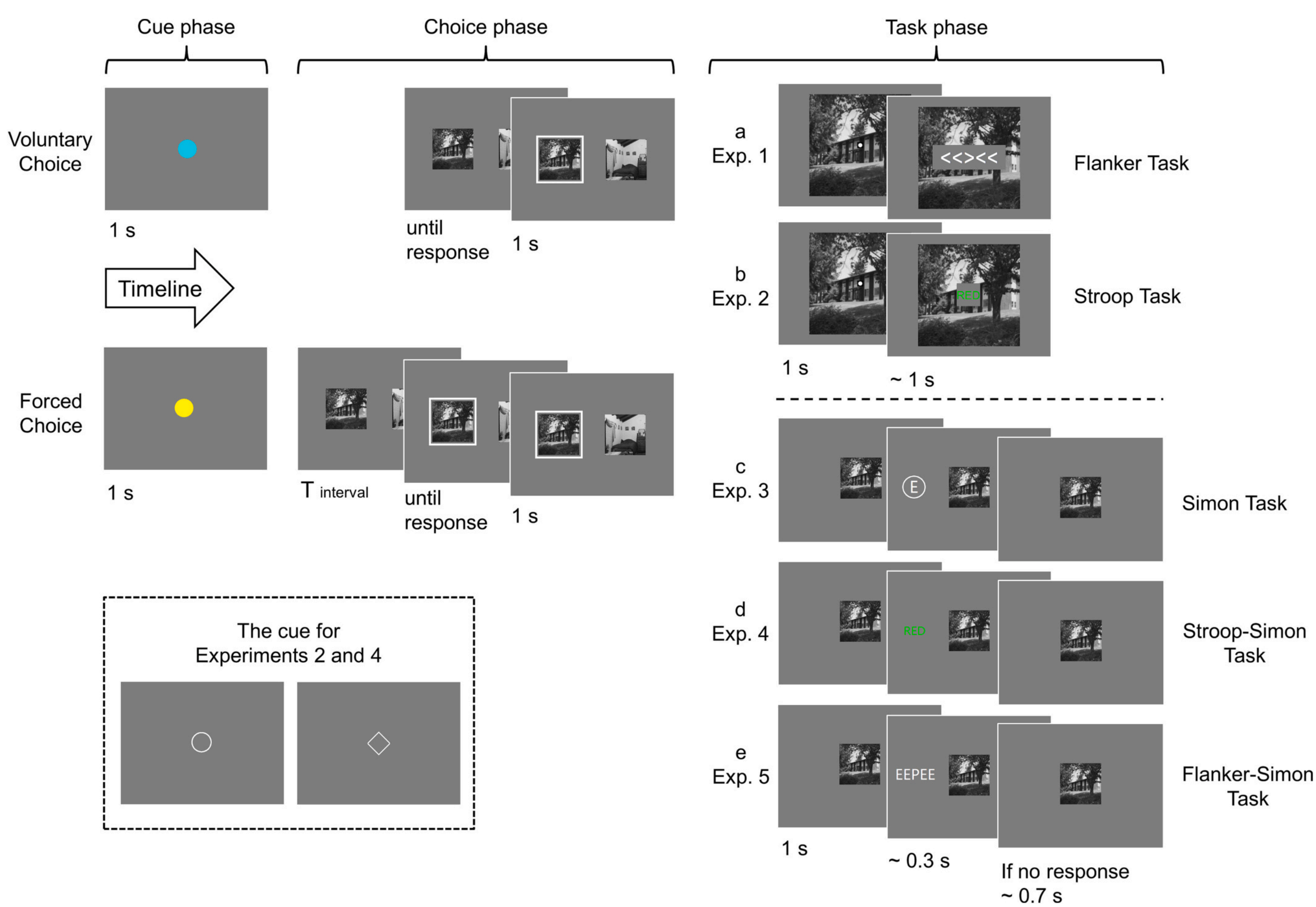

Fig. 1. The trial structure of all experiments. In the cue phase, a cue (different color dots for Experiments 1, 3, and 5, and different shapes for Experiments 2 and 4) was presented to indicate the choice condition (voluntary vs. forced) for the current trial. In the choice phase, a pair of two pictures was presented, and participants were free or forced to choose one by button press. Note that the inclusion of "$T_{interval}$" in the forced-choice condition was to control the exposure time of the options between the two conditions (see *Supplementary Materials*, pp. 2–3, for details). In the task phase, the chosen picture was presented as a task-irrelevant background, and participants were asked to (a) identify the direction of the central arrow and ignore other arrows in Experiment 1 (i.e., a Flanker task), (b) identify the ink-color of a central color-word and ignore the word-meaning in Experiment 2 (i.e., a Stroop task), (c) identify a lateralized letter and ignore the location of the letter in Experiment 3 (i.e., a Simon task), (d) identify the ink-color of a lateralized color-word and ignore the word-meaning and the location of the word in Experiment 4 (i.e., a Stroop-Simon task), and (e) identify the central letter of a lateralized letter-string and ignore other letters and the location of the letter-string in Experiment 5 (i.e., a Flanker-Simon task).

1 s elapsed. If no response was given within 1 s, a feedback (“Too slow”) would be presented at the center of the screen for 0.5 s (not shown in Fig. 1). There were two types of stimulus based on the Flanker congruency: congruent (“< < < < <” or “> > > > >”) and incongruent (“< < > < <” or “> > < > >”).

Experiment 1 had a 2 (Choice Type: voluntary vs. forced) × 2 (Flanker Congruency: congruent vs. incongruent) within-subject design. There were 240 trials in total, with 60 trials for each condition. Trials were intermixed and divided into 5 blocks with 48 trials in each block. Trials of the four conditions were distributed with equal probability in each block. Prior to the formal experiment, participants were provided with 16 example trials.

A total of 250 black and white pictures of outdoor houses or indoor furnishings (adopted from Luo, Wang, & Zhou, 2022) were used as the optional pictures in the choice phase, in which 240 pictures were included in the formal experiment and 10 pictures were included in the example trials. For each participant in the formal experiment, the 240 pictures were randomly assigned into 120 picture pairs without repetition. The same 120 pairs were presented as options in the choice phase of the voluntary- and forced-choice conditions; that is, each pair appeared only once in the voluntary- or forced-choice condition.

2.2.2. Experiment 2

The stimuli and procedure were the same as in Experiment 1 with the following exceptions. In the cue phase, considering that the subsequent task was color discrimination (i.e., the Stroop task), we replaced the cyan or yellow dots with a circle or a diamond ($1.7^\circ \times 1.7^\circ$, see the top-right of Fig. 1), which was unrelated to colors, to indicate whether the current trial was a voluntary or forced choice one.

In the task phase (Fig. 1b), participants were asked to complete a Stroop task (MacLeod, 1991; Stroop, 1935), in which a color word was embedded inside a grey rectangle ($3.3^\circ \times 3.3^\circ$) and presented on the top of the background picture until a button press was given or 1 s elapsed. Specifically, a 4:2 stimulus-response mapping design was adopted to dissociate the perceptual and response-selection processing of Stroop conflict effects (see also de Houwer, 2003; Schmidt & Cheesman, 2005). That is, a word ($2.5^\circ \times 2.5^\circ$) “red”, “green”, “yellow”, or “blue” was presented, and the ink color of the word could be either red, green, yellow, or blue. Participants were asked to indicate the ink color of the word by pressing “J” or “K” using the index and middle fingers of the right hand while ignoring the meaning of the word. For half of the participants, “J” corresponded to red or green, and “K” corresponded to yellow or blue; for the other half of the participants, the color-button association was reversed. There were three types of stimulus based on the Stroop congruency: (1) “S + R+” (congruent) where the word meaning and the ink color were congruent, including “red” in red, “green” in green, “yellow” in yellow, and “blue” in blue; (2) “S–R+” (semantically incongruent) where the word-meaning and the ink-color were semantically incongruent, although the potential response buttons for the word-meaning and the ink-color were congruent, including “red” in green, “green” in red, “yellow” in blue, and “blue” in yellow; (3) “S–R–” (double incongruent) where the word-meaning and the ink-color were semantically incongruent, and the potential response buttons for the word-meaning and the ink-color were also incongruent, including “red” in blue or yellow, “green” in blue or yellow, “yellow” in red or green, and “blue” in red or green.

Experiment 2 had a 2 (Choice Type: voluntary vs. forced) × 3 (Stroop Congruency: S + R+, S–R+ vs. S–R–) within-subject design. There were 240 trials in total with 40 trials for each condition. The settings of example trials were the same as in Experiment 2. Prior to the example trials, participants were additionally provided with 48 practice trials in which only the Stroop stimuli were provided. Participants were required to repeat these practice trials if the accuracy was below 80%.

2.2.3. Experiment 3

The stimuli and procedure were the same as in Experiment 1 with the following exceptions. In the choice phase, participants chose a picture by pressing “E” (the picture on the left) using the index finger of the left hand or “P” (the picture on the right) using the index finger of the right hand.

