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BRIEF REPORT

The benefit of making voluntary choices generalizes across multiple effectors

Xiaoxiao Luo[1,2,3] · Lihui Wang[4,5,6] · Jiayan Gu[2,7] · Qiongting Zhang[2] · Hongyu Ma[8] · Xiaolin Zhou[2,3,7,9]

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Abstract
It has been shown that cognitive performance could be improved by expressing volition (e.g., making voluntary choices), which necessarily involves the execution of action through a certain effector. However, it is unclear if the benefit of expressing volition can generalize across different effectors. In the present study, participants made a choice between two pictures either voluntarily or forcibly, and subsequently completed a visual search task with the chosen picture as a task-irrelevant background. The effector for choosing a picture could be the hand (pressing a key), foot (pedaling), mouth (commanding), or eye (gazing), whereas the effector for responding to the search target was always the hand. Results showed that participants responded faster and had a more liberal response criterion in the search task after a voluntary choice (vs. a forced choice). Importantly, the improved performance was observed regardless of which effector was used in making the choice, and regardless of whether the effector for making choices was the same as or different from the effector for responding to the search target. Eye-movement data for oculomotor choice showed that the main contributor to the facilitatory effect of voluntary choice was the post-search time in the visual search task (i.e., the time spent on processes after the target was found, such as response selection and execution). These results suggest that the expression of volition may involve the motor control system in which the effector-general, high-level processing of the goal of the voluntary action plays a key role.

Keywords Volition · Voluntary choice · Effector-specific · Effector-general · Motor system

Introduction

Volition, the capacity for willful action, particularly the goal-directed endogenous action, is suggested to be the foundation of mental health and human society (Haggard, 2019). The expression of volition through our actions affecting the external world can help us achieve a wanted outcome and/or avoid an unwanted outcome, thus gaining a sense of agency and self-efficacy (Bandura & Wood, 1989; Haggard, 2017, 2019) and motivating subsequent behavior (Luo et al., 2022a, b; Patall et al., 2008; Ryan & Deci, 2006). Restriction of the expression of volition, however, leads to suffering, which is related to learned helplessness, depression (Huys & Dayan, 2009; Maier &

✉ Xiaoxiao Luo
luoxiaoxiao@ynnu.edu.cn

✉ Xiaolin Zhou
xz104@psy.ecnu.edu.cn

1 Faculty of Education, Yunnan Normal University, 650500 Kunming, China

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

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

4 Shanghai Key Laboratory of Psychotic Disorders, Shanghai Mental Health Center, Shanghai Jiao Tong University School of Medicine, Shanghai, China

5 Institute of Psychology and Behavioral Science, Shanghai Jiao Tong University, Shanghai, China

6 Shanghai Center for Brain Science and Brain-Inspired Intelligence Technology, Shanghai, China

7 Institute of Linguistics, Shanghai International Studies University, Shanghai, China

8 Department of Psychological & Brain Sciences, Boston University, Boston, MA, USA

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

Seligman, 1976; Mineka & Hendersen, 1985), and schizophrenia (Daprati et al., 1997).

In real life, volition is often expressed by making voluntary choices (e.g., choosing what to wear, where to go, when to leave, etc.). An important benefit of making voluntary choices is that it can enhance subsequent task performance. Specifically, when individuals can make choices based on their own volition (i.e., voluntary choice), compared to when they have to make choices based on external volition (i.e., forced choice), their performance in subsequent tasks is improved (Murayama et al., 2016; Patall, 2019; Patall et al., 2008). Even when the choice is irrelevant to the task, this volition-motivated performance effect is observed in motor skill learning (Lewthwaite et al., 2015), time estimation (Murayama et al., 2015), declarative memory (Murty et al., 2015), visual search (Luo et al., 2022a), and conflict control (Luo et al., 2022b).

While the expression of volition necessarily engages the execution of action through a certain effector (e.g., taking up an item by hand, kicking a ball by foot, commanding others through mouth and speech, expressing oneself by making eye movements, etc.), it is unclear if the benefit of expressing volition can generalize into different effectors. This question links volition with a long-standing controversial issue: whether a cognitive process that is related to motor control is effector-specific or effector-general (e.g., Castiello & Stelmach, 1993; Ehrsson et al., 2003; Janczyk & Leuthold, 2018; Merton, 1972; Penfield, 1954).

On the one hand, it is suggested that some action-related effects can generalize across different effectors. For example, phrases written by hand, mouth, or foot showed temporal and spatial similarities, suggesting a generalized representation of motor program across effectors (Castiello & Stelmach, 1993; Merton, 1972). The response conflict effect occurring at an effector (e.g., the Simon effect at hand; see Hommel, 2011; Simon & Rudell, 1967) could be affected by the previously controlled processing at a different effector (e.g., controlled saccade), indicating a generalized conflict control mechanism (Buetti & Kerzel, 2010; Luo et al., 2022c; Verghese et al., 2018). At the neural level, it is has been found that actions produced by different effectors were all related to the premotor cortex (PMC), supplementary motor area (SMA), and posterior parietal cortex (PPC) (Heed et al., 2011; Rijntjes et al., 1999; Rizzolatti & Kalaska, 2013), suggesting that the neural bases for generating different actions are independent of effectors (i.e., effector-general).

On the other hand, it has been shown that some other action-related effects cannot generalize across different effectors. For example, the conflict adaptation effect (i.e., a greater reduction of conflict effect in the current trial when a conflict has been encountered in the previous trial than when no conflict is encountered in the previous trial; see Egner, 2007; Gratton et al., 1992) did not appear when the effectors used in the current trial and the previous trial were different (Janczyk & Leuthold, 2018), suggesting an effector-specific response activation in conflict resolution. Similarly, the psychological refractory period (PRP) effect (i.e., individuals show a delayed response to the second stimulus that is in close succession to the first, compared with the response to the same stimulus presented alone or presented after a longer time interval after the first stimulus; see Pashler, 1994; Smith, 1967) was less pronounced when response effectors for the two stimuli were different compared to when the effectors were the same (De Jong, 1993; McLeod, 1977), suggesting an effector-specific response mechanism underlying the preparation and initiation of an action. At the neural level, it has been found that when different effectors were involved in action execution, different areas of the primary motor cortex (M1) were activated (e.g., Ehrsson et al., 2003; Penfield, 1954), indicating an effector-specific organization (i.e., a pattern of somatotopic mapping) in the human brain (see also Gordon et al., 2023).

