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The role of cognitive control in the interaction of the SNARC and MARC effects

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Abstract

Many studies have identified two types of spatial congruency effects in number parity judgment tasks: the SNARC effect (Spatial-Numerical Association of Response Codes), related to numerical magnitude, and the MARC effect (Linguistic Markedness Association of Response Codes), associated with parity. Although previous work has found that these effects interact, the mechanisms underlying the interaction are unclear. Previous studies have investigated the effect of linguistic connections on the activation of the SNARC and MARC effects in right-to-left readers by manipulating the time interval between tasks. We propose that a cognitive control mechanism mediates this phenomenon, with the level of cognitive conflict induced by the MARC effect under varying conditions being a critical factor in influencing spatial-numerical associations. We first performed four behavioral experiments manipulating time intervals between parity-to-response mappings. The results demonstrate that interactions between the SNARC and MARC effects are not sensitive to changes in time intervals but are primarily influenced by the congruency between the two effects. We then performed an event related potentials study. The response patterns observed in the P300 component support the hypothesis that cognitive conflict levels influence spatial-numerical associations. In conclusion, this study highlights the essential role of cognitive control in modulating the conflict between the SNARC and MARC effects, providing a new theoretical perspective on the dynamic characteristics of spatial-numerical associations.

Keywords Numerical cognition, SNARC effect, MARC effect, Cognitive control, Time interval, Spatial-numerical association

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Introduction

In the field of numerical cognition, it is widely accepted that there is a close relationship between numerical representation and spatial processing [1–4]. Studies suggest that humans may possess an intrinsic "number-space mapping" mechanism, where smaller numbers are associated with the left side, and larger numbers are associated with the right side. This phenomenon is typically studied through the spatial-numerical association of response codes (SNARC) effect, first proposed by Dehaene et al. [2]. The SNARC effect is characterized by faster left-hand responses to smaller numbers and faster right-hand responses to larger numbers. Parity judgment tasks are commonly used to investigate the SNARC effect [5–7], where participants determine whether a number is odd or even. Another related phenomenon is the linguistic markedness association of response codes (MARC) effect, where participants respond faster with the left hand to odd numbers and the right hand to even numbers [8]. Both numerical magnitude and parity influence response patterns, eliciting SNARC or MARC effects within the same task. Some studies have found interactions between the SNARC and MARC effects. For instance, early research found that the presence of the MARC effect made detecting the SNARC effect more challenging, suggesting a masking interaction [9]. This observation indicates that when both SNARC and MARC effects co-occur, the MARC effect may reduce the magnitude of the SNARC effect.

Theorizing that processing parity information might impact the analysis of the SNARC effect, Dehaene et al. grouped numbers into increasing pairs containing two numbers from different parity-to-response mappings (e.g., 2/3, 4/5, 6/7, 8/9) [2]. Recent studies also suggest that in parity tasks, the MARC effect can reduce the SNARC effect [10]. Zohar-Shai et al. examined the SNARC effect in Hebrew speakers, who write words from right to left but write numbers from left to right. They manipulated the time intervals (from minutes to a full day) between performance of the two parity mappings. Their findings demonstrated that time intervals significantly influence the SNARC and MARC effects; with extended intervals (one day), the MARC effect diminished, and the SNARC effect emerged [10]. Zohar-Shai et al. hypothesized that when shorter time intervals (e.g., 10 minutes) separate the parity mappings, participants co-activate both mappings, which enhances linguistic linkages, which in turn leads participants to focus more on parity information and parity-to-response mappings. Consequently, the enhanced MARC effect influence s task performance, diminishing the SNARC effect [10]. We refer to this theory as the "Language Link Strengthening Hypothesis".

The Language Link Strengthening Hypothesis of the relationship between the SNARC and MARC effects cannot account for all previous research findings [10]. The SNARC effect has been widely observed across a variety of experimental paradigms [2, 5, 7], and is observable in contexts ranging from parity judgments to magnitude classifications [11–15]. Its underlying mechanism involves the automatic spatial encoding of numerical values. Even when a task is unrelated to numerical magnitude, such as distinguishing the color of numbers, numbers still evoke spontaneous spatial associations. In contrast, the MARC effect exhibits a notable task-dependence feature: when the task format involves explicit odd-even cues (such as a judgment of "odd/even" with left/right key labels), it reliably induces a leftward advantage in odd-even number association patterns; however, if a response method without clear spatial cues is used, or the task goal is unrelated to odd-even concepts, the spatial encoding of odd-even concepts is difficult to activate [8, 16–19]. According to the dual-route model [17], when both the SNARC and MARC effects are activated in the same task, cognitive resources need to be allocated simultaneously, which allows for the concurrent processing of both the SNARC and MARC effects. This may interfere with the representation of the MARC effect, especially under complex or changing task demands.

Furthermore, the interaction between the SNARC and MARC effects can be influenced by task rules. In parity judgment task, the MARC effect functions as a spatial congruence effect, reflecting the semantic association between numerical parity (odd/even) and specific hand responses—odd numbers align naturally with left-hand responses, and even numbers with right-hand responses. When task rules align parity information with intuitive spatial associations—assigning odd numbers to left-hand responses and even numbers to right-hand responses (referred to as map1)—MARC-congruent conditions are established. Conversely, when task rules are reversed—assigning even numbers to left-hand responses and odd numbers to right-hand responses (referred to as map2)—MARC-incongruent conditions occur due to mismatches between parity information and spatial associations. In such incongruent conditions, cognitive conflict is higher than in congruent conditions. Cognitive control is crucial in regulating this interaction, especially in monitoring conflicts and allocating cognitive resources. According to Botvinick and colleagues, cognitive conflict can trigger cognitive control to allocate attention appropriately, thereby influencing task responses [20]. Zhang et al. further argued that the interaction between the SNARC and MARC effects can be divided into a conflict-monitoring phase and a resource-allocation phase [21]. During conflict monitoring, cognitive control intervenes to resolve contradictions when the representations or response rules of the two effects conflict, thereby coordinating their performance. For instance, when the parity-to-response mapping is incongruent, cognitive control reduces the conflict through monitoring, influencing task outcomes. In the resource-allocation phase, cognitive control dynamically manages limited cognitive resources to balance conflicts between the SNARC and MARC effects. However, due to heightened cognitive conflict in incongruent conditions, resources are often prioritized to resolve MARC effect conflicts, potentially weakening the SNARC effect [20]. Overall, cognitive control coordinates contradictions between the SNARC and MARC effects by monitoring conflict intensity and allocating attention resources, thereby enhancing task performance. Furthermore, when responses occur under incongruent conditions of both the SNARC and MARC effects, the dual cognitive conflict requires the allocation of additional cognitive resources to resolve [22–24]. This may result in faster responses to trials under such conditions compared to trials with incongruent MARC effects but congruent SNARC effects, leading to a potential reversal of the SNARC effect—faster left-hand responses to larger numbers and faster right-hand responses to smaller numbers.