In the task phase (Fig. 1c), participants were asked to complete a Simon task (Hommel, 2011; Simon & Rudell, 1967), in which a white letter “E” or “P” ($1.2^\circ \times 1.2^\circ$) inside a white circle ($3.3^\circ \times 3.3^\circ$) was presented 9.8° left or right to the center of the screen. Participants were asked to indicate the letter (“E” vs. “P”) in the circle by pressing “E” (if the letter was “E”) using the index finger on the left hand or “P” (if the letter was “P”) using the index finger on the right hand while ignoring the location of the letter. The centrally presented background was $5.3^\circ \times 5.3^\circ$ of visual angle. The task stimulus was presented left or right to the background picture for 0.3 s. If a response was given within this time window of 0.3 s, the current trial would be terminated, otherwise, the displayed stimulus on the screen would be replaced with the background for another 0.7 s. The button press was recorded within this total time window of 1 s.

There were two types of stimulus based on the Simon congruency: congruent (including “E” presented at the left of the screen, and “P” presented at the right of the screen), and incongruent (including “E” presented at the right of the screen, and “P” presented at the left of the screen). Experiment 3 had a 2 (Choice Type: voluntary vs. forced) × 2 (Simon Congruency: congruent vs. incongruent) within-subject design.

It should be noted that, in the Simon task described above, the response button (i.e., the key “E” or “P”) was the same as the Simon stimulus (i.e., the letter “E” or “P”), which might produce additional overlaps between the stimulus and response sets (e.g., Hommel, 1998, 2004; Hommel, Müsseler, Aschersleben, & Prinz, 2001). To exclude the potential contribution of the additional overlaps to the observed effects and replicate the effect of voluntary choice on the Simon effect, we conducted a new experiment, Experiment 3b (preregistered at https://osf.io/cvjqp) in which a shape (i.e., a circle or a diamond) was included as the Simon stimulus and the association between shapes and response buttons was counterbalanced across participants.

2.2.4. Experiment 4

The stimuli and procedure were the same as in Experiment 3 with the following exceptions. In the cue phase, the cyan or yellow dots were again replaced with a circle or a diamond for a reason similar to that of Experiment 2. In the task phase of Experiment 4 (Fig. 1d), participants were asked to complete a Stroop-Simon task (Hommel, 1997; Luo, Gu, et al., 2022). In this task, a color word (i.e., the Stroop stimulus which was the same as Experiment 2) was presented 9.8° left or right to the center of the screen (i.e., the same Simon manipulation as in Experiment 3). Participants were asked to identify the ink color of the color word by pressing “E” or “P” respectively using the index fingers on the left or right hand while ignoring the meaning of the word and the location of the stimulus. The color-button association was counterbalanced across participants.

Experiment 4 had a 2 (Choice Type: voluntary vs. forced) × 3 (Stroop Congruency: S + R+, S–R+ vs. S–R–) × 2 (Simon Congruency: congruent vs. incongruent) within-subject design. There were 384 trials in total with 32 trials for each condition. Trials were intermixed and divided into 8 blocks with 48 trials in each block. The settings of the example trials and practice trials were the same as in Experiment 2.

A total of 394 outdoor or indoor pictures were used (adopted from Experiment 1 and Ahmed & Moustafa, 2016, https://github.com/emanhamed/Houses-dataset), in which 384 pictures were included in the formal experiment and 10 pictures were included in the example trials. A similar pairing of pictures as Experiment 1 was applied to ensure that each picture pair appeared only once in the voluntary- or forced-choice condition.

2.2.5. Experiment 5

Experiment 5 was preregistered (https://osf.io/vx8fe). The stimuli and procedure were the same as in Experiment 3 with the following exceptions. In the task phase of Experiment 5 (Fig. 1e), participants were asked to complete a Flanker-Simon task (Hommel, 1997; Wendt et al., 2006). In this task, a string of five letters (i.e., "EEEEE", "PPPPP", "EEPEE", or "PPEPP", 1.2° × 1.2° for each letter) was presented, with the central target letter 9.8° left or right to the center of the screen. Participants were asked to indicate the central letter ("E" vs. "P") of the string by pressing "E" (if the letter was "E") using the index finger of the left hand or "P" (if the letter was "P") using the index finger of the right hand while ignoring other flanking letters and the location of the letter-string.

Experiment 5 had a 2 (Choice Type: voluntary vs. forced) × 2 (Flanker Congruency: congruent vs. incongruent) × 2 (Simon Congruency: congruent vs. incongruent) within-subject design. There were 320 trials in total, with 40 trials in each condition. All trials were divided into 10 blocks, with trials of different conditions equally distributed in each block. There were 32 practice trials prior to the formal experiment. The settings of practice trials and example trials were the same as in Experiment 2. There were 330 pictures used in Experiment 5 (adopted from Experiment 4) with 320 for the formal experiment and 10 for the example trials.

2.3. Statistical analysis

2.3.1. Behavioral data

2.3.1.1. Reaction time (RT) and error rate (ER). For each participant, omissions and trials with incorrect responses were first excluded. Then trials with RTs (including RTs of the conflict task in the task phase and RTs of choice in the choice phase) beyond 3SD of the mean RT in each condition were excluded (2.92%, 2.00%, 2.30%, 1.83%, and 2.44% of trials in Experiments 1, 2, 3, 4, and 5, respectively). The mean RT of the conflict task was calculated based on the remaining correct response trials in each condition. The error rate (ER) in each condition was calculated as the proportion of omissions and incorrect response trials in that condition.

For each experiment, repeated-measures analysis of variance (ANOVA) was performed on RTs and ERs of the conflict task. Experiment 1: the 2 (Choice Type: voluntary vs. forced) × 2 (Flanker Congruency: congruent vs. incongruent) ANOVA. Experiment 2: the 2 (Choice Type: voluntary vs. forced) × 3 (Stroop Congruency: S + R+, S–R+ vs. S–R–) ANOVA. Experiment 3: the 2 (Choice Type: voluntary vs. forced) × 2 (Simon Congruency: congruent vs. incongruent) ANOVA. Experiment 4: the 2 (Choice Type: voluntary vs. forced) × 3 (Stroop Congruency: S + R+, S–R+ vs. S–R–) × 2 (Simon Congruency: congruent vs. incongruent) ANOVA. Experiment 5: the 2 (Choice Type: voluntary vs. forced) × 2 (Flanker Congruency: congruent vs. incongruent) × 2 (Simon Congruency: congruent vs. incongruent) ANOVA. In addition, we also conducted the Bayesian ANOVA (van den Bergh et al., 2020) using JASP 0.16.2 (Wagenmakers et al., 2018; Wagenmakers et al., 2018) to obtain the Bayes Factor (BF) for all effects. In particular, following the conventional ANOVA results, the BF_{01} was reported to quantify the extent to which the null hypothesis was supported against the alternative hypothesis. Note that "matched" models were considered in the Bayesian ANOVA (i.e., all models with the interaction effect were compared to models with the same predictors except for the interaction effect) because interaction effects were the primary concern here (van den Bergh et al., 2020). Per convention, a BF_{01} between 1 and 3, between 3 and 10, or >10 is considered to be weak, moderate, or strong evidence in favor of the null hypothesis, respectively (van Doorn et al., 2021); in contrast, a BF_{01} between 1 and 0.33, between 0.33 and 0.1, or < 0.1 is considered to be weak, moderate, or strong evidence in favor of the alternative hypothesis, respectively.

To compare the conflict effects in the voluntary- and forced-choice conditions, the conflict effects in terms of the RT difference between the congruent and incongruent conditions in each experiment were calculated, and paired *t*-tests were conducted. The Flanker effect was calculated as "$RT_{Flanker\text{-}incongruent} - RT_{Flanker\text{-}congruent}$"; the Stroop effect at the pre-response level was calculated as "$RT_{S-R+} - RT_{S+R+}$"; the Stroop effect at the response-selection level was calculated as "$RT_{S-R-} - RT_{S-R+}$"; the Simon effect was calculated as "$RT_{Simon\text{-}incongruent} - RT_{Simon\text{-}congruent}$". In cases where the null hypothesis was accepted, the Bayes Factor (referred to as BF_{01}) was calculated through the Bayesian t-test to quantify the extent to which the null hypothesis was supported against the alternative hypothesis.

2.3.1.2. Comparison across experiments. To show the consistency of the result patterns across Experiments 1–3, a 2 (Choice Type: voluntary vs. forced) × 2 (Congruency: congruent vs. incongruent) × 3 (Task: Flanker, Stroop vs. Simon) mixed-measures ANOVA was conducted on RTs and ERs, with the three experiments regarded as a between-participant variable (i.e., Task). Note that, for the Stroop task (i.e., Experiment 2) in this cross-experiment comparison, we took the S + R+ condition as the congruent condition, and combined trials in the S–R+ and S–R– conditions as the incongruent condition.