It seems that the human motor system, which is strongly related to the expression of human volition (Haggard, 2019), shows both effector-specific and effector-general characteristics. However, it is unclear how the benefit of expressing volition can be affected by the change of effectors in sequential actions. In studies on the facilitatory effect of voluntary choice, the most commonly used effector category is the hand, and the same effector category is used (i.e., pressing a key) both for making choices and for completing the subsequent task (e.g., Luo et al., 2022a, b; Murayama et al., 2015; Murty et al., 2015). At the neural level, it is suggested that human volition engages the SMA and PMC (Haggard, 2019), areas that are typically effector-general but do show effector-specific characteristics (Dum & Strick, 2002; Ehrsson et al., 2003). Therefore, it is possible that the facilitatory effect of the voluntary choice can generalize across effectors regardless of whether the effector for making voluntary choices and the effector for completing the subsequent task are the same or different. Alternatively, it is also possible that the facilitatory effect of voluntary choice is restricted to a specific effector used to make the voluntary choice.

The aim of this study was to investigate whether the facilitatory effect of voluntary choice can generalize across different effectors. In three experiments, we adopted the volition-motivated performance (VMP) paradigm (Luo et al., 2022a) where task performance is improved following a voluntary choice. Specifically, participants were asked to voluntarily or forcedly choose a picture from two pictures and then to complete a visual search task with the chosen picture as the task-irrelevant background. Crucially, the effector for responding in the visual search task was always the hand to ensure that the reaction times of the visual search in the three experiments were on the same scale. However, the effector for choosing the picture varied across situations (i.e., hand, foot, mouth, or eye); that is, participants could make choices through pressing (Experiments 1, 2, and 3), pedaling

(Experiment 1), vocal commanding (Experiment 2), or gazing (Experiment 3). Moreover, given that the "same effector" in the present study was liberally defined as using the same category of effector, i.e., hand category, regardless of the side of the hand (e.g., left or right hand), to make choices and respond to the target of visual search, one might argue that the left hand (the effector for making choices) and the right hand (the effector for responding to the search target) are "different effectors." To provide evidence concerning this argument, in a control experiment, Experiment 4 (preregistered at https://osf.io/pu5bc), we further tested the robustness of our findings by adopting a more conservative definition of "same effector," i.e., the same hand/finger was used in both the choice and the task phases.

Methods

Participants

Four independent groups of 40 participants each took part in Experiments 1, 2, 3, and the control experiment, Experiment 4, respectively. The sample size in each experiment (n = 40) was determined using G*power 3.1 (Faul et al., 2007), which showed that at least 36 participants were required to detect the differences across four measurements (i.e., a 2 × 2 within-subject design) in each group given a medium effect size ($f = 0.25$), $\alpha = 0.05$, and *power* = 95%. One participant in Experiment 1, one participant in Experiment 2, and one participant in Experiment 4 were excluded from data analysis because their response accuracies in the visual search task were below 3 SDs of the group mean, leaving 39 participants in Experiment 1 (30 females; 18–27 years old, $M = 22.00$, $SD = 2.43$), 39 participants in Experiment 2 (29 females; 18–26 years old, $M = 21.67$, $SD = 2.64$), 40 participants in Experiment 3 (29 females; 18–26 years old, $M = 21.35$, $SD = 1.83$), and 39 participants in Experiment 4 (29 females; 19–28 years old, $M = 21.74$, $SD = 2.01$).

Participants received monetary compensation for their participation (¥50 per hour). All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. Informed consent was obtained from each participant before the experiment. This study was approved by the Committee on Human Research Protection, East China Normal University, and was performed in accordance with the Declaration of Helsinki.

Stimuli and procedures

Each participant was tested individually in a dimly lit laboratory. All stimuli were presented on a black screen (44 × 33 cm, refresh rate: 100 Hz, resolution: 1,024 × 768 pixels) connected to a PC. A chinrest was used to maintain the head position (eye-to-monitor distance was 70 cm). Manual responses were made on a standard American keyboard. Stimulus presentation and response recording were controlled by Psychophysics Toolbox (Brainard, 1997, http://www.psychtoolbox.org/) in MATLAB. The trial structure of all the experiments is shown in Fig. 1.

Experiment 1

Each trial consisted of a cue phase, a choice phase, and a task phase. There were two sessions based on whether the effector used in the choice phase was the same as or different from the effector used in the task phase. Below we first describe the effector-same session of Experiment 1 in detail.

In the cue phase, a white dot (0.7° × 0.7° in visual angle) was presented in the center of the screen, serving as a fixation for 0.8–1.2 s. Then a colored dot (either cyan or yellow, 1.6° × 1.6°) was presented to replace the white dot for 1 s, indicating the choice type (voluntary vs. forced) of the current trial. The association between the two colors and the two choice types was counterbalanced across participants.

In the choice phase, after a fixation of 0.5–0.8 s, two pictures (each 5.3° × 5.3°) were presented at 4.9° to the left and right of the screen center. Participants would choose a picture by pressing "D" (to choose the left picture) or "F" (to choose the right picture) on the keyboard using the middle or index finger of the left hand. For a voluntary-choice condition, participants could freely choose a picture (see Online Supplementary Materials (OSM) for the proportion of key presses in each experiment). In the forced-choice condition, participants had to choose the picture randomly marked by the computer (i.e., the picture with a gray frame). In both the voluntary- and forced-choice conditions, a white frame marking the chosen picture was presented together with the two pictures for 1 s after the key-press. To balance the exposure time of the two pictures between the voluntary- and forced-choice conditions, we followed the setting in our previous study (Luo et al., 2022a). Specifically, in the forced-choice condition, an interval was added between the onset of the pictures and the onset of the gray frame, with the duration of the interval ($T_{interval}$) determined by the reaction time (RT) needed to choose a picture in the latest voluntary choice trial (RT_{lvc}), i.e., [$T_{interval} = RT_{lvc} - 0.56$ s]. The 0.56 s was the mean RT of making a forced choice obtained from Luo et al., (2022a). The $T_{interval}$ was set to be 0 if a negative value was obtained from the calculation.