Zohar-Shai et al. found that variations in time intervals between two parity-to-response mappings affected the SNARC and MARC effects, particularly noting significant changes in the SNARC effect after the MARC effect disappeared [10]. They attributed this to co-activation of both mappings at shorter time intervals, which strengthened linguistic markedness linkages. Linguistic processing plays a crucial role in producing the MARC effect [25]; for instance, in Hebrew, the lexical encoding of parity differs crucially between numbers: "even" is denoted by the standalone term "zugi", whereas "odd" requires morphological negation through the prefix e- ("e-zugi"), effectively framing oddness as "the absence of evenness" (cf. "non-even" in English morphology). Therefore, the terms for "even" ("zugi") and "odd" ("e-zugi") may enhance the markedness of parity during linguistic processing, potentially amplifying the MARC effect and weakening the SNARC effect [10]. While studies on animals and human infants further suggest that number-space associations exist independently of cultural factors [26–31], it is possible that these associations are influenced by reading habits [32–35]. Research has demonstrated that the SNARC effect manifests a consistent spatial-numerical association pattern among populations with left-to-right reading orientation [36, 37]. However, it remains unclear whether the competitive relationship between the SNARC and MARC effects holds cross-culturally. Previous studies have indicated that parity processing may influence the SNARC effect, but the nature of this influence remains unclear.

This study aims to explore the interaction between the SNARC and MARC effects among left-to-right writing readers by manipulating the time interval (1 day, 10 minutes, or no time interval) between performance of two mapping rules in parity judgment tasks. According to Meiran et al., prior tasks continue to influence subsequent tasks due to residual task sets, and with longer time intervals, individuals become less sensitive to task rule changes, reducing their perception of conflicts [38]. Thus, we designed experiments with different time intervals to examine whether the SNARC effect in parity tasks among left-to-right writing readers would be affected by the MARC effect. We identified cognitive control as a critical factor in the interaction between the SNARC and MARC effects, particularly in navigating and resolving stimulus-response mapping conflicts. By regulating conflict monitoring and resource allocation, cognitive control plays a vital role in ensuring task performance. Taking into account the linguistic habits of previous study groups, we hypothesize the following for left-to-right writing readers: the SNARC effect will never be completely masked by the MARC effect and will consistently appear. However, the form of the SNARC effect is expected to be influenced by parity-to-response mapping rules. Under map1 conditions (MARC-congruent conditions), the SNARC effect is predicted to emerge with statistical significance, while under map2 conditions (MARC-incongruent conditions), the SNARC effect may either disappear or demonstrate a significant reverse effect. To test these hypotheses, we conducted a series of behavioral experiments with time intervals varying between 1 day, 10 minutes, and no time interval, to investigate the interaction between the SNARC and MARC effects (see Fig. 1a).

In addition to behavioral methods we tested the cognitive control hypothesis using event-related potential (ERP) technology in Experiment 5 (see Fig. 1b). The cognitive control hypothesis posits that a conflict-monitoring system evaluates ongoing levels of conflict and transmits this information to cognitive control mechanisms. These mechanisms, in turn, adjust attention to task-relevant dimensions [20]. The P300, a positive waveform occurring 250–850 milliseconds after feedback stimulus, is mainly observed in the parietal region, with a peak at the central parietal area. It is closely associated with advanced cognitive processes, including selective attention, motivational states, and resource allocation in decision-making [39–41]. Based on these findings, Experiment 5 utilized ERPs technology to investigate the neural mechanisms underlying the interaction between the SNARC and MARC effects from an electrophysiological perspective, and to further test the cognitive control hypothesis. It is generally believed that deeper or more complex processing tends to elicit greater P300 amplitudes [42]. A larger P300 amplitude typically indicates that more attentional resources are allocated to the stimuli [43–45]. Therefore, we expect to observe a larger P300 amplitude under the incongruent condition of the MARC effect.

Experiment 1

Zohar-Shai et al. discovered that time intervals have a significant impact on the MARC effect. Their experiments revealed that the MARC effect was observed when the

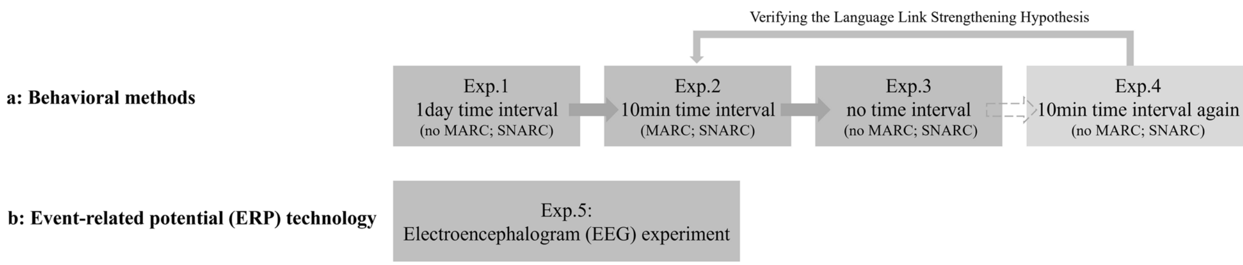

Fig. 1 Experimental logic flowchart. The experiments used Behavioral methods (**a**) and Event-related potential (ERP) technology (**b**). The dark gray experimental box represents the core verification group for the cognitive control hypothesis, while the light gray box reflects the follow-up study on the results of Exp2. The arrows indicate the progressive relationship between experiments, with dashed arrows representing exploratory paths triggered by unexpected findings. Experiments 1–3 validate the cognitive control hypothesis through behavioral methods, where Exp2 reveals a significant MARC effect, inconsistent with the Language Link Strengthening Hypothesis. To address this, a dashed arrow leads to Exp4, introducing an additional test of the moderating effect of language association. Exp5 employs ERP technology, utilizing P300 component analysis to reveal the impact of cognitive control neural mechanisms on the above interactions

time interval was one day or shorter. However, no MARC effect was observed under conditions with one week interval, suggesting that a one-day interval may be the critical time point for the emergence or disappearance of the MARC effect [10]. Given the known instability of the MARC effect and the aim of this study to examine the interaction between the SNARC and MARC effects, establishing the presence of a MARC effect becomes particularly important. Therefore, this study initially sets the time interval to one day to determine whether the MARC effect emerges.