It is worth noting that in Experiments 1 and 2, participants were asked to press "D" and "F" by using the left hand in the choice phase, and press "J" and "K" by using the right hand in the task phase; however, in Experiments 3, 4, and 5, the same two response buttons "E" and "P" were used for both the choice and task phases, with one button pressed by the left hand and the other by the right hand. This might have led to confounds that the effects of voluntary choice in different types of conflict tasks were due to the difference in response buttons. To test this alternative, we compared the effect of Choice Type on the Flanker conflict between Experiments 1 and 5, and on the Stroop conflict between Experiments 2 and 4. Specifically, a 2 (Choice Type: voluntary vs. forced) × 2 (Flanker Congruency: congruent vs. incongruent) × 2 (Experiment: 1 vs. 5) mixed-measures ANOVA, and a 2 (Choice Type: voluntary vs. forced) × 3 (Stroop Congruency: S + R+, S–R+ vs. S–R–) × 2 (Experiment: 2 vs. 4) mixed-measures ANOVA was conducted on RTs. In addition, Bayesian ANOVAs as in the RT analysis illustrated above were conducted to evaluate the extent to which the null hypothesis was supported over the alternative hypothesis.

2.3.1.3. RT distributional analysis. Previous studies have shown that RT distributions (i.e., the time course of an effect, known as the "delta plot", De Jong et al., 1994; Miller & Schwarz, 2021; Pratte et al., 2010) were different for the Flanker, Stroop, and Simon effects: while the Simon effect tends to decrease as RT increases (i.e., a negative-going delta plot), both the Flanker and Stroop effects tend to increase with RT increases (i.e., a positive-going delta plot). Here we conducted the RT distributional analysis (see *Supplementary Materials*, pp. 22–27, for details) to shed light on how the voluntary choice interacts with the temporal dynamics of different types of conflict effects. Specifically, for each participant and condition, trials with a correct response were sorted and equally divided into 5 RT bins. Mean RT was obtained for each RT bin, and the conflict effect in each RT bin was calculated respectively for the voluntary- and forced-choice conditions. A liner regression function [$Y = a + b^*(RT - RT_{ave})$] was respectively fitted for the voluntary- and forced-choice conditions, where Y is the conflict effect, RT is the mean RT for each bin, and RT_{ave} is the RT averaged across all conditions and participants in the corresponding experiment (De Jong et al., 1994). To investigate how voluntary choice modulates conflict resolution along with the response speed, the estimated parameters (intercept a and slope b) between the voluntary- and forced-choice conditions were compared by paired *t*-test for each experiment.

2.3.2. Diffusion Model for Conflict Tasks

To further assess how voluntary choice affects different types of conflict control, the observed behavioral data (RTs and ERs) were fitted with the Diffusion Model for Conflict Tasks (DMC, Ulrich et al., 2015). Below we briefly describe the DMC. Please see *Supplementary Materials*, pp. 4–6, for more details on the features and the model fitting of DMC in the current study (a formal description of the DMC is provided in Ulrich et al., 2015).

DMC is a variant of the Drift-Diffusion Model (DDM). DDM assumes that when a two-alternative forced-choice (2AFC) response is required, evidence for one response over the other response accumulates gradually over time, and the response is executed whenever the accumulated evidence exceeds a certain threshold (Ratcliff, 1978; Ratcliff & McKoon, 2008). Based on the assumption of DDM, DMC proposes that when a 2AFC response is required in a conflict task, a single evidence accumulation process triggers the response by combining processes for the task-relevant information (i.e., controlled processes) and processes for the task-irrelevant information (i.e., automatic processes). Here, the activation elicited by the task-irrelevant information decays spontaneously or is actively suppressed (Burle et al., 2002; Ridderinkhof, 2002), and automatic processes facilitate (impede) controlled processes in the congruent (incongruent) trials.

Specifically, as in the standard DDM (Ratcliff & McKoon, 2008), in DMC, the RT of the conflict task is the combination of the decision time (D) and the non-decision time (R), i.e., $\mathrm{RT} = D + R$. The D is determined by evidence accumulation processes, and the R is sampled from a normal distribution with a given mean (R_{mean}) and standard deviation (R_{SD}). All evidence accumulation processes are estimated by the standard Wiener diffusion process with a scale parameter (σ). Evidence accumulates over time (t) after the onset of the conflict stimulus. The evidence accumulation of controlled processes, $\mathrm{X_c}(t)$, and the evidence accumulation of automatic processes, $\mathrm{X_a}(t)$, are superimposed to produce the total evidence accumulation processes, $\mathrm{X}(t)$, i.e., $\mathrm{X}(t) = \mathrm{X_c}(t) + \mathrm{X_a}(t)$. Responses are generated whenever the accumulated evidence exceeds a boundary (b). The upper boundary and lower boundary represent the correct response and the error response, respectively.

As shown in Fig. 2a, the expected mean of $\mathrm{X_c}(t)$ (i.e., controlled processes) is modeled by a linear function with a constant drift rate (μ_c). The expected mean of $\mathrm{X_a}(t)$ (i.e., automatic processes) is modeled by a Gamma density function (pulse-like function) which represents that the automatic activation rises rapidly to the maximum and then gradually decays to zero. This Gamma distribution is defined by a shape parameter (α), a scale parameter (τ), and a peak-amplitude parameter (A). The time spent to reach the peak amplitude (t_{peak}) can be calculated as $\tau^*(\alpha - 1)$. Note that automatic processes initially drift toward the upper boundary in the congruent trials and toward the lower boundary in the incongruent trials. In addition, the starting point of the evidence accumulation is sampled from a beta distribution centered around zero within the boundary range with a shape parameter (α_s) to allow for trial-to-trial variability of the starting point.

For each experiment, by using the R-package DMCfun (Mackenzie & Dudschig, 2021, https://github.com/igmmgi/DMCfun), the DMC was fitted to individuals' data of the voluntary- and forced-choice conditions, respectively. For Experiments 1 and 3 where a single type of conflict was involved (i.e., the simple Flanker or Simon conflict), all trials of the congruent and incongruent conditions were included in the DMC. For Experiment 2 where two incongruent conditions (i.e., S–R+ and S–R–) were involved, trials in these two conditions were combined to form a new, overall incongruent condition, and trials in the S + R+ condition were regarded as the congruent trials (this treatment for the Stroop conflict was also applied to Experiment 4 described below). For Experiment 4 where two types of conflict were investigated simultaneously (i.e., the Simon conflict was mixed with the Stroop conflict), the Stroop-congruent and Stroop-incongruent trials in the Simon-congruent condition were selected to fit the DMC to the Stroop conflict. This selection was to control the confounding contribution of the Simon conflict. Similarly, the Simon-congruent and Simon-incongruent trials in the Stroop-congruent (i.e., S + R+) condition were selected to fit the DMC to the Simon conflict. For Experiment 5, the same data selection was applied to fit the DMC to both the Flanker and Simon conflicts.

Following previous studies using the DMC (e.g., Luo, Yang, & Wang, 2022; Mittelstädt, Miller, Leuthold, Mackenzie, & Ulrich, 2022; Ulrich et al., 2015), the diffusion parameter σ was fixed at 4. The starting values for fitting each parameter were decided following Ulrich et al. (2015) and the suggestion from Mackenzie and Dudschig (2021), see Table S2 in *Supplementary Materials* for details. The model was fitted simultaneously to the cumulative distribution function (CDF) of RT and the conditional accuracy function (CAF) by minimizing the root mean squared error (RMSE) between observed values and predicted values. The CDF described the probability distribution of the RT; there were 5 quantiles of the RT distribution for both congruent and incongruent conditions (see also Luo, Yang, & Wang, 2022). The CAF described response accuracies on different response speeds. Here all RT data of a given condition were sorted and equally divided into 5 RT bins from fastest to slowest RTs; then for each RT bin, the proportion of correct responses was calculated. The differential evolution optimization algorithm was applied to minimize RSMEs using the R-package DEoptim (Mullen, Ardia, Gil, Windover, & Cline, 2011) provided by the DMCfun (see also Mittelstädt et al., 2022).

By fitting the DMC, we obtained best-fitting parameters for the voluntary- and forced-choice conditions in each experiment, including the shape parameter of automatic processes (α), the scale parameter of automatic processes (τ), the peak amplitude of automatic processes (A), the time-to-peak amplitude of automatic processes (t_{peak}), the drift rate of controlled processes (μ_c), the decision boundary (b), the shape parameter of the starting point (α_s), the mean (R_{mean}) and standard deviation (R_{SD}) of the non-decision time. Then we focused on the psychologically relevant parameters A, t_{peak}, μ_c, b, and R_{mean} to assess how the voluntary choice-making had modulated conflict control. Specifically, for Experiments 1–3, the 2 (Choice Type: voluntary vs. forced) × 3 (Task: Flanker, Stroop vs. Simon) mixed-measures ANOVA was conducted on the 5 parameters; for Experiment 4, the 2 (Choice Type: voluntary vs. forced) × 2 (Conflict Type: Stroop vs. Simon) repeated-measures ANOVA was conducted on the 5 parameters; for Experiment 5, the 2 (Choice Type: voluntary vs. forced) × 2 (Conflict Type: Flanker vs. Simon) repeated-measures ANOVA was conducted on the 5 parameters.