In the task phase, after a central fixation of 0.5–0.8 s, the chosen picture was presented at the center of the screen for 1 s, serving as a task-irrelevant background (11.4° × 11.4°). Then an array of visual search was presented on the top of the background and remained on the screen for 1.5 s or until

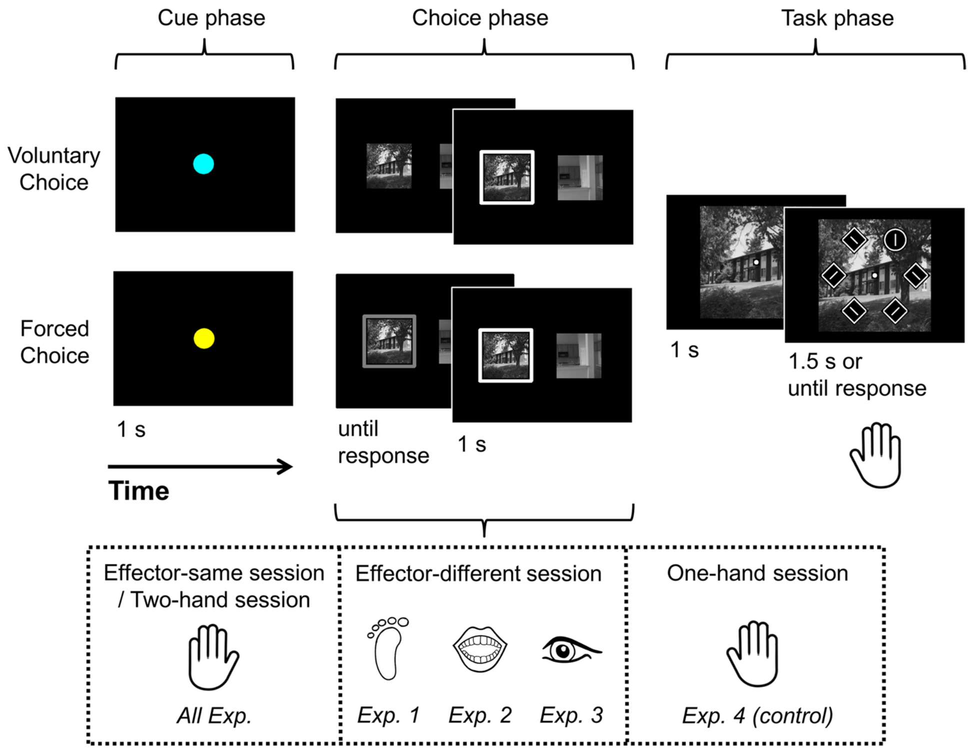

Fig. 1 The sequence of events in each trial. In the cue phase, a colored dot indicated the choice type (voluntary vs. forced) for the current trial. Then in the choice phase, participants could freely choose a picture in the voluntary choice condition or had to choose the pre-defined picture in the forced choice condition. In the task phase, participants completed a visual search task with the chosen picture as the background. Crucially, each experiment consisted of two sessions. For Experiments 1–3, in the "effector-same session," participants chose a picture and responded to the target of visual search by hand (i.e., key-press); in the "effector-different session," participants still responded to the search target by hand, but they chose a picture by foot in Experiment 1 (i.e., pedaling), by mouth in Experiment 2 (i.e., commanding the experimenter to press the key), or by eye in Experiment 3 (i.e., gazing at the picture). For the control experiment, Experiment 4, in the "two-hand session," participants chose a picture using the left hand, and responded to the target of the visual search using the right hand; in the "one-hand session," participants used the same right hand to choose a picture and respond to the target of the visual search. Note that there were blank screens with a central fixation between phases, which are omitted in this figure

a response was given. In this array, six white items (one diamond among five circles or one circle among five diamonds, each 2.5° × 2.5°) were presented at equal distance along an imaginary circle of 4.9° radius. A horizontal or vertical white line (length 1.6°) was presented inside the unique shape while a white line (length 1.6°) tilted 45° to the left or right was presented inside each of the other five shapes. Participants were asked to search for the unique shape and judge the orientation of the line inside the shape (horizontal vs. vertical) by pressing "J" or "K" on the keyboard using the index or middle finger of the right hand. The association between the two keys and the two orientations was counterbalanced across participants. Visual feedback ("too slow") was displayed at the center of the screen for 0.5 s if no response was given within 1.5 s.

In the effector-different session of Experiment 1, all the stimuli and procedures were the same as in the effector-same session described above. The only exception is that, in the choice phase, participants chose a picture by pushing a left pedal (to choose the left picture) or a right pedal (to choose the right picture) using the left foot or the right foot. During this session, participants were asked to maintain their left hand on the keyboard in the same way as the effector-same session, but not to make a key press.

Therefore, Experiment 1 had a 2 (Choice Type: voluntary vs. forced) × 2 (Effector Congruency: same vs. different) factorial design. There were eight blocks with 48 trials in each block (384 trials in total). The voluntary- and forced-choice conditions were equally distributed in each block. The effector-same session covered half of the blocks, and the effector-different session covered the other half of the blocks. The order of the two sessions was counterbalanced across participants. At the beginning of the experiment, participants were asked to practice the visual search task (but without the background picture) for 48 trials, and they would be required to repeat this practice if the accuracy was below 80%. At the beginning of each session, participants were provided with ten exemplar trials of the current session.

A total of 384 black and white pictures of outdoor houses or indoor furnishings were used in the formal experiment (with another ten pictures for the exemplar trials). All the pictures were adopted and edited from Luo et al. (2022a) and Ahmed and Moustafa (2016) (https://github.com/emanhamed/Houses-dataset). For each participant in the formal experiment, each session consisted of 192 pictures, which were randomly matched to produce the 96 pairs of picture options. These 96 pairs of picture options were presented in both the voluntary- and forced-choice conditions to ensure that any potential difference between the two conditions could not be attributed to differences in pictures.

Experiment 2

The stimuli and procedures of Experiment 2 were the same as those of Experiment 1 except that in the choice phase of the effector-different session, participants chose a picture by saying "left" (to choose the left picture) or "right" (to choose the right picture). This choice was implemented by the experimenter who made the key press following the oral command. The experimenter sat behind the participant and make the key press through another keyboard connected to the same PC.

Experiment 3

The stimuli and procedure of Experiment 3 were the same as those of Experiment 1, but with the following exceptions.