Method

Participants

The sample sizes used in previous research studying the SNARC and MARC effect were typically about 25 [10, 25, 46]. Before performing our experiments, we conducted a prior power analyses using G*Power 3.1.9.2, and calculated that we would need a minimum sample size of 21. Our calculation was based on performing a repeated-measures ANOVA with 2 (response side : left vs. right) * 4 (magnitude bin : 1/2, 3/4, 6/7 and 8/9) * 2 (parity : odd vs. even) within-factor design (effect size =.25, significant level α =.05, power level 1-β =.99; the software G*Power 3.1.9.2) [47, 48]. The medium effect size (.25) was determined according to that in similar research [49].

We recruited participants through on-campus posters, WeChat, and online platforms such as Bilibili. Twenty-seven healthy participants (16 females, mean age of 19.19, range from 18 to 23) voluntarily participated in this study. All of them were fluent readers of modern Mandarin Chinese, which is a Left-to-right writing system. They were all right-handed with normal or corrected-to-normal vision. After the experiment, the participants received modest monetary compensation. This study was approved by the Institutional Review Board of Henan Philosophy and Social Sciences Planning Annual Project. We obtained informed consent from all participants before the experiment. After the experiment, the participants were compensated with 20 RMB.

Stimuli and procedure

The stimuli were single Arabic numbers, ranging from 1 to 9 (5 excluded), presented one at a time at the center of a 23-inch LCD computer screen. The numbers were displayed in 56-point Arial font, bold, and in white against a black background. E-Prime 2 Professional Software (Psychology Software Tools) was used to present the stimuli and to collect the responses. The viewing distance was approximately 60 cm from the screen, which had a resolution of 1920 × 1080 pixels and a refresh rate of 60 Hz; thus, each stimulus subtended approximately 4° of the visual field.

The participants were instructed to complete a parity judgment task, classifying each number as odd or even by pressing the left-side key ("D" on the keyboard) with the left index finger or the right-side key ("L" on the keyboard) with the right index finger. The duration of each trial was 2000 ms. At the beginning of each trial, a fixation cross (approximately 0.5° × 0.5° of visual angle) appeared at the center of the screen for 500 ms, followed by a blank dark screen for 500 ms, and then, the number appeared until the participant made a motor response (followed immediately by a blank screen), or the response deadline (1000 ms) was reached. There was no feedback after the response. Reaction time (RT) and accuracy were recorded for each trial (see Fig. 2a).

There were two sessions for each participant: one session with the left hand assigned to odd numbers and the right hand to even numbers and another session with the opposite assignment (odd-left/even-right vs. even-left/odd-right). In Experiment 1, participants

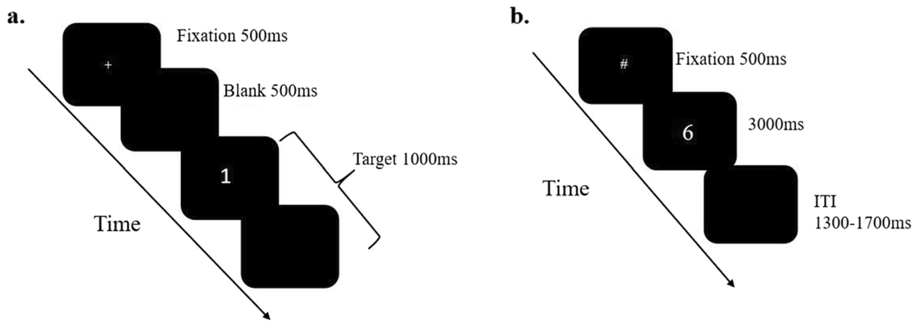

Fig. 2 The flowchart of a single trial in Experiments 1–4 (**a**), and in Experiment 5 (**b**)

Table 1 Means and standard deviations (SD) of the response times (RTs)

			Exp.1		Exp.2		Exp.3		Exp.4	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
left	bin1	odd	494	65	469	56	473	41	454	41
		even	516	58	500	50	513	55	486	47
	bin2	odd	521	76	501	65	502	44	488	52
		even	519	62	494	50	506	40	484	50
	bin3	odd	518	67	498	57	512	43	493	56
		even	517	64	512	52	515	55	502	55
	bin4	odd	555	66	524	42	539	53	521	59
		even	518	72	493	55	496	51	477	47
right	bin1	odd	507	64	479	57	493	46	461	40
		even	530	79	486	54	508	50	493	53
	bin2	odd	511	68	505	61	497	41	477	41
		even	517	72	485	45	501	45	490	53
	bin3	odd	514	69	493	53	493	32	486	49
		even	516	64	486	44	503	44	491	57
	bin4	odd	543	56	516	54	533	43	512	54
		even	493	67	467	54	480	47	468	52

performed two tasks during the same time period over two consecutive days, which was counterbalanced across participants. Due to the relatively poor test-retest reliability and temporal stability of the SNARC and MARC effects, increasing the number of trials can somewhat enhance the reliability of the experimental evaluation [50–54]. For each session, the participants first completed 16 practice trials and then completed the experimental trials. The session was divided into two blocks, between which the participants could take a short break. To prevent the same key response from occurring more than three times in succession, each number was presented 30 times, resulting in 240 pseudo-random trials per block [44]. The experiment lasted approximately 20 minutes in total.