3. Results

3.1. Behavioral results

Main behavioral results are illustrated in Fig. 3. Overall, classical conflict effects were replicated in all experiments, i.e., the Flanker effect in which participants responded more slowly in the Flanker-incongruent condition than in the Flanker-congruent condition (Experiments 1 and 5); the Stroop effect at both the pre-response and the response-selection levels, that is, participants responded not only more slowly in the S–R– condition than the S–R+ and S + R+ conditions, but also more slowly in the S–R+ condition than in the S + R+ condition (Experiments 2 and 4); the Simon effect in which participants responded more slowly in the Simon-incongruent condition than in the Simon-congruent condition (Experiments 3, 4, and 5).

To investigate the effect of voluntary choice-making on different types of conflict control, here we focused on the main effect of Choice Type (voluntary vs. forced) and its interaction with other variables in the ANOVA of each experiment. Full results can be found in *Supplementary Materials*, pp. 7–16.

3.1.1. Experiment 1

3.1.1.1. Reaction times. As shown in Fig. 3a, the main effect of Choice Type was significant, F (1, 35) = 15.09, $p < .001$, $\eta_p^2 = 0.30$ (BF_{01} = 0.11), indicating that participants generally responded faster after a

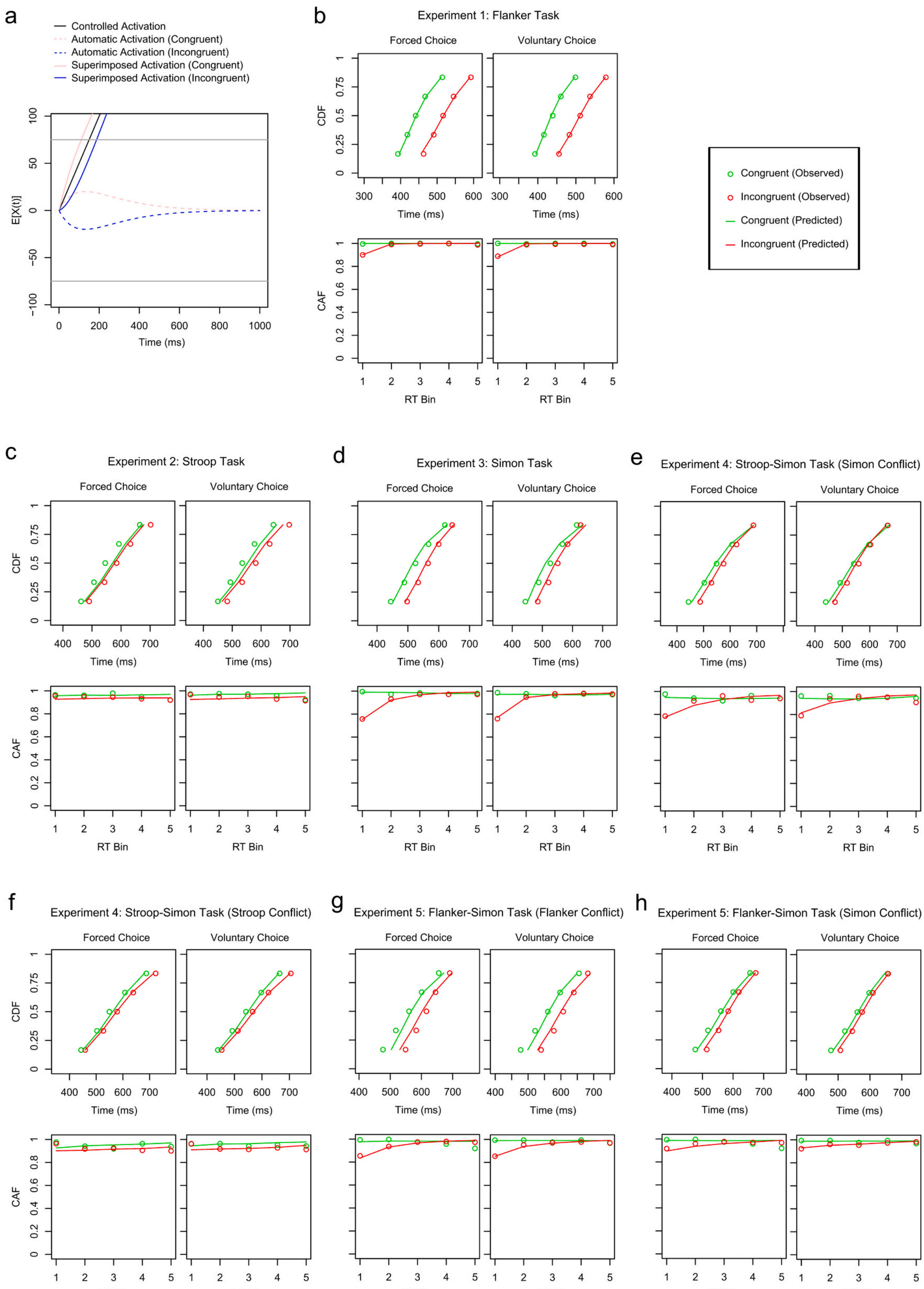

Fig. 2. Illustrations of the simulation for mean activations of different processes, the observed experimental data, and the model predictions of the Diffusion Model for Conflict Tasks (DMC, Ulrich et al., 2015). (a) Mean activation functions of simulation involving 10^5 trials for each congruency condition with $\tau = 130$, $A = 20$, $\alpha = 2$, $\mu_c = 0.5$, $b = 75$, $\alpha_s = 3$, $R_{\text{mean}} = 300$, $R_{\text{SD}} = 30$. (b – h) Observed and predicted cumulative distribution functions (CDFs) and conditional accuracy functions (CAFs) for the voluntary- and forced-choice conditions in each experiment. Each sub-figure includes 4 panels; The upper two and bottom two panels show the CDF and CAF, respectively; and the left two and right two panels depict the forced- and voluntary-choice conditions, respectively. For both the congruent and incongruent conditions, the CDF includes 5 quantiles of the reaction time (RT) distribution; and the CAF describes the proportion of correct responses in 5 RT bins from fastest to slowest RTs. These plots are created and edited by using the R-package DMCfun (Mackenzie & Dudschig, 2021, https://github.com/igmmgi/DMCfun).