First, eye movements were monitored with an Eyelink 1000 plus system (SR Research) at a sampling rate of 1,000 Hz during the whole experiment. Nine-point calibration and verification were performed at the beginning of the experiment. Drift correction (and recalibration if necessary) was performed at the beginning of each block. Participants were asked to fixate on the central fixation at the beginning of each trial to check the recording of eye movements. Drift correction (and recalibration if necessary) was performed again if the participant's fixation was not located in the 1° area of the central fixation within 5 s after the onset of the central fixation.

Second, in the choice phase of the effector-different session, participants were required to choose a picture by gazing at the left or the right picture on the screen. After the onset of the two optional pictures, a valid choice was identified if eye fixations were continuously localized within one picture (i.e., 6.3° × 6.3° area around the center of the picture) over 0.5 s (i.e., the summed dwell time of all fixations within the target picture was over 0.5 s).

Third, each of the effector-same and effector-different sessions consisted of three blocks with 48 trials. The reason for including a smaller number of trials in Experiment 3 is that monitoring eye movements was more time-consuming and demanding compared to tasks in Experiment 1 or Experiment 2. In this way, the number of pictures used in Experiment 3 was reduced to 288.

Experiment 4

Experiment 4 (the control experiment) was preregistered (https://osf.io/pu5bc). There were also two sessions in Experiment 4 based on how many hands were used. For the "two-hand session," the stimuli and procedure were the same as those of the "effector-same session" in Experiment 1 (i.e., participants used the left hand to make choices, and used the right hand to respond to the search target). For the "one-hand session," the stimuli and procedure were the same as those of the "effector-same session" in Experiment 1 except that in the choice phase, participants chose a picture by pressing "J" (to choose the left picture) or "K" (to choose the right picture) on the keyboard using the index or middle finger of the right hand (i.e., participants used the index and middle fingers of the right hand to make choices and respond to the search target).

Statistical analysis

For each condition, the RT and error rate (ER) of the visual search task were computed. Trials with incorrect responses or missing responses in the visual search task were excluded when the mean RTs were computed. Trials with RT (in both the visual search task and the choice phase) beyond 3 SDs of the mean RT in each condition were also excluded (2.58%, 2.30%, 2.64%, and 2.26% of trials in Experiments 1, 2, 3, and 4, respectively). Trials with missing responses were regarded as incorrect trials when ERs were computed. To compare the performance across Experiments 1–3, the "Experiment" was regarded as a between-subject variable. Thus, a 2 (Choice Type: voluntary vs. forced) × 2 (Effector Congruency: same vs. different) × 3 (Experiment: 1, 2, vs. 3) mixed-measures ANOVA was conducted on both RTs and ERs. For Experiment 4, based on the preregistered analysis plan (https://osf.io/pu5bc), a 2 (Choice Type: voluntary vs. forced) × 2 (Effector Session: two-hand vs. one-hand) repeated-measures ANOVA was conducted on both RTs and ERs. Moreover, for the one-hand session, an additional analysis was conducted according to whether the finger used for the choice was the same as or different from the finger used for visual search (i.e., a "finger-same" condition and a "finger-different" condition). Thus, a further 2 (Choice Type: voluntary vs. forced) × 2 (Finger Congruency: same vs. different) repeated-measures ANOVA was performed on RTs and ERs of the one-hand session.

In addition, to avoid making statistical inferences based on non-significant effects, such as that the interaction of Choice Type × Effector Congruency or the interaction of Choice Type × Experiment was not significant in the ANOVA on RTs (see *Results* below), we conducted Bayes Factor analysis for Experiments 1–3 to quantify the extent to which the facilitatory effect of voluntary choice between the effector-same and effector-different sessions or across the three experiments was equivalent (i.e., the evidence of support for the null hypothesis was required). The facilitatory effect of voluntary choice was calculated by subtracting the RT of visual search in the voluntary-choice condition from the RT of visual search in the forced-choice condition. A Bayesian paired t-test (Wagenmakers et al., 2018a) between the two sessions and a Bayesian one-way ANOVA (van den Bergh et al., 2020) across the three experiments (including only the effector-different sessions) were conducted using JASP (Wagenmakers et al., 2018a, b). Similarly, for Experiment 4, we also conducted Bayesian paired t-tests between the two-hand and one-hand sessions, and between the finger-same and finger-different conditions of the one-hand session. It is suggested that the Bayes Factor (BF_{01}) between 1 and 3, between 3 and 10, and greater than 10 can be considered as weak, moderate, and strong evidence, respectively, in favor of the null hypothesis over the alternative hypothesis (van Doorn et al., 2021).

Moreover, we applied the EZ-diffusion model (Wagenmakers et al., 2007), a variation of the drift-diffusion model (DDM, Ratcliff, 1978; Ratcliff & McKoon, 2008), to transform RTs and ERs during the visual search task into drift rate (v), boundary separation (a), and non-decision time (T_{er}). The v, a, and T_{er}, respectively, represent the speed of information accumulation, the response criterion, and the time spent on processes that are not directly involved in deciding between response alternatives (e.g., execution of motor response) during the visual search task. The EZ-diffusion model was adopted because it is applicable to data-sparse situations and provides a powerful test of simple empirical effects (Luo et al., 2022a; van Ravenzwaaij et al., 2017). For Experiments 1–3, we calculated v, a, and T_{er} (the code can be accessed at https://osf.io/29kvw/) for each condition and then conducted the 2 (Choice Type: voluntary vs. forced) × 2 (Effector Congruency: same vs. different) × 3 (Experiment: 1, 2, vs. 3) mixed-measures ANOVA on the three parameters. In addition, the EZ-diffusion model was also applied to Experiment 4 (see OSM for details).

Furthermore, in Experiment 3, we also analyzed the eye-movement data in the visual search task by using the Edf2Mat MATLAB Toolbox (Etter & Biedermann, 2018, https://www.github.com/uzh/edf-converter). We separated the RT in the visual search task into the search time (i.e., the time spent on finding the target in the search array) and the post-search time (i.e., the time spent on other processes after the target was found, such as response selection and response execution). For a certain trial, the search time was defined as the time interval between the onset of the visual search array and the onset of the first fixation located in the target area (i.e., 3.5° × 3.5° area around the center of the target shape); the post-search time was defined as the difference between the RT and the search time of the current trial. Note that only trials that were included in the RT analysis were used in the eye-movement data analysis. Trials with no fixation located in the target area during the display of the visual search array and trials with a search time shorter than 80 ms (i.e., anticipation; see also van Zoest et al., 2004) were excluded (20.06% of all the trials). According to these criteria, eight participants were excluded from the subsequent eye-movement data analysis due to the exclusion of a high proportion of data (over 50% of trials). Based on the eye-movement data of the remaining 32 participants in Experiment 3, a 2 (Choice Type: voluntary vs. forced) × 2 (Effector Congruency: same vs. different) repeated-measures ANOVA was conducted on both the search time and the post-search time in Experiment 3. In addition, given that both the choice and task phases involved moving the eyes to the left or right, the eye movements in the task phase could be congruent or incongruent with the eye movements in the choice phase. To explore the potential effects of the eye-movements congruency (between the choice phase and the task phase) on the visual search performance, we conducted an additional analysis based on the target location of the visual search (see OSM for details). This analysis did not undermine our main conclusions.