Results and discussion

One participant with a mean accuracy rate less than 85% was excluded. Correlation analysis indicated that there was no speed-accuracy trade-off (r =.08, p =.70). Trials with incorrect responses (5.35%) and RTs more than 3 *SD*s from the individual mean (1.24%) were removed from further analysis. The average RT was 518 ms (*SD* = 59 ms), and mean correct RTs of each condition were calculated for each participant. Following Zohar-Shai et al, the eight numbers (1–9, not including 5) were divided into four bins by magnitude (1/2, 3/4, 6/7, 8/9) [10]. We used the number bin, not the number itself, to estimate the SNARC effect [10, 55].

We performed a three-way repeated-measures ANOVA with the response side (2: left vs. right), the magnitude bin (4: 1/2, 3/4, 6/7 and 8/9), and parity (2: odd vs. even) (see Table 1 for the descriptive data). The only significant main effect was magnitude [F (3, 75) = 10.93, p <.001, η^2_p =.30]. The average RTs across magnitude bins gradually increased as follows: 512, 517, 516, and 527 ms in bins 1/2, 3/4, 6/7, and 8/9, respectively. The polynomial contrast confirmed this linear increasing trend [F (1, 25) = 30.04, p <.001, η^2_p =.55]. Magnitude interacted with parity, F (3, 75) = 28.58, p <.001, η^2_p =.53. As the number magnitude increased, the RTs for odd numbers tended to increase, but the RTs for even numbers tended to decrease. The significant interaction between magnitude and response side indicated that there was a SNARC effect [F (3, 75) = 6.91, p <.001, η^2_p =.22]; left-side responses were faster than the right-side responses for number bin 1/2 (p =.05, η^2_p =.15), and the right-side responses were faster than the left-side responses for number bin 8/9 (p =.007, η^2_p =.26). There was no significant difference between the left-side and right-side responses for number bins 3/4 and 6/7. The interaction effect between parity and response side was not significant [F (1, 25) <.001, p =.99, η^2_p <.001], suggesting that there was no MARC effect. Moreover, the three-way interaction between response side, magnitude, and parity was also not significant [F (3, 75) =.95, p =.42, η^2_p =.04].

Additionally, in order to verify the cognitive control hypothesis, reaction time differences (dRT) were calculated for each effect by subtracting the reaction times for congruent conditions from those for incongruent conditions. The following steps were taken to perform the calculations necessary to measure each effect [13]:

- *To compute the SNARC effect using dRTs(across MARC-congruent and -incongruent trials)*:

 a) Compute mean RTs for SNARC-congruent trials (left responses to 1–4, right responses to 6–9)
 b) Compute mean RTs for SNARC-incongruent trials (right responses to 1–4, left responses to 6–9)
 c) Compute dRT = b – a

- *To compute the SNARC effect in the MARC-congruent conditions(map1)*:

 d) Compute mean RTs for SNARC-congruent trials (left responses to 1 and 3, right responses to 6 and 8)
 e) Compute mean RTs for SNARC-incongruent trials (right responses to 2 and 4, left responses to 7 and 9)
 f) Compute dRT = e - d

- *To compute the SNARC effect in the MARC-incongruent conditions(map2)*:

 g) Compute mean RTs for SNARC-congruent trials (left responses to 2 and 4, right responses to 7 and 9)
 h) Compute mean RTs for SNARC-incongruent trials (right responses to 1 and 3, left responses to 6 and 8)
 i) Compute dRT = h - g

- *To compute the MARC effect using dRTs(across SNARC-congruent and -incongruent trials)*:

 j) Compute mean RTs for MARC-congruent trials (map1: left responses to 1, 3, 7, and 9, right responses to 2, 4, 6, and 8)
 k) Compute mean RTs for MARC-incongruent trials (map2: right responses to 1, 3, 7, and 9, left responses to 2, 4, 6, and 8)
 l) Compute dRT = k – j

- *A positive dRT in (c), (f), and (i) indicates a small-left/large-right advantage (i.e., SNARC effect), while a positive dRT in (l) indicates an odd-left/even-right advantage (i.e., MARC effect).*

The dRTs derived from (c) and (l), with one dRT per participant, were analyzed using a one-sample t-test against zero to evaluate the overall SNARC effect and MARC effects. The results indicated a significant SNARC effect [Mean = 6.81, t (25) = 2.17, p =.04, Cohen's d =.43], and still no MARC effect [Mean =.34, t (25) =.04, p =.97, Cohen's d <.01]. To further investigate the influence of MARC effect compatibility on spatial-numerical associations, the dRTs from (f) and (i) were tested against zero in a one-sample t-test to assess the SNARC effect in the both MARC-congruent (map1) and MARC-incongruent (map2) conditions. We discovered a more substantial SNARC effect in the MARC-congruent condition (map1-SNARC) [Mean = 23.27, t (25) = 5.35, p <.001, Cohen's d = 1.05], but a significant reverse SNARC effect in the MARC-incongruent condition (map2-SNARC) [Mean = − 9.45, t (25) = − 2.19, p =.038, Cohen's d = -.43] (see Fig. 3, Exp.1). Furthermore, a paired t-test comparing the dRTs from (f) and (i) demonstrated a significant difference between the map1-SNARC and map2-SNARC effects [t (25) = 5.46, p <.001, Cohen's d = 1.07]. These results indicated that the spatial-numerical associations varied in different conditions of MARC effect, which might support that the level of cognitive conflict in the task at hand affected the SNARC effect.

In Experiment 1, we only observed the SNARC effect, not the MARC effect, differing from the findings of Zohar-Shai et al [10]. However, the results of Experiment 1 with a one-day time interval were identical to that of Zohar-Shai et al with a one-week time interval. That is,