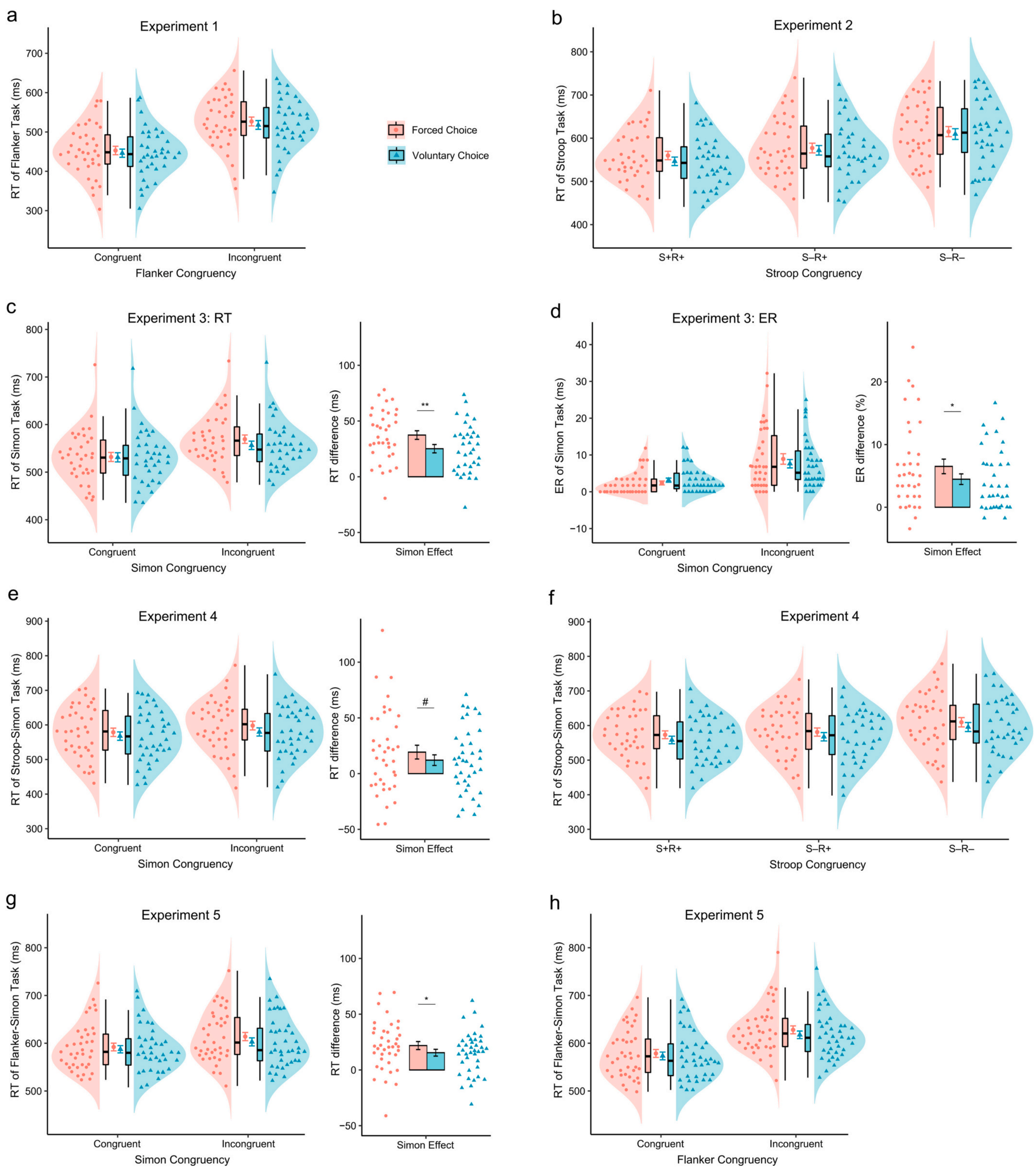

Fig. 3. Main results of all the experiments. The reaction time (RT) of the flanker task (a), the RT of the Stroop task (b), the RT and error rate (ER) of the Simon task (c, d), the RT of the Stroop-Simon task (e, f), and the RT of the Flanker-Simon task (g, h) as a function of Choice Type (voluntary vs. forced) and Congruency in all of the experiments. Each plot illustrates the data distribution, box plot, and mean with SEM in each condition. The dots and triangles inside the shape of the distribution represent individual data. In each box plot, the central line represents the median; the bottom and top of the box represent the 25th and 75th percentiles; the whiskers represent values within 1.5 times the interquartile range above the upper quartile and below the lower quartile. In panels b and f, S + R+ = congruent condition where the word meaning is congruent with the ink color; S–R+ = semantically incongruent condition where the word meaning and the ink color are semantically incongruent, although the potential response buttons are congruent; S–R– = double incongruent condition where the word meaning and the ink color are semantically incongruent, and the potential response buttons are also incongruent. In panels c, d, e, and g, given the interaction between Choice Type and Simon Congruency, the Simon effect in each type of choice is calculated by subtracting the value in the congruent condition from the value in the incongruent condition, and is illustrated as a bar-plot which displays the mean with SEM (individual data are shown by dots and triangles); ** $p < .01$, * $p < .05$, # $p = .061$. These plots are created and edited by using the R-package raincloudplots (Allen, Poggiali, Whitaker, Marshall, & Kievit, 2018, https://github.com/RainCloudPlots/RainCloudPlots).

voluntary choice than a forced choice (482 vs. 490 ms). However, the interaction between Choice Type and Flanker Congruency was not significant, $F < 1$. This null effect of interaction was moderately supported by the $BF_{01} = 4.04$ (i.e., the null hypothesis was 4.04 times more likely to be true than the alternative hypothesis) in the Bayesian ANOVA. Further paired *t*-tests on the Flanker effect did not show a significant difference between the voluntary- and forced-choice conditions, t (35) = 0.60, p = .555. Bayesian t-test showed that the BF_{01} = 4.73, moderately supporting the null effect of voluntary choice-making on the Flanker effect.

3.1.1.2. Error rates. Neither the main effect of Choice Type, F (1, 35) = 1.33, p = .256, nor the interaction, F (1, 35) = 1.62, p = .212, was significant.

3.1.2. Experiment 2

3.1.2.1. Reaction times. As shown in Fig. 3b, participants responded faster after a voluntary choice than a forced choice (576 vs. 584 ms), F (1, 35) = 9.53, p = .004, $\eta_p^2 = 0.21$ ($BF_{01} = 0.16$). The interaction between Choice Type and Stroop Congruency was not significant, F (2, 70) = 1.24, p = .297. This null effect of interaction was also moderately supported by the $BF_{01} = 5.85$ in the Bayesian ANOVA. Further paired *t*-tests on the Stroop effect at the pre-response level, t (35) = 1.56, p = .128, or at the response-selection level, t (35) = 0.06, p = .950, did not show a significant difference between the two choice conditions. Although the Bayesian t-test on the Stroop effect at the pre-response level showed only weak evidence ($BF_{01} = 1.85$), the Bayesian t-test on the Stroop effect at the response-selection level showed moderate evidence ($BF_{01} = 5.58$) in favor of the null hypothesis.

3.1.2.2. Error rates. The main effect of Choice Type or the interaction was not significant, all *Fs* < 1, *ps* > 0.491.

3.1.3. Experiments 3 and 3b

3.1.3.1. Reaction times. As shown in Fig. 3c, the generally improved response speed in the voluntary (vs. forced) choice condition (544 vs. 551 ms) was again observed in Experiment 3, F (1, 34) = 10.13, p = .003, $\eta_p^2 = 0.23$ ($BF_{01} = 0.26$). Importantly, the interaction between Choice Type and Simon Congruency was significant, F (1, 34) = 8.60, p = .006, $\eta_p^2 = 0.20$ ($BF_{01} = 0.32$). That is, the Simon effect on RTs was smaller in the voluntary-choice condition than in the forced-choice condition (25 vs. 37 ms), t (34) = 2.93, p = .006, d = 0.50.

The above RT results were replicated in Experiment 3b (preregistered at https://osf.io/cvjqp) in which the potential overlaps between the stimulus and response sets were controlled (see *Supplementary Materials*, pp. 28–31 for details). Thus, the potential confounds in the setup in Experiment 3 did not affect the effect of voluntary choice on the Simon conflict.

3.1.3.2. Error rates. As shown in Fig. 3d, although the main effect of Choice Type was not significant, $F < 1$, the interaction between Choice Type and Simon Congruency was significant in Experiment 3, F (1, 34) = 5.48, p = .025, $\eta_p^2 = 0.14$. That is, the Simon effect on ERs was smaller after making a voluntary choice (4.47%) than after making a forced choice (6.52%), t (34) = 2.34, p = .025, d = 0.40, which was consistent with the RT results.

3.1.4. Experiment 4

3.1.4.1. Reaction times. The 2 × 3 × 2 repeated-measures ANOVA showed a significant main effect of Choice Type, F (1, 37) = 30.09, p < .001, $\eta_p^2 = 0.45$ ($BF_{01} < 0.1$), again replicating the generally improved response speed in the voluntary (vs. forced) choice condition (574 vs. 589 ms). Importantly, although the interaction between Choice Type and Simon Congruency (Fig. 3e) did not reach significance, F (1, 37) = 3.86, p = .057, $\eta_p^2 = 0.09$, this marginally significant result implied that the Simon effect tended to be smaller in the voluntary-choice condition than in the forced-choice condition (12 vs. 19 ms), t (37) = 1.93, p = .061, d = 0.31 (the $BF_{01} = 1.08$), which was consistent with the pattern of Experiment 3. The marginally significant interaction was supported to a certain extent by the Bayesian ANOVA, as the null hypothesis was only weakly supported by BF_{01} = 2.89. More evidence of the effect of voluntary choice on the Simon conflict (e.g., Experiments 3b and 5) is needed.

In contrast, the interaction between Choice Type and Stroop Congruency (Fig. 3f) was not significant, F (2, 74) = 0.02, p = .982. This null effect of interaction was strongly supported by the BF_{01} = 21.66 in the Bayesian ANOVA. Further paired *t*-tests on the Stroop effect at the pre-response level, t (37) = 0.34, p = .737, or at the response-selection level, t (37) = 0.04, p = .971, did not show a significant difference between the voluntary- and forced-choice conditions. Moreover, the Bayesian t-test on these two levels of the Stroop effect showed moderate evidence (BF_{01} = 5.43 and 5.72) in favor of the null hypothesis.

The three-way interaction between Choice Type, Stroop Congruency, and Simon Congruency was not significant, F (2, 74) = 0.50, p = .608 ($BF_{01} = 8.68$).

3.1.4.2. Error rates. The main effect of Choice Type was not significant, F (1, 37) = 2.81, p = .102, nor was its interaction with other variables (all *Fs* < 1, *ps* > 0.468).

3.1.5. Experiment 5

3.1.5.1. Reaction times. In the 2 × 2 × 2 repeated-measures ANOVA, the main effect of Choice Type was significant, F (1, 38) = 19.14, p < .001, $\eta_p^2 = 0.34$ ($BF_{01} < 0.1$), indicating again that participants had generally faster responses after making a voluntary choice than a forced choice (596 vs. 604 ms), which was also in line with the preregistered prediction (https://osf.io/vx8fe). Importantly, the interaction between Choice Type and Simon Congruency was again replicated (Fig. 3g), F (1, 38) = 4.98, p = .032, $\eta_p^2 = 0.12$ ($BF_{01} = 1.98$). That is, the Simon effect was significantly smaller after making a voluntary choice than a forced choice (15 vs. 22 ms), t (38) = 2.29, p = .028, d = 0.37, consistent with the findings in Experiments 3 and 4, and with the preregistered prediction (https://osf.io/vx8fe).