Results

A descriptive summary of data for Experiments 1–3 is shown in Table 1. Results of ANOVAs on RT and ER of the visual search task, parameters of the EZ-diffusion model applied on the visual search task (i.e., v, a, and T_{er}), and indexes related to eye-movement performance in Experiment 3 (i.e., search time and post-search time) are presented in Table 2. Significant effects are highlighted in bold in Table 2.

Visual search performance

Figure 2 shows the raincloud plot of RTs. The 2 × 2 × 3 ANOVA showed only a significant main effect of Choice Type (see Table 2), indicating that participants generally responded faster in the visual search task after making a voluntary choice than after making a forced choice (767 vs. 775 ms). In other words, the facilitatory effect of voluntary choice could be observed regardless of whether the effector in the choice phase was the same as or different from the effector in the visual search task, and regardless of whether the effector in the choice phase was the foot, mouth, or eye. By calculating the facilitatory effect of voluntary choice, this inference was moderately supported by the $BF_{01} = 5.74$ in the Bayesian paired t-test between the effector-same and effector-different sessions, and by the $BF_{01} = 9.85$ in the Bayesian one-way ANOVA across the effector-different sessions of the three experiments.

Table 1 Descriptive results of Experiments 1–3 (means with standard deviations in parentheses)

Index	Exp.	Effector-same session		Effector-different session	
		Voluntary choice	Forced choice	Voluntary choice	Forced choice
RT (ms)	**1**	755 (93)	762 (87)	764 (84)	776 (89)
	2	747 (90)	752 (89)	754 (89)	766 (91)
	3	792 (90)	801 (94)	787 (93)	795 (89)
ER (%)	**1**	4.99 (5.11)	5.59 (4.89)	5.57 (4.49)	6.03 (4.96)
	2	6.56 (5.32)	6.03 (6.02)	5.23 (5.27)	5.10 (4.25)
	3	5.59 (4.26)	5.70 (4.63)	4.49 (3.51)	4.54 (4.45)
v	**1**	.279 (.053)	.269 (.056)	.270 (.051)	.262 (.055)
	2	.252 (.056)	.258 (.060)	.269 (.057)	.265 (.054)
	3	.265 (.043)	.262 (.046)	.276 (.048)	.276 (.060)
a	**1**	.1258 (.0210)	.1264 (.0228)	.1220 (.0208)	.1276 (.0219)
	2	.1230 (.0168)	.1296 (.0212)	.1256 (.0196)	.1271 (.0195)
	3	.1290 (.0201)	.1332 (.0225)	.1329 (.0222)	.1342 (.0224)
T_{er}	**1**	.542 (.077)	.542 (.072)	.555 (.070)	.550 (.072)
	2	.525 (.075)	.520 (.072)	.536 (.074)	.542 (.070)
	3	.564 (.070)	.562 (.070)	.558 (.069)	.562 (.062)
ST (ms)	**3**	399 (50)	393 (49)	397 (53)	402 (51)
P-ST (ms)	**3**	411 (78)	423 (76)	409 (69)	413 (72)

RT = reaction time, *ER* = error rate, v = drift rate, a = boundary separation, T_{er} = non-decision time, *ST* = search time, *P-ST* = post-search time

EZ-diffusion model

Figure 3 shows the raincloud plot of boundary separation (a). Similar to the RT results, the 2 × 2 × 3 ANOVA showed only a significant main effect of Choice Type (see Table 2), indicating that participants generally had lower boundary separation (a) in the visual search task after making a voluntary choice than after making a forced choice (0.126 vs. 0.130).

Eye movements in the visual search task of Experiment 3

Figure 4 shows the raincloud plot of search times and post-search times. Only the main effect of Choice Type on post-search times reached significance (see Table 2), indicating that participants had a shorter post-search time in the visual search task after making a voluntary choice than after making a forced choice (410 vs. 418 ms).

Experiment 4

Consistent with our preregistered predictions (https://osf.io/pu5bc), the 2 (Choice Type: voluntary vs. forced) × 2 (Effector Session: two-hand vs. one-hand) repeated-measures ANOVA on RTs showed only a significant main effect of Choice Type, F (1, 38) = 10.91, p = .002, η_p^2 = .22, indicating that participants generally responded faster after making a voluntary choice than after a forced choice (767 vs. 777 ms), regardless of whether the choice and task phases were completed with one (same) hand or two (different) hands (see the left panel of Fig. 5). The main effect of Effector Session and the interaction were not significant, all *ps* > .175. This pattern replicated the main findings in Experiments 1–3.

Moreover, in the one-hand session, the 2 (Choice Type: voluntary vs. forced) × 2 (Finger Congruency: same vs. different) ANOVA also showed a significant main effect of Choice Type, F (1, 38) = 21.21, $p < .001$, $\eta_p^2 = .36$, with no interaction between the two factors ($p = .221$). This pattern again replicated the facilitatory effect of making voluntary choices relative to forced choices (761 vs. 779 ms) regardless of whether the fingers used in the choice and task phases were the same or different (see the right panel of Fig. 5). Note that the main effect of Finger Congruency was significant, F (1, 38) = 4.59, p = .039, η_p^2 = .11, indicating that participants generally responded more slowly when the fingers used in the choice and task phases were the same than when the fingers were different (774 vs. 766 ms), a pattern reminiscent of the psychological refractory period (PRP) effect (Pashler, 1994; Smith, 1967) for the same effector (De Jong, 1993; McLeod, 1977).