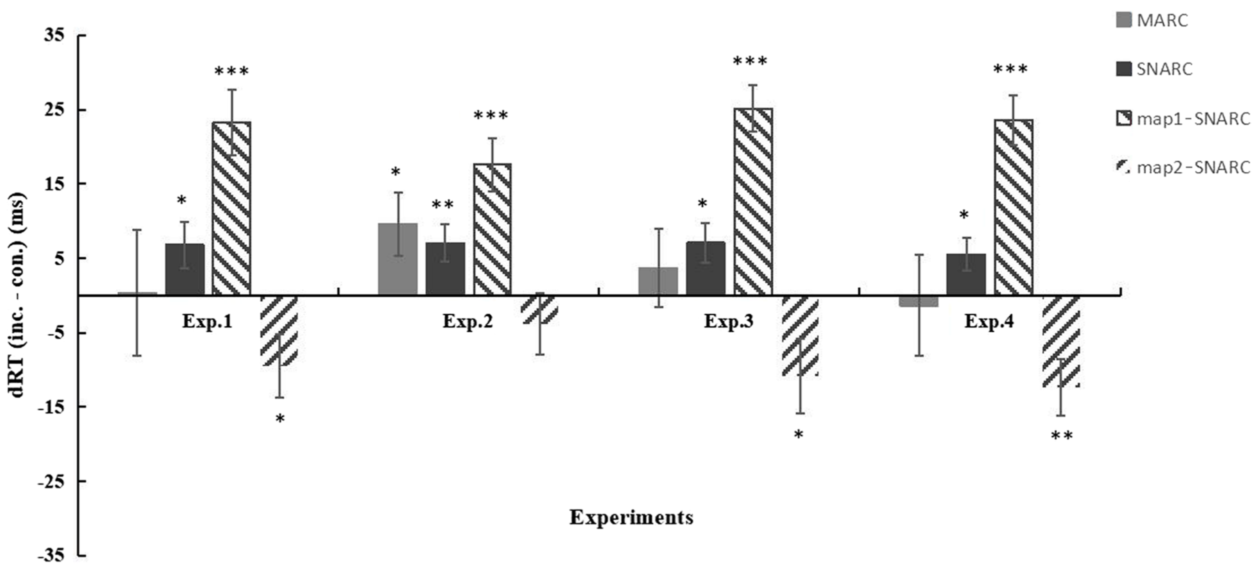

Fig. 3 The different RTs (dRT: incongruent minus congruent conditions) for SNARC (across MARC-congruent and MARC-incongruent trials), MARC (across SNARC-congruent and SNARC-incongruent trials), map1-SNARC (SNARC only in MARC-congruent trials), and map2-SNARC (SNARC only in MARC-incongruent trials) effects in four behavioral experiments. The experiments were from left to right Exp1 with one day time interval between two parity-to-response side mappings ("time interval" for short), Exp2 with 10 minutes time interval for the first operation, Exp3 with no time interval, and Exp4 with 10 minutes time interval for the second operation. Error bars are confidence intervals. Note: **p < 0.05, **p< 0.01, ***p< 0.001*

the MARC effect disappeared when the time interval was one day for Chinese participants, but it disappeared when the time interval was one week for Hebrew speakers [10]. We suggest that the influence of the time interval on the MARC effect might be relatively diminished for left-to-right writing readers. However, it is unclear whether the MARC effect would be enhanced by reducing the time interval. Thus, we conducted Experiment 2 to explore this issue, and reveal the interactions between the SNARC and MARC effects again.

Experiment 2

In Experiment 2, the time interval was set to 10 minutes to further investigate the changes in the SNARC and MARC effects, as well as the interactions between them. If the time interval has the expected impact on both effects, we would anticipate observing diminished SNARC effect and an enhanced MARC effect.

Method

The selection criteria for the subjects are consistent with those in Experiment 1, we need at least 21 participants in the experiment (effect size =.25, significant level α =.05, power level 1-β =.99) [47–49]. In Experiment 2, twenty-eight new participants participated (16 females, mean age 18.36 years, range from 18 to 19). The procedure of Experiment 2 was identical to that of Experiment 1, except that there was a 10-minute interval between the two mappings; Participants were instructed to complete the first part of the task, then engage in activities of their choice outside the laboratory for 10 minutes before beginning the next part. The order of the two mappings was counterbalanced across participants. Participants received monetary compensation of 10 RMB for completing the experiment, which took approximately 20 minutes.

Results and discussion

Using the same statistical analysis as in Experiment 1, one participant with an accuracy rate less than 85% was excluded. Correlation analysis indicated that there was no speed-accuracy trade-off (r = -.27, p =.17). Trials with incorrect responses (4.00%) and RTs more than 3 SDs from the individual mean (1.18%) were removed from further analysis. The average RT was 494 ms (SD = 48 ms), and mean correct RTs for each condition were compared using a three-way repeated-measures ANOVA with independent variables consisting of the response side (2: left vs. right), the magnitude bin (4: 1/2, 3/4, 6/7 and 8/9), and parity (2: odd vs. even).

In Experiment 2, the main effects of all three factors were found to be significant. The right-side responses were faster (490 ms) than the left-side responses (499 ms), F (1, 26) = 7.49, p =.01, η^2_p =.22. The average RTs across the magnitude bins gradually increased as follows: 484, 496, 497, and 500 ms for bins 1/2, 3/4, 6/7, and

8/9, respectively. The significant main effect of magnitude [F (3, 78) = 13.00, p <.001, η^2_p =.33] and the polynomial contrast confirmed this linear increasing trend [F (1, 26) = 57.67, p <.001, η^2_p =.69]. The main effect of parity, F (1, 26) = 12.45, p =.002, η^2_p =.32, indicated that even numbers were responded to faster (490 ms) than odd numbers (498 ms). There was an interaction between parity and magnitude, F (3, 78) = 27.69, p <.001, η^2_p =.52. As the number magnitude increased, the RTs to odd numbers increased, while the RTs to even numbers decreased. There was an interaction between magnitude and response side [F (3, 78) = 3.92, p =.01, η^2_p =.13], suggesting that there is a SNARC effect. The simple effect analysis showed that there was no significant difference between the left-side and right-side responses for number bin 1/2 (p =.80, η^2_p =.003) and 3/4 (p =.62, η^2_p =.01), the right-side responses were faster than the left-side responses for number bin 6/7 (p =.001, η^2_p =.33) and 8/9 (p =.001, η^2_p =.35). More importantly, there was also an interaction between parity and response side, F (1, 26) = 4.99, p =.034, η^2_p =.16, suggesting that there is a significant MARC effect. The right-side responses (481 ms) were faster than the left-side responses (500 ms) for even numbers (p <.001, η^2_p =.40), but there was no significant difference between the left- (498 ms) and right-side responses (498 ms) for odd numbers.