In contrast, the interaction between Choice Type and Flanker Congruency did not reach significance, F (1, 38) = 3.44, p = .071, $\eta_p^2 = 0.08$, which was also consistent with the null interaction in Experiment 1 and with the preregistered prediction (https://osf.io/vx8fe). This null effect of interaction was weakly supported by the $BF_{01} = 2.53$ in the Bayesian ANOVA. Further paired t-test on the Flanker effect between the voluntary- and forced-choice conditions did not reach significance, t (38) = 1.80, p = .080, d = 0.29 (the $BF_{01} = 1.35$).

The three-way interaction between Choice Type, Flanker Congruency, and Simon Congruency was not significant, F (1, 38) = 1.76, p = .193 ($BF_{01} = 2.92$).

3.1.5.2. Error rates. The main effect of Choice Type was significant, F (1, 38) = 7.46, p = .010, $\eta_p^2 = 0.16$ (voluntary choice vs. forced choice: 6.42% vs. 7.80%), showing the same pattern as the RT results. Choice Type did not interact with Flanker Congruency or Simon Congruency, all *Fs* < 1, *ps* > 0.447. The three-way interaction was not significant, F (1, 38) = 3.06, p = .088.

3.1.6. Comparisons across experiments

3.1.6.1. Reaction times of Experiments 1–3. In the 2 × 2 × 3 mixed-measures ANOVA, the main effect of Choice Type was significant, F (1, 104) = 35.88, p < .001, $\eta_p^2 = 0.26$, indicating that participants responded generally faster after making a voluntary choice than a forced choice (531 vs. 539 ms). The two-way interaction between Choice Type and Congruency or between Choice Type and Task was not significant, both *ps* > 0.409. Importantly, the three-way interaction was significant, F (2, 104) $= 5.58$, $p = .005$, $\eta_p^2 = 0.10$, demonstrating that there were reliably different patterns for the Choice Type × Congruency interaction in different conflict tasks, i.e., the significant interaction between Choice Type and Congruency was presented only in the Simon task, but not in the Flanker or Stroop tasks, as reported above.

3.1.6.2. Error rates of Experiments 1–3. The main effect of Choice Type was not significant, F (1, 104) $= 1.73$, $p = .192$. The two-way interaction between Choice Type and Congruency or between Choice Type and Task was not significant, both *ps* > 0.546. Although the three-way interaction did not reach significance, F (2, 104) $= 3.00$, $p = .054$, $\eta_p^2 = 0.05$, this marginally significant result implied a trend of different patterns for the Choice Type × Congruency interaction in different conflict tasks, consistent with the RT results.

3.1.6.3. The Flanker conflict of Experiments 1 and 5. The 2 × 2 × 2 mixed-measures ANOVA taking Experiment as a between-participant factor, which showed that the main effect of Choice Type was significant, F (1, 73) $= 33.37$, $p < .001$, $\eta_p^2 = 0.314$, indicating again that participants responded generally faster after making a voluntary choice than a forced choice (539 vs. 547 ms). The two-way interaction between Choice Type and Flanker Congruency or between Choice Type and Experiment was not significant, both *ps* > 0.109. Importantly, the three-way interaction was not significant, F (1, 73) $= 0.50$, $p = .480$. The Bayesian ANOVA showed the $BF_{01} = 4.36$, moderately supporting that the effect of voluntary choice on the Flanker conflict was comparable between Experiments 1 and 5. Thus, the effect of voluntary choice on the Flanker task cannot be due to the differences in response buttons between Experiments 1 and 5.

3.1.6.4. The Stroop conflict of Experiments 2 and 4. The 2 × 3 × 2 mixed-measures ANOVA taking Experiment as a between-participant factor, which showed that the main effect of Choice Type was significant, F (1, 72) $= 35.07$, $p < .001$, $\eta_p^2 = 0.328$, indicating again that participants responded generally faster after making a voluntary choice than a forced choice (575 vs. 586 ms). The two-way interaction between Choice Type and Stroop Congruency or between Choice Type and Experiment was not significant, both *ps* > 0.116. Importantly, there was also no significant three-way interaction either, F (1, 72) $= 0.50$, $p = .503$. The Bayesian ANOVA showed the $BF_{01} = 7.95$, moderately supporting that the effect of voluntary choice on the Stroop conflict was comparable between Experiments 2 and 4. Thus, the effect of voluntary choice on the Stroop task cannot be due to the differences in response buttons between Experiments 2 and 4.

3.2. RT distributional analysis

Full results of the RT distributional analysis can be found in *Supplementary Materials*, pp. 22–27. As can be seen in Fig. S1 and Fig. S2, while the Flanker (Experiment 1) and Stroop (Experiments 2 and 4) effects increased (or unchanged) with the increasing of RT (i.e., positive-going delta plots) in both the voluntary- and forced-choice conditions, all Simon effects (Experiments 3–5) decreased with the increasing of RT (i.e., negative-going delta plots) in both the voluntary- and forced-choice conditions, suggesting distinct underlying mechanisms between the Simon effect and the Flanker/Stroop effect (Burle et al., 2002; Pratte et al., 2010; Ridderinkhof, 2002). More importantly, the analysis on the intercept a consistently showed that, after the potential contribution of response speed had been regressed out, making a voluntary choice still facilitated the resolution of the Simon effect (i.e., smaller intercept a of the Simon effect) relative to making a forced choice. However, the intercept a of the Flanker and Stroop effects did not show a reliable difference between the voluntary- and forced-choice conditions. These results were consistent with classical analyses of conflict effects reviewed above.

3.3. Diffusion Model for Conflict Tasks (DMC) fitting results

Mean best-fitting parameters and mean RMSEs are shown in Table 1. As can be seen in Fig. 2b – Fig. 2h which illustrate the predicted and observed results, the DMC provided a reasonable fit to the behavioral data. To investigate the effect of voluntary choice-making, here we focused on the effect of Choice Type (voluntary vs. forced) and its interaction with other variables. Full results can be found in *Supplementary Materials*, pp. 17–21.

The effect of voluntary choice was only observed on the parameter A which estimated the peak amplitude of automatic processes (see Fig. 4). Other ANOVAs on the t_{peak}, μ_c, b, or R_{mean} did not show the significant main effect of Choice Type or its interaction with other variables (all *ps* > 0.087). In addition, we also verified the results of the peak amplitude of automatic processes (parameter A) by setting the shape parameter a to 2 in fitting the DMC model (as recommended by Ulrich et al., 2015). Result patterns were virtually identical to the above-reported results (see *Supplementary Materials*, pp. 18–20, for details), suggesting the reliability of the DMC results.

For Experiments 1–3 (Fig. 4a), the 2 (Choice Type: voluntary vs. forced) × 3 (Task: Flanker, Stroop vs. Simon) mixed-measures ANOVA on A showed that, although the main effect of Choice Type was not significant, F (1, 104) $= 0.70$, $p = .404$, the interaction was, F (2, 104) $= 5.73$, $p = .004$, $\eta_p^2 = 0.10$. That is, the peak amplitude of automatic processes (A) was smaller after making a voluntary choice than a forced choice in the Simon task (i.e., Experiment 3, 26.68 vs. 32.03), t (34) $= 2.96$, $p = .006$, $d = 0.50$, but did not differ between the two choice conditions in the Flanker task (i.e., Experiment 1, 35.96 vs. 35.95), t (35) $= 0.01$, $p = .992$, or in the Stroop task (i.e., Experiment 2, 30.96 vs. 28.13), t (35) $= 1.29$, $p = .205$.

For Experiment 4 (Fig. 4b), the 2 (Choice Type: voluntary vs. forced) × 2 (Conflict Type: Stroop vs. Simon) repeated-measures ANOVA on A showed a significant interaction, F (1, 37) $= 4.88$, $p = .033$, $\eta_p^2 = 0.12$, demonstrating again that the peak amplitude of automatic processes (A) was smaller after making a voluntary choice than a forced choice for the Simon conflict (25.09 vs. 31.43), t (37) $= 3.01$, $p = .005$, $d = 0.49$, but it did not differ between the two choice conditions for the Stroop conflict (27.13 vs. 26.73), t (37) $= 0.17$, $p = .863$. The main effect of Choice Type did not reach significance, F (1, 37) $= 3.55$, $p = .067$, $\eta_p^2 = 0.09$.