In addition, the Bayesian paired t-test on the facilitatory effect of voluntary choice showed a BF_{01} = 2.40 for the comparison between the two-hand and one-hand sessions, and a

Table 2 Results of analysis of variance for each index in Experiments 1–3

Index	Effect (df, $df_{residuals}$)	F	p	η_p^2
RT	**Choice Type (1, 115) *** **	**28.936**	**<.001**	**.201**
	Effector Congruency (1, 115)	0.809	.370	.007
	Experiment (2, 115)	2.461	.090	.041
	Choice Type × Effector Congruency (1, 115)	1.104	.296	.010
	Choice Type × Experiment (2, 115)	0.080	.923	.001
	Effector Congruency × Experiment (2, 115)	0.718	.490	.012
	Choice Type × Effector Congruency × Experiment (2, 115)	0.383	.683	.007
ER	Choice Type (1, 115)	0.174	.677	.002
	Effector Congruency (1, 115)	2.637	.107	.022
	Experiment (2, 115)	0.268	.765	.005
	Choice Type × Effector Congruency (1, 115)	0.027	.869	< .001
	Choice Type × Experiment (2, 115)	1.283	.281	.022
	Effector Congruency × Experiment (2, 115)	2.290	.106	.038
	Choice Type × Effector Congruency × Experiment (2, 115)	0.181	.835	.003
v	Choice Type (1, 115)	1.598	.209	.014
	Effector Congruency (1, 115)	1.798	.183	.015
	Experiment (2, 115)	0.500	.608	.009
	Choice Type × Effector Congruency (1, 115)	0.114	.736	< .001
	Choice Type × Experiment (2, 115)	1.638	.199	.028
	Effector Congruency × Experiment (2, 115)	2.963	.056	.049
	Choice Type × Effector Congruency × Experiment (2, 115)	0.745	.477	.013
a	**Choice Type (1, 115) ***	**6.746**	**.011**	**.055**
	Effector Congruency (1, 115)	0.076	.784	< .001
	Experiment (2, 115)	1.875	.158	.032
	Choice Type × Effector Congruency (1, 115)	0.224	.637	.002
	Choice Type × Experiment (2, 115)	0.097	.907	.002
	Effector Congruency × Experiment (2, 115)	0.592	.555	.010
	Choice Type × Effector Congruency × Experiment (2, 115)	1.898	.155	.032
T_{er}	Choice Type (1, 115)	0.020	.888	< .001
	Effector Congruency (1, 115)	2.219	.139	.019
	Experiment (2, 115)	2.364	.099	.039
	Choice Type × Effector Congruency (1, 115)	1.232	.269	.011
	Choice Type × Experiment (2, 115)	0.315	.731	.005
	Effector Congruency × Experiment (2, 115)	1.150	.320	.020
	Choice Type × Effector Congruency × Experiment (2, 115)	1.772	.175	.030
ST	Choice Type (1, 31)	0.121	.731	.004
	Effector Congruency (1, 31)	0.409	.527	.013
	Choice Type × Effector Congruency (1, 31)	2.055	.162	.062
P-ST	**Choice Type (1, 31) ** **	**7.873**	**.009**	**.203**
	Effector Congruency (1, 31)	0.259	.614	.008
	Choice Type × Effector Congruency (1, 31)	0.746	.395	.023

*$p < .05$, **$p < .01$, ***$p < .001$

RT = reaction time, *ER* = error rate, v = drift rate, a = boundary separation, T_{er} = non-decision time, *ST* = search time, *P-ST* = post-search time

$BF_{01} = 2.83$ for the comparison between the finger-same and finger-different conditions in the one-hand session. Although each BF_{01} was smaller than 3, not as strong as the preregistered predictions, they still favored our inference that the facilitatory effect of voluntary choice was comparable between the one-hand and two-hand sessions, or between the finger-same and finger-different conditions in the one-hand session.

Results of the ER and EZ-diffusion model for Experiment 4, presented in the OSM, did not affect our main conclusions.

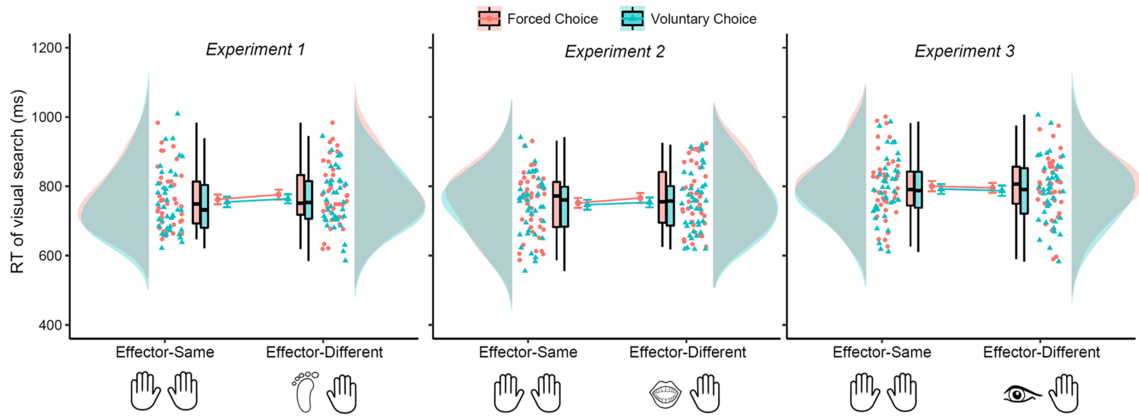

Fig. 2 Reaction times (RTs) of the visual search task as a function of Effector Congruency (same vs. different), Choice Type (voluntary vs. forced), and Experiment (1, 2, vs. 3). Each raincloud plot includes data distribution, individual data, boxplot, and mean with SEM (Allen et al., 2018, https://github.com/RainCloudPlots/RainCloudPlots)

Discussion

The present study investigated whether the benefit of expressing volition can generalize across multiple effectors. To answer this question, we tested if the facilitatory effect of voluntary choice on subsequent visual search performance could be observed across different effectors, and if the facilitatory effect could be observed even when the effector for making the voluntary choice is different from the effector for responding in the visual search task. Across three experiments using a volition-motivated performance (VMP) paradigm (Luo et al., 2022a), we found that participants generally responded faster in the visual search task after making a voluntary choice than after making a forced choice regardless of which effector was used in making the voluntary choice. This result replicated and extended the VMP effect in previous studies (e.g., Lewthwaite et al., 2015; Luo et al., 2022a, b; Murayama et al., 2016; Murty et al., 2015), and further indicated that this effect is not specific to a certain effector category such as the most common manual response in cognitive experiments. Importantly, the facilitatory effect was observed regardless of whether the effector category for making the voluntary choice (i.e., hand, foot, mouth, or eye) was the same as or different from the effector category for responding in the visual search task (i.e., hand), indicating that the benefit of expressing volition could generalize to the effector category that is different from the effector category for expressing volition. Moreover, the EZ-diffusion model showed that participants had lower boundary separation (*a*) in the visual search task after making a voluntary choice than after making a forced choice, demonstrating a more liberal response criterion after the expression of volition compared to after the restriction of the expression of volition (see also Luo et al., 2022a). Furthermore, the eye-movement