Similar to the Experiment 1, we computed the dRTs for the SNARC, MARC, map1-SNARC, and map2-SNARC effects. We then applied a one samples t-test on these dRTs to evaluate the reliability of these effects. The t-test also yielded a significant SNARC effect [Mean = 7.04, t (26) = 2.86, p =.008, Cohen's =.55], MARC effect [Mean = 9.57, t (26) = 2.23, p =.035, Cohen's d =.43], and a greater significant map1-SNARC effect [Mean = 17.59, t (26) = 4.91, p <.001, Cohen's d =.95], but a nonsignificant reverse map2-SNARC effect [Mean = − 3.78, t (26) = -.92, p =.37, Cohen's d = -.18] (see Fig. 3, Exp.2). The paired sample t-test indicated that there was a significant difference between map1-SNARC and map2-SNARC effects [t (26) = 3.60, p <.001, Cohen's d = 0.69]. These results might again support that the level of cognitive conflict in the task at hand affected the SNARC effect.

When the time interval was set to 10 minutes, we observed both the SNARC and MARC effect [56, 57]. In contrast to the SNARC effect in Experiment 1 (η^2_p =.22), the effect size in Experiment 2 decreased (η^2_p =.13), but this difference is merely descriptive, as no statistical comparison test was conducted. This reduction may indicate an inverse relationship between the SNARC and MARC effects. These results seem to support the view that if the time interval is sufficiently short, then the co-activation of the two mappings will increase the MARC effect [10]. For Hebrew speakers, Zohar-Shai et al found that the MARC effect dominated task performance and masked the SNARC effect when the time interval was 10 minutes [10]. For left-to-right writing readers, whether the MARC effect would dominate the task performance when the time interval was further shortened or the SNARC effect would still dominate the task performance was unclear. We designed Experiment 3 further to investigate this issue.

Experiment 3

In Experiment 3, no time interval was set to examine the changes in SNARC and MARC effects once more. Based on the language link strengthening hypothesis from Zohar-Shai et al [10], it was anticipated that the MARC effect would be more pronounced, potentially overriding the SNARC effect.

Method

The selection criteria for the subjects are consistent with those in Experiment 1, we need at least 21 participants in the experiment (effect size =.25, significant level α =.05, power level 1-β =.99) [47–49]. In Experiment 3, thirty new participants were recruited for this experiment (17 females, mean age of 19.03, range from 18 to 23). The procedure of Experiment 3 was similar to that of the previous experiments, except that there was no break between the two sessions. The order of the two response assignments was counterbalanced across participants. Participants received monetary compensation of 10 RMB upon completing the experiment, which took approximately 20 minutes.

Results and discussion

One participant with a mean accuracy rate less than 85% was excluded. Correlation analysis indicated that there was no speed-accuracy trade-off (r =.16, p =.41). Trials with incorrect responses (4.10%) and RTs more than 3 SDs from the individual mean (1.27%) were removed from the analysis. As in the previous experiments, we performed a three-way repeated-measures ANOVA with independent variables consisting of the response side (2 levels: left vs. right), the magnitude bin (4 levels: 1/2, 3/4, 6/7 and 8/9), and parity (2 levels: odd vs. even).

The main effect of magnitude was significant [F (3, 84) = 9.06, p <.001, η^2_p =.24], with a gradual increase in the average RTs across the magnitude bins: 497, 502, 506, and 512 ms for bins 1/2, 3/4, 6/7, and 8/9, respectively. The polynomial contrast confirmed this linear increasing trend, F (1, 28) = 24.99, p <.001, η^2_p =.47. There was also an interaction between magnitude and parity, F (3, 84) = 37.45, p <.001, η^2_p =.57. As the number magnitude increased, the RTs for odd numbers tended to increase, but the RTs for even numbers tended to decrease. The interaction effect between magnitude and response side was significant [F (3, 84) = 5.83, p =.001, η^2_p =.17], indicating a significant SNARC effect. The right-side responses were faster than the left-side responses for number bin 6/7 (p =.007, η^2_p =.24) and 8/9 (p =.069, η^2_p =.11), but there was no significant difference between the left-side and right-side responses for number bin 1/2, 3/4. Moreover, the interaction effect between parity and response side was not significant, F (1, 28) =.50, p =.49, η^2_p =.02, suggesting an absence of the MARC effect.

Following the same analytical procedures as in Experiment 1, the t-test also yielded a significant SNARC effect [Mean = 7.06, t (28) = 2.61, p =.014, Cohen's =.49], but no MARC effect [Mean = 3.70, t (28) =.71, p =.49, Cohen's d =.13], which was not consistent with the prediction of a greater MARC effect and a smaller, perhaps nonsignificant SNARC effect. More importantly, there still was a greater significant map1-SNARC effect [Mean = 25.16, t (28) = 8.19, p <.001, Cohen's d = 1.52], and a significant reverse map2-SNARC effect [Mean = − 10.88, t (28) = − 2.17, p =.039, Cohen's d = -.40] (see Fig. 3, Exp.4). The paired sample t-test indicated that there was a significant difference between map1-SNARC and map2-SNARC effects [t (28) = 5.66, p <.001, Cohen's d = 1.05], suggesting that the spatial-numerical associations varied in different conditions of MARC effect. These results again supported that the level of cognitive conflict in the task at hand might be the basic reason of the interactions between the SNARC and MARC effects.

In first three experiments, we did not observe regular changes in both effects along the shortening of the time intervals; there was a quite consistent SNARC effect for left-to-right writing readers, but a significant MARC effect only in Experiment 2 with 10 minutes time interval. Previous research has indicated that the reproducibility of the MARC effect is relatively low; only about 60% of participants show this effect [58], The repeatability of the SNARC effect is also called into question [59]. To control for potential contextually-driven contingencies, we set the time interval to 10 minutes and once again investigated the SNARC and MARC effects.

Experiment 4

If the short time interval was indeed a necessary factor for the MARC effects in parity judgment task, then observing this effect again in Experiment 4 would be expected.

Method

The selection criteria for the subjects are consistent with those in Experiment 1, we need at least 21 participants in the experiment (effect size =.25, significant level α =.05, power level 1-β =.99) [47–49]. In Experiment 4, thirty-one new participants participated in Experiment 4 (16 females, mean age 20.74 years, range from 18 to 26). The procedure of Experiment 4 was identical to that of Experiment 2. Participants received monetary compensation of 10 RMB upon completing the experiment, which took approximately 20 minutes.