For Experiment 5 (Fig. 4c), the 2 (Choice Type: voluntary vs. forced) × 2 (Conflict Type: Flanker vs. Simon) repeated-measures ANOVA on A showed a significant main effect of the Choice Type, F (1, 38) $= 4.56$, $p = .039$, $\eta_p^2 = 0.11$, indicating that the peak amplitude of automatic processes (A) was generally smaller after making a voluntary choice (26.99) than a forced choice (29.85) for both the Simon and Flanker conflicts. The interaction was not significant, F (1, 38) $= 1.44$, $p = .238$.

4. Discussion

The present study differentiated three processing levels (the pre-response, response-selection, and response-execution levels) by adopting different conflict tasks and investigated the locus of the impact of voluntary choice-making on behavioral performance. Results across five experiments showed generally faster responses in all tasks after making a voluntary choice than a forced choice, replicating the facilitatory effect of voluntary choice-making (e.g., Luo et al., 2023; Luo, Wang, & Zhou, 2022; Murayama et al., 2015). Importantly, although the voluntary choice-making did not modulate the Flanker (Experiments 1 and 5) and Stroop (Experiments 2 and 4) effects, it did reduce the Simon effect (Experiments 3, 4, and 5), suggesting that expressing volition can motivate subsequent response execution, but may not affect pre-

Table 1
Best-fitting parameters and root mean square errors (RMSEs) of the Diffusion Model for Conflict Tasks (DMC) with standard deviations in parentheses.

Parameter	Exp. 1: Flanker Task		Exp. 2: Stroop Task		Exp. 3: Simon Task		Exp. 4: Stroop-Simon Task				Exp. 5: Flanker-Simon Task			
							Stroop Conflict		Simon Conflict		Flanker Conflict		Simon Conflict	
	VC	FC	VC	FC	VC	FC	VC	FC	VC	FC	VC	FC	VC	FC
A	35.96	35.95	30.96	28.13	26.68	32.03	27.13	26.73	25.09	31.43	30.12	31.43	23.86	28.26
	(6.76)	(4.52)	(9.13)	(10.81)	(9.55)	(7.16)	(9.53)	(11.13)	(9.78)	(7.40)	(7.45)	(7.87)	(10.30)	(10.03)
τ	120.54	113.03	165.63	167.58	85.25	89.50	180.01	181.56	72.26	104.31	96.21	93.11	111.97	131.38
	(60.66)	(64.68)	(71.89)	(93.45)	(69.11)	(66.24)	(95.64)	(78.94)	(68.31)	(81.19)	(64.86)	(54.77)	(89.84)	(68.22)
α	2.20	2.22	2.40	2.32	1.72	1.95	2.31	2.18	1.89	1.67	2.04	2.05	1.99	1.84
	(0.52)	(0.51)	(0.60)	(0.66)	(0.54)	(0.54)	(0.71)	(0.76)	(0.60)	(0.57)	(0.54)	(0.60)	(0.66)	(0.71)
t_{peak}	132.1	116.4	243.2	223.8	42.8	78.1	273.1	227.6	72.7	61.3	89.90	83.4	108.1	112.9
	(76.3)	(45.3)	(154.7)	(178.7)	(42.9)	(93.4)	(199.1)	(185.8)	(117.7)	(74.0)	(66.04)	(54.2)	(136.1)	(129.1)
μ_c	0.86	0.84	0.71	0.69	0.67	0.74	0.60	0.59	0.58	0.57	0.76	0.74	0.84	0.77
	(0.14)	(0.14)	(0.20)	(0.21)	(0.20)	(0.22)	(0.22)	(0.21)	(0.23)	(0.22)	(0.21)	(0.20)	(0.19)	(0.18)
α_s	3.62	3.63	3.61	3.49	2.90	3.05	3.60	3.58	3.24	3.17	3.34	3.47	3.59	3.49
	(0.50)	(0.46)	(0.51)	(0.65)	(0.73)	(0.71)	(0.57)	(0.52)	(0.76)	(0.76)	(0.68)	(0.57)	(0.56)	(0.68)
b	109.94	109.17	72.13	73.05	81.73	91.66	72.84	73.16	77.34	86.87	97.40	90.10	89.40	80.74
	(31.30)	(29.29)	(36.24)	(40.26)	(28.34)	(35.97)	(34.36)	(37.25)	(30.97)	(35.62)	(35.17)	(40.17)	(42.31)	(41.23)
R_{mean}	352.44	356.17	456.43	463.57	431.42	433.05	439.00	443.52	428.22	426.50	462.26	474.53	465.28	471.42
	(43.03)	(42.72)	(62.87)	(75.97)	(42.91)	(43.49)	(78.36)	(86.33)	(69.80)	(73.99)	(46.15)	(58.60)	(66.75)	(66.69)
R_{SD}	10.32	14.80	74.27	65.90	23.89	30.32	80.79	85.74	46.68	45.10	34.89	36.04	49.68	47.39
	(4.83)	(15.16)	(23.22)	(33.07)	(20.94)	(24.96)	(26.90)	(24.41)	(34.17)	(33.58)	(25.47)	(29.77)	(31.15)	(33.39)
RMSE	13.62	14.35	51.58	54.34	29.42	29.08	55.44	62.21	63.48	55.00	33.25	43.19	32.91	43.77
	(9.66)	(12.85)	(21.40)	(27.13)	(19.89)	(22.69)	(26.48)	(33.22)	(27.79)	(34.77)	(25.73)	(25.82)	(25.30)	(29.34)

Note: VC = voluntary-choice condition; FC = forced-choice condition; A = the peak amplitude of automatic processes; τ = the scale parameter of automatic processes. α = the shape parameter of automatic processes; $t_{\text{peak}} = \tau^*(\alpha - 1)$, the time-to-peak amplitude of automatic processes; μ_c = the drift rate of controlled processes; α_s = the shape parameter of the starting point; b = the decision boundary; R_{mean} = the mean of the non-decision time; R_{SD} = the standard deviation of the non-decision time.

response processing or response selection. This notion was further supported by the RT distributional analysis which also demonstrated differential patterns of the effect of making voluntary choices on different conflict tasks, even after the potential contribution of response speed had been regressed out. DMC fitting results further revealed that in the Simon conflict, the peak amplitude of automatic processes (A) was smaller after making a voluntary choice than a forced choice. Considering that the "automatic process", as defined by the DMC modeling for the Simon task, *is* the automatic activation of the motor response elicited by the laterally presented stimulus, here the facilitation of expressing volition on the subsequent response execution was interpreted as attenuating the motor activation from task-irrelevant processes.

The general facilitation on response speed across different tasks and the specific facilitation on the resolution of the Simon conflict by making voluntary choices consistently demonstrate not only a general motivational role of volition, but also a constraint of this volition-related motivation, at least in tasks that require fast motor responses. Considering that the Simon conflict mainly occurs at the response-execution level (Burle et al., 2002; Ridderinkhof, 2002) and the enhanced response speed by voluntary choice-making was generally observed regardless of tasks, we suggest that the facilitation of voluntary choice-making mainly functions on response execution, i.e., the cognitive process which is necessarily involved in all tasks that require motor responses. This inference was also supported by our recent study (Luo et al., 2023) which showed that making a voluntary choice could facilitate the post-search time of the subsequent visual search task (i.e., the time spent on processes after the target was found, such as response execution) rather than the search time (i.e., the time spent on searching for the target).

This volition-related motivation echoes the emotion-related motivation which also facilitates the resolution of the Simon conflict (Kanske & Kotz, 2011). According to the affective-signaling hypothesis, the affective information may trigger the conflict-monitoring system and modulate conflict control processes (Dignath, Eder, Steinhauser, & Kiesel, 2020). Moreover, having voluntary choices is favorable (Luo, Wang, & Zhou, 2022; Patall et al., 2008) and inherently rewarding, which may elicit reward-like activations in the brain (Leotti & Delgado, 2011; Murayama et al., 2015; Murty et al., 2015), echoing the intrinsic motivation that is closely related to positive experiences and inherent reward (Murayama et al., 2016; Patall et al., 2008). Intrinsic motivation is often viewed as a spontaneous tendency for action (Radel et al., 2016), which provides an advantage to engage in actions and recruits the motor system (Murayama, Izuma, Aoki, & Matsumoto, 2016). At the neural level, compared with stimulus-driven actions, voluntary actions induce stronger activity in the supplementary motor area (SMA) (Cunnington, Windischberger, Deecke, & Moser, 2002; Deiber, Honda, Ibañez, Sadato, & Hallett, 1999) which is a key area of the motor system for generating voluntary actions and is associated with the experience of volition (Haggard, 2019). In the present study, the voluntary choice and its outcome were irrelevant to and separated from the subsequent conflict task. Thus, the event of making a voluntary choice to control its outcome (i.e., choose a picture to control the displayed background) would act as a task-irrelevant primer of volition, which enhances intrinsic motivation and the preparation of the motor system. As a result, the prepared motor system can better handle the execution of behavioral responses required by the following task, leading to faster responses and better resolution of the conflict at the response-execution level.