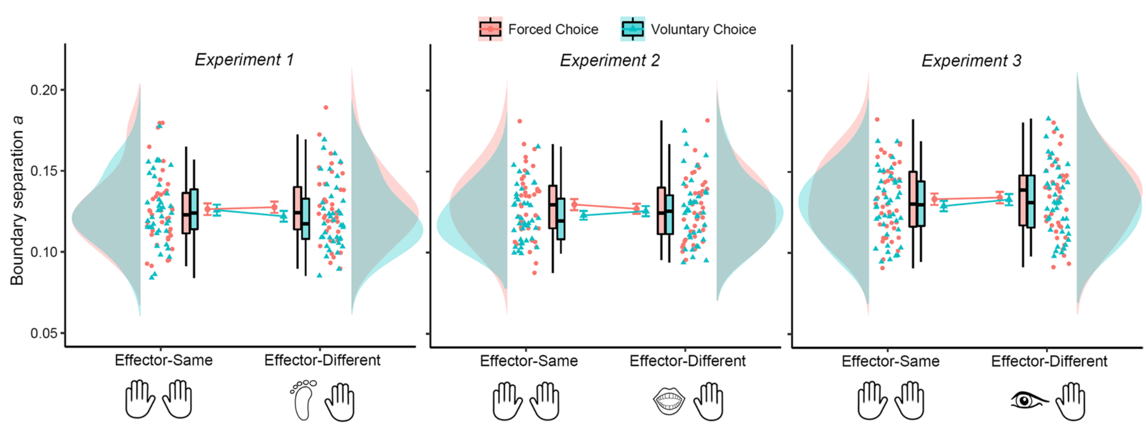

Fig. 3 Boundary separation (*a*) as a function of Effector Congruency (same vs. different), Choice Type (voluntary vs. forced), and Experiments (1 and 2 vs. 3). Each raincloud plot includes data distribution, individual data, boxplot, and mean with SEM (Allen et al., 2018, https://github.com/RainCloudPlots/RainCloudPlots)

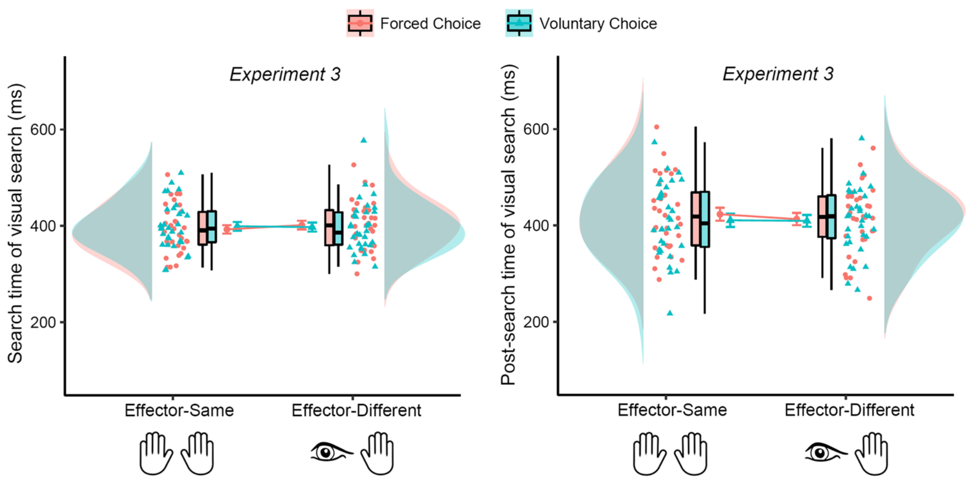

Fig. 4 Search time (left panel) and post-search time (right panel) as a function of Effector Congruency (same vs. different), and Choice Type (voluntary vs. forced) in Experiment 3. Each raincloud plot includes data distribution, individual data, boxplot, and mean with SEM (Allen et al., 2018, https://github.com/RainCloudPlots/RainCloudPlots)

data in Experiment 3 showed that the facilitatory effect of voluntary choice was observed for the post-search time in the visual search task (i.e., the time spent on processes after the target of visual search is found, such as response selection and response execution) rather than the search time (i.e., the time spent on finding the target, such as perceptual processing), suggesting that the benefit of expressing volition is closely related to the human motor system. Finally, in a pre-registered control experiment, a more conservative definition of "same effector" (i.e., the same hand/finger) was adopted for the choice and task phases, and the facilitatory effect of voluntary choice was observed regardless of whether the hand/finger used for making choices was the same as or different from the hand/finger used for responding to the search target. These results again demonstrated that the facilitatory effect of voluntary choice is not subject to the distance between effectors' somatotopic mappings in the brain.

Although the expression of volition necessarily entails the execution of action, our results highlighted the role of the processing for the goal of expressing volition in the VMP paradigm. Here in the current design, processes for executing the action of voluntary choices were quite different (i.e., to control hands, feet, mouth, or eyes), but the goal of making voluntary choices was the same (i.e., to