Results and discussion

Using the same statistical analysis as in Experiment 2, one participant with an accuracy rate less than 85% was excluded. Correlation analysis indicated that there was no speed-accuracy trade-off (r =.24, p =.20). Trials with incorrect responses (5.91%) and RTs more than 3 SDs from the individual mean (1.54%) were removed from further analysis. The average RT was 486 mms (SD = 41 ms), and mean correct RTs for each condition were compared using a three-way repeated-measures ANOVA with independent variables consisting of the response side (2: left vs. right), the magnitude bin (4: 1/2, 3/4, 6/7 and 8/9), and parity (2: odd vs. even).

In Experiment 4, the average RTs across the magnitude bins gradually increased as follows: 474, 484, 493, and 494 ms for bins 1/2, 3/4, 6/7, and 8/9, respectively. The significant main effect of magnitude [F (3, 87) = 17.29, p <.001, η^2_p =.37] and the polynomial contrast confirmed this linear increasing trend [F (1, 29) = 41.95, p <.001, η^2_p =.59]. There was an interaction between parity and magnitude, F (3, 87) = 47.41, p <.001, η^2_p =.62. As the number magnitude increased, the RTs to odd numbers increased, while the RTs to even numbers decreased. More importantly, there was an interaction between magnitude and response side [F (3, 87) = 3.17, p =.028, η^2_p =.10], suggesting that there is a SNARC effect. The right-side responses were faster than the left-side responses for number bin 6/7 (p =.001, η^2_p =.33) and 8/9 (p =.001, η^2_p =.35), but there was no significant difference between the left-side and right-side responses for number bin 1/2, 3/4. The interaction between parity and response side was not significant, F (1, 29) =.05, p =.83, η^2_p =.002, suggesting that there is no MARC effect.

Following the same analytical procedures as in Experiment 1, the t-test also yielded a significant SNARC effect [Mean = 5.47, t (29) = 2.48, p =.019, Cohen's =.45], but no MARC effect [Mean =− 1.37, t (29) = -.20, p =.84, Cohen's d = -.04]. There still was a greater significant map1-SNARC effect [Mean = 23.59, t (29) = 6.95, p <.001, Cohen's d = 1.27], and a significant reverse map2-SNARC effect [Mean = − 12.33, t (29) = − 3.265, p =.003, Cohen's d = − 4.61] (see Fig. 3, Exp.4). The paired sample t-test indicated that there was a significant difference between map1-SNARC and map2-SNARC effects [t (29) = 6.39, p <.001, Cohen's d = 1.17].

In Experiment 4, when the time interval was set to 10 minutes again, the SNARC effect remained significant, but the MARC effect disappeared, indicating that the MARC effect is indeed affected. These results also illustrated that neither the SNARC effect was weakened, nor the MARC effect strengthened along with the time interval gradually shorten, which did not support the explanation of Zohar-Shai et al about the interactions between the SNARC and MARC effect [10]. However, there was a very consistent phenomenon in the first four experiments, that is, the SNARC effect varied in different conditions of MARC effect; a stronger SNARC effect in congruent conditions of MARC effect (map1) but a weaker or reverse SNARC effect in incongruent conditions (map2). In parity judgment task, the SNARC and MARC effect were all belong to the stimulus-response compatibility effects, and there was cognitive conflict between the congruent and incongruent conditions. There was only one type of cognitive conflict from the congruency of SNARC effect in map1, however, there were two types of cognitive conflict from the congruency of SNARC and MARC effects in map2, suggesting that the level of cognitive conflict might be the fundamental reason for the interactions between both effects.

Experiment 5

The cognitive control hypothesis argues that there exists a conflict monitoring system to evaluate the current levels of conflict, which are transferred into the cognitive control to adjust attention to the task relevant dimensions, and thereby influences processing of task irrelevant dimensions [20]. An ERP component associated with attentional resources is the P300 [60, 61], which is recorded at site Pz and defined as positive deflections between 250 ~ 850 ms after stimulus onset [17]. If the level of cognitive conflict determines the variation in SNARC effect across the two mappings, we would predict that attention resources would be changed, and would result in different P300 components. Thus, in Experiment 5, we used the ERP method to test this hypothesis.

Method

Procedure

We conducted the ERP study following the same experimental procedure as in experiment 1–4. Two previously published ERP studies on the SNARC effect included sample sizes of fourteen [17] and twenty-two [62], respectively. According to power analyses, we need at least 21 participants in the experiment (effect size =.25, significant level α =.05, power level 1-β =.99) [47–49]. Twenty-two new participants (13 females, mean age 21.41 years, ranging from 18 to 27) participated in the ERP experiment, in which we repeated each mapping twice for a total of four blocks. At the beginning of each block, participants first completed 8 practice trials and then completed the experimental trials. Similar to the procedure of Experiment 1, each number was presented 30 times, resulting in 240 pseudo-random trials per block. In each experimental trial, a fixation point appeared for 500 ms, and then the number appeared until the participant made a motor response, or the response deadline (3000 ms) was reached, followed by a blank dark screen for random period of 1300 ms to 1700 ms with 100 ms interval (see Fig. 2b). The order of the two mappings was counterbalanced across participants in an ABBA format (map1-map2-map2-map1 vs. map2-map1-map1-map2). The EEG (Electroencephalography) data, which measures electrical activity in the brain through electrodes placed on the scalp, was recorded simultaneously while the participant performed the parity judgment task. This method allows for the tracking of brain activity in real-time, providing insights into cognitive processes such as attention and decision-making. After completing the experiment, participants received monetary compensation of 40 RMB. The entire process took approximately 50 minutes.

EEG data recording and processing

We used a 64 electrode BrainVision system (BrainProcedure, Germany) to record EEG data. The scalp electrodes were placed according to the international 10–20 system (band-pass: 0.016–125 Hz; sampling rate: 2500 Hz). FCz was the online reference electrode, and AFz was the ground electrode. Horizontal electro-oculograms (HEOGs) were recorded at the right and left outer canthi, and vertical electro-oculogram (VEOG) recorded above the left eye to monitor eye blinks and ocular movements. The electrode impedances were kept lower than 5 kΩ. Raw data was analyzed with EEGLAB (https://sccn.ucsd.edu/eeglab/index.php), an interactive MATLAB toolbox. First, raw data was resampled to 1000 Hz, then band-pass filtered 0.1–30 Hz, and then re-referenced to the average of the bilateral mastoids. The continuous EEG data was segmented into epochs using a time window of 3000 ms, ranging from 1000 ms pre-stimulus to 2000 ms post-stimulus. We applied independent component analysis (ICA) algorithm to reject the eye-movement artifacts. The epochs belonging to incorrect responses and RTs longer than 1000 ms or shorter than 200 ms trials were discarded [62]. Available epochs were re-segmented into short epochs with the time window of 1200 ms, ranging from 200 ms pre-stimulus to 1000 ms post-stimulus, and baseline correction was performed using the pre-stimulus interval (− 200 to 0 ms), then set the amplitude threshold ± 80 μV to exclude out of range signals.