The present study further revealed the underlying processes of different conflict tasks by fitting the DMC (Ulrich et al., 2015), which suggested that the reduction of the Simon conflict after making voluntary choices may be due to the attenuation of the automatic motor activation induced by the task-irrelevant stimulus location. In other words, the expression of volition may attenuate the inappropriate activation of the motor response. These findings are reminiscent of the capacity to veto a willed action (i.e., "free won't"), which is an important aspect of human volition (Haggard, 2008; Hallett, 2007) and is also associated with the motor system. It has been shown that the frontomedial cortex (including SMA) is activated when prepared manual actions are intentionally canceled (Brass & Haggard, 2007). Similarly, readiness potentials that originate from SMA are engaged during not only voluntary muscle contraction but also voluntary muscle relaxation (Terada, Ikeda, Nagamine, & Shibasaki, 1995). In the Simon task, the inhibition of the inappropriate motor activation also involves (pre-)SMA (Verbruggen & Logan, 2008; Wang et al., 2019). The motor system activated by the expression of volition (i.e., voluntary choice-making) might function efficiently not only in the execution of task-required responses but also in the inhibition of responses that are inappropriate to the current task.

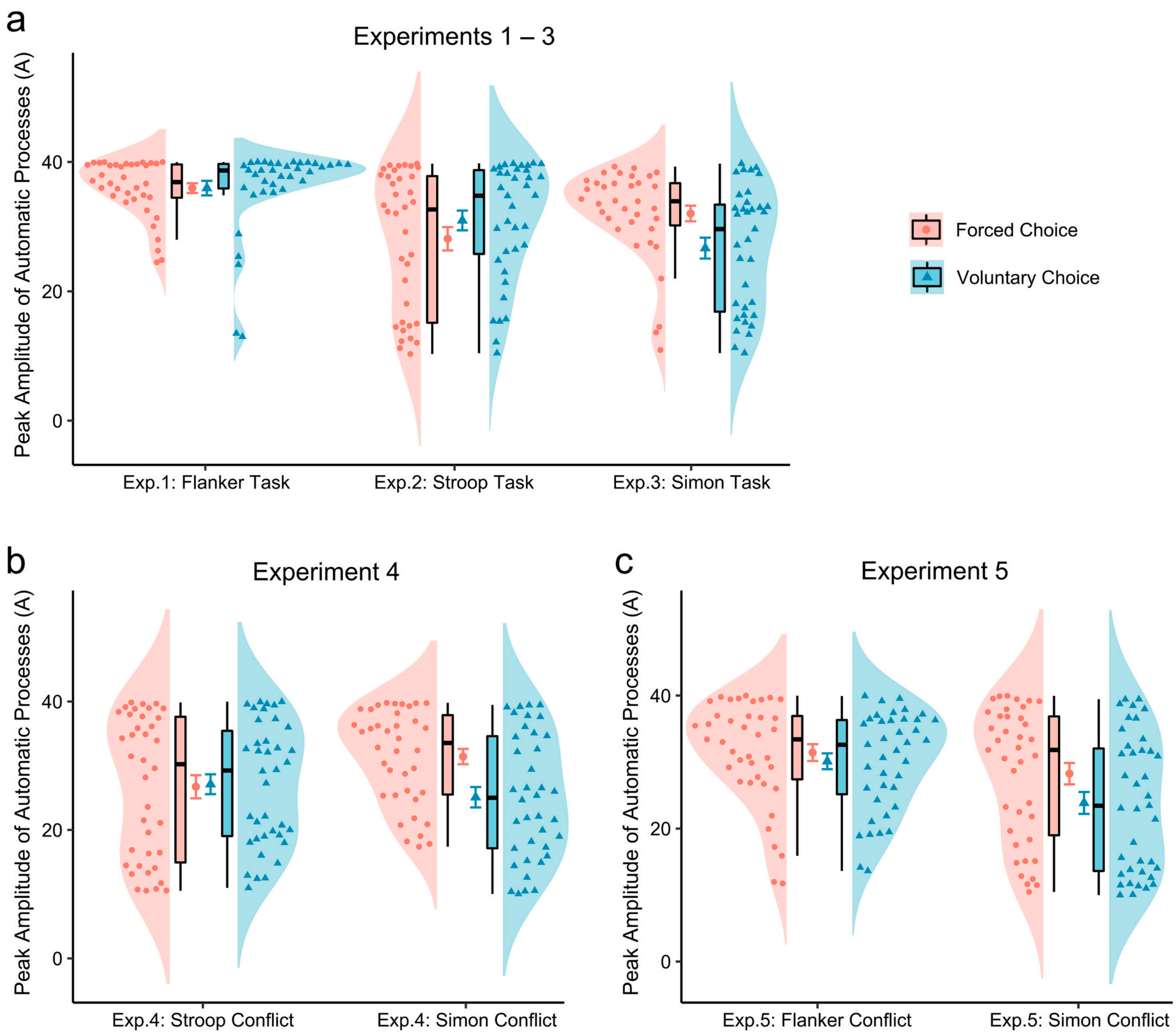

Fig. 4. The peak amplitude of automatic processes (i.e., *A*) in Experiments 1–3 (a), Experiment 4 (b), and Experiment 5 (c) as a function of Choice Type (voluntary vs. forced) and different types of conflict. The *A* was obtained by fitting the Diffusion Model for Conflict Tasks (DMC). Each plot illustrates the data distribution, box plot, and mean with SEM in each condition. The dots and triangles inside the shape of the distribution represent individual data. In each box plot, the central line represents the median; the bottom and top of the box represent the 25th and 75th percentiles; the whiskers represent values within 1.5 times the interquartile range above the upper quartile and below the lower quartile. These plots are created and edited by using the R-package raincloudplots (Allen et al., 2018, https://github.com/RainCloudPlots/RainCloudPlots).

Note that a prevailing view in the literature (e.g., the dimensional overlap theory, Egner, 2008; Hommel, 2011; Kornblum, Hasbroucq, & Osman, 1990) is that the Simon effect only involves the stimulus-response conflict whereas the Flanker and Stroop effects involve both the stimulus-stimulus and stimulus-response conflicts. However, we did not adopt this view in the present study because the "stimulus-response conflict" in the Simon effect is different from the "stimulus-response conflict" in the Flanker or Stroop effect in a number of ways (Burle et al., 2002; Nee et al., 2007; Pratte et al., 2010; Ridderinkhof, 2002; see also the RT distributional analysis of the present study). Specifically, while the Flanker or Stroop effect occurs because the S-R mappings for the target and distractor could be incongruent, the Simon effect occurs because the automatic motor response elicited by the stimulus could be incongruent with the required motor response regardless of the learned S-R mapping. The "stimulus-response conflict" in previous studies rarely distinguished the two different response-related processes we argued here: the response-selection process (i.e., to select a response according to learned S-R mappings) and the response-execution process (i.e., to execute the selected response). Thus, the statement "stimulus-response conflict" could be misleading in the current context since it may contain two levels of conflict (i.e., the conflict at the response-selection level, such as for the Flanker/Stroop effect, and the conflict at the response-execution level, such as for the Simon effect). Therefore, we adopted the framework of processing levels based on the time course of information processing (e.g., Donders, 1969; Töllner et al., 2012) to distinguish the response-related processes in the Simon, Flanker, and Stroop conflicts.

Although the Flanker and Stroop conflicts are thought to be largely irrelevant to the response-execution level (Egner, 2008; Zhang & Kornblum, 1998), some studies did find an interaction between the

Simon conflict and the Flanker or Stroop conflict (e.g., Rey-Mermet & Gade, 2016; Weissman, 2020). It is possible that a conflict task can tap into conflicts at all cognitive levels but with differential weights, e.g., the Flanker effect may have larger weights at the pre-response and response-selection levels, and a smaller weight at the response-execution level. Nevertheless, this limitation does not weaken our main conclusion because the effect of voluntary choice-making was mainly observed in the Simon effect which is firmly believed to occur at the response-execution level (Burle et al., 2002; Ridderinkhof, 2002) and which is clearly different from the Flanker and Stroop effects (Egner, 2008; Nee et al., 2007; Pratte et al., 2010).

In conclusion, the present study demonstrates that volition can motivate subsequent cognitive processing at the response-execution level by attenuating task-irrelevant motor activations. This motivational effect is probably due to that expressing volition activates the motor system which functions efficiently to facilitate not only the execution of task-required responses but also the inhibition of inappropriate responses.

CRediT authorship contribution statement

Xiaoxiao Luo: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Lihui Wang:** Conceptualization, Methodology, Writing – review & editing. **Xiaolin Zhou:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

None.

Data availability

All data, codes, and materials can be accessed at https://osf.io/6k72r/

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Appendix A. Supplementary data

All data, codes, and materials can be accessed at https://osf.io/6k72r/

Experiments 1–4 were not preregistered. The preregistration for Experiment 3b can be accessed at https://osf.io/cvjqp. The preregistration for Experiment 5 can be accessed at https://osf.io/vx8fe. Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2024.105738.

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