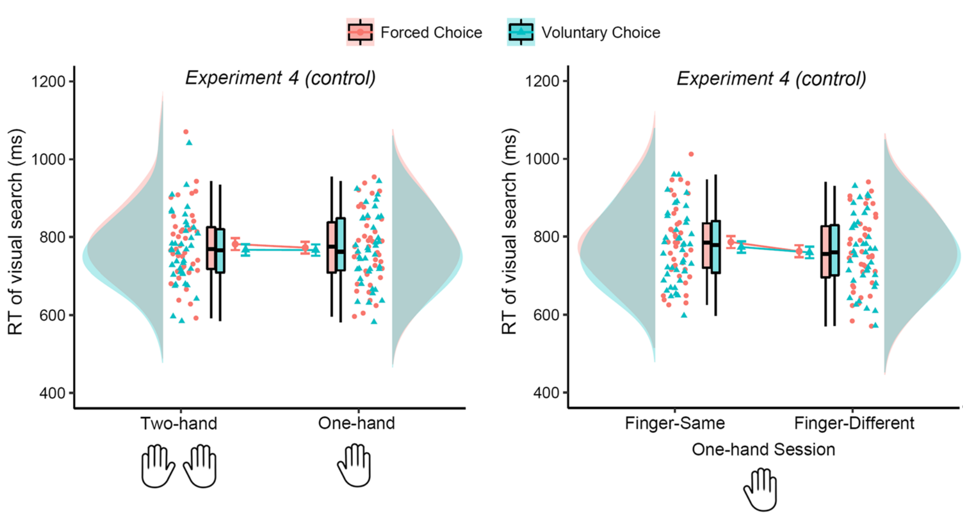

Fig. 5 Reaction times (RTs) of the visual search task as a function of Choice Type (voluntary vs. forced) and Effector Session (one-hand vs. two-hand) in Experiment 4 (the left panel), and as a function of Choice Type (voluntary vs. forced) and Finger Congruency (same vs. different) in the one-hand session of Experiment 4 (the right panel). Each raincloud plot includes data distribution, individual data, boxplot, and mean with SEM (Allen et al., 2018, https://github.com/RainCloudPlots/RainCloudPlots)

determine the background of the subsequent visual search following one's own volition). This design allowed us to disentangle the contribution of action goal and the contribution of action execution by distinguishing between effector-specific effects and effector-general effects, because the effector-specific effects may mainly involve the processes related to the execution of action, whereas the effector-general effects may mainly involve the processes related to the goal of action. For example, the conflict adaptation effect, which is found to be effector-specific (Janczyk & Leuthold, 2018), involves the suppression of response activation at a certain effector (Stürmer et al., 2002), whereas the effect of phrase-writing similarities, which is found to be effector-general (Castiello & Stelmach, 1993; Merton, 1972), involves the high-level representation of a motor program to construct a meaningful word (i.e., the goal of phrase-writing). Thus, the benefit of expressing volition, which is effector-general here, may be related to processes surrounding the goal of expressing volition.

The processes for the goal of expressing volition involve not only the representation of the goal (i.e., intended outcome) of the voluntary action, but also the comparison between the intended outcome and the actual outcome after the action is executed (Blakemore et al., 2000; Haggard, 2017). The goal of an action is considered to be achieved when the intended outcome and the actual outcome are consistent, which is fundamental to perceived control (Leotti et al., 2010) and a sense of agency (Haggard, 2017). This comparison is consistent with the core feature of human volition, i.e., teleology (Haggard, 2019), that is, a voluntary action is made to achieve or advance a goal state. When the goal of an action cannot be achieved, any effect related to this action may collapse. In agreement with this notion, we have shown that the facilitatory effect of voluntary choice disappears when the action of choice could not determine the outcome of the choice (Luo et al., 2022a). It is possible that the achievement of the goal of voluntary action (i.e., a consistency between the intended outcome and the actual outcome) is a core element in the expression of volition. Any voluntary action that has helped achieve (or advance) an intended goal can be taken as a successful expression of volition regardless of which specific effector is used to achieve (or advance) the goal.

The generally liberal response criterion (i.e., low boundary separation in the EZ-diffusion model) after making voluntary choices further demonstrates the importance of the motor control system in the expression of volition. It has been shown that the liberal response criterion led to responses at a cost of accuracy and was associated with the activation of motor areas (e.g., SMA, which is essential for the generation of voluntary actions) (Bogacz et al., 2009; Forstmann et al., 2008). Importantly, making a self-initiated action could lead to higher activation in SMA compared with making a stimulus-driven action (Cunnington et al., 2002; Deiber et al., 1999). Therefore, the expression of volition may recruit the motor control system, which biases the response criterion in the subsequent task that also requires the recruitment of the motor control system.

By analyzing the eye-movement data in Experiment 3, we separated the search time and the post-search time from the RT of the visual search task. The facilitatory effect on the post-search time, but not on the search time, reflected the liberal response criterion discussed above, implying again that the motor control system is involved in the expression of volition. To complete the visual search task, individuals would experience at least three processes: pre-response processing, response selection, and response execution (Töllner et al., 2012). The search time may reflect the pre-response processing, whereas the post-search time may reflect response selection and response execution. The expression of volition might recruit the motor control system, which then facilitated the subsequent task performance at response-related levels.

Although the post-search time appeared to be similar to the parameter of non-decision time (T_{er}) in the EZ-diffusion model, unlike the post-search time, we did not find a significant effect for T_{er} in Experiments 1–3. This discrepancy could be because T_{er} includes all non-decision components (i.e., both responding and encoding processes; Ratcliff & McKoon, 2008; Wagenmakers et al., 2007) that might not be sensitive to the facilitatory effect of preceding voluntary choices. Moreover, in the control experiment, Experiment 4, making a voluntary choice shortened the T_{er} relative to a forced choice (see OSM for details), consistent with the pattern of the post-search time. It is also possible that the close/identical somatotopic mappings in the brain may enrich the routes to enhance performance by making voluntary choices (e.g., not only biasing the response criterion but also shortening the non-decision time). Nevertheless, more evidence based on the EZ-diffusion model is required in the future to test the benefit of expressing volition on the non-decision time of a subsequent speed-response task.

In summary, the present study replicated volition-motivated performance and found that this benefit of expressing volition can generalize across different effectors. The expression of volition may involve the motor control system in which the effector-general processing for the goal of voluntary actions plays a key role.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13423-023-02350-x.

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Open Practice Statements Experiments 1–3 were not preregistered. The preregistration of Experiment 4 can be accessed at https://osf.io/pu5bc.

Author Contributions **Xiaoxiao Luo:** Conceptualization, methodology, software, formal analysis, writing – original draft, visualization. **Lihui Wang:** Conceptualization, writing – review and editing. **Jiayan Gu:** Investigation. **Qiongting Zhang:** Investigation. **Hongyu Ma:** Investigation. **Xiaolin Zhou:** Conceptualization, methodology, writing – review and editing, resources, supervision.

Data Availability All data, codes, and materials can be accessed at https://osf.io/29kvw/

Declarations

Conflict of interests The authors declare no competing interests.

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