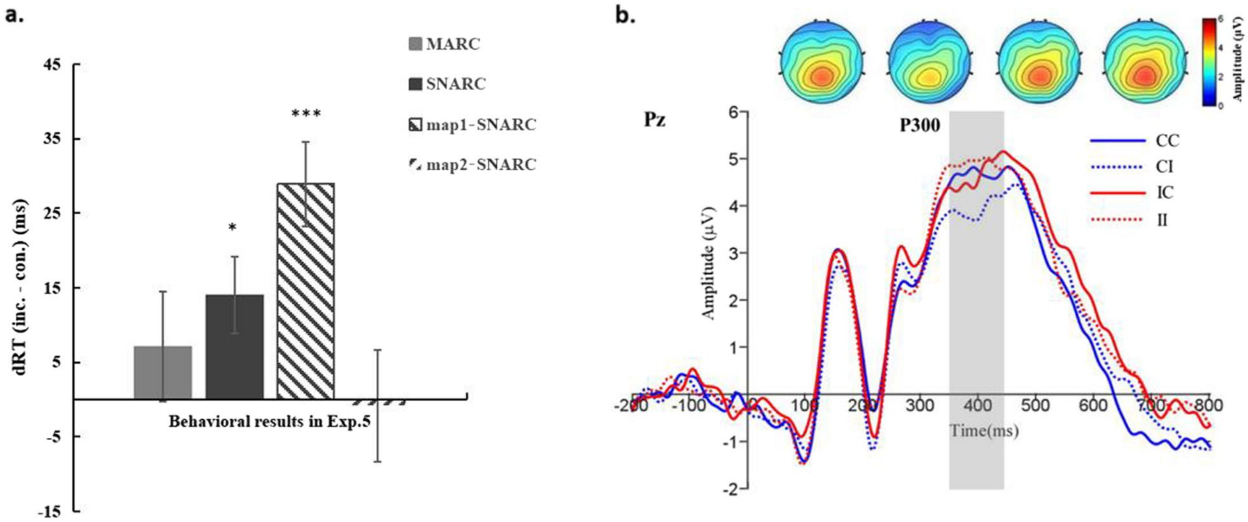

Fig. 4 Results of Experiment 5 (an ERP study). **a** The different RTs (dRT: incongruent minus congruent conditions) for SNARC (across MARC-congruent and MARC-incongruent trials), MARC (across SNARC-congruent and SNARC-incongruent trials), map1-SNARC (SNARC only in MARC-congruent trials), and map2-SNARC (SNARC only in MARC-incongruent trials) effects in ERP experiment. Error bars are confidence intervals. **b** The P300 amplitude for CC (the congruent condition of SNARC effect in congruent condition of MARC effect), CI (the incongruent condition of SNARC effect in congruent condition of MARC effect), IC (the congruent condition of SNARC effect in incongruent condition of MARC effect), II (the incongruent condition of SNARC effect in incongruent condition of MARC effect) at site Pz, and the corresponding scalp topographical maps (350 - 450 ms). The gray bar indicates the time window within which there was a significant interaction between the SNARC and MARC effect (p =.02)

Results and discussion

Behavioral

Trials with incorrect responses (4.26%) and RTs greater than 1000 ms or less than 200 ms (7.44%) were removed from further analysis. The RTs could be approximated by a normal distribution (Skewness = -.57), and average RT was 577 ms (SD = 69 ms). Following the same analytical procedures as in Experiment 1, we calculated the dRTs for the SNARC, MARC, map1-SNARC, and map2-SNARC effects, followed by a one samples t-test on these dRTs to evaluate each effect. There was a significant SNARC effect [Mean = 14.01, t (21) = 2.70, p =.013, Cohen's =.58], but not a significant MARC effect [Mean = 7.09, t (21) =.97, p =.35, Cohen's d =.21]. Similar to the behavioral experiments, there was a significant map1-SNARC effect [Mean = 28.93, t (21) = 5.08, p <.001, Cohen's d = 1.08], but not a significant map2-SNARC effect [Mean = -.80, t (21) = -.11, p =.92, Cohen's d = -.02] (see Fig. 4a). The paired sample t-test indicated that there was a significant difference between map1-SNARC and map2-SNARC effects [t (21) = 3.56, p =.002, Cohen's d =.76], suggesting that the spatial-numerical associations varied in different conditions of MARC effect. These results were consistent with that of behavioral experiments in current study.

Electrophysiological results

For each subject, the epochs time-locked to stimulus onset were averaged for each condition to get the mean waveforms. The group-level peak latencies and amplitudes of the P300 component were computed from the mean waveforms, and the corresponding scalp topographical maps were provided to reflect the distributions of P300 component. We applied a two-way repeated-measures ANOVA with MARC effect (2: congruent vs. incongruent) and SNARC effect (2: congruent vs. incongruent) for the amplitudes of P300 (time window 350 - 450 ms), finding that there was a significant SNARC effect [F (1, 21) = 3.87, p =.06, η^2_p =.16]. More importantly, we observed the interactions between the SNARC and MARC effects [F (1, 21) = 6.38, p =.02, η^2_p =.23] (see Fig. 4b). The simple effect analysis showed that there was a greater significant SNARC effect in the congruent condition of MARC effect (p =.002, η^2_p =.38), but not significant SNARC effect in the incongruent condition (p =.39, η^2_p =.04). There was no significant effect for the peak latency of P300 component. The amplitude of P300 in different conditions was in line with the behavioral RTs of ERP experiment, supporting that the level of cognitive conflict determined the interactions between the SNARC and MARC effects.

General discussion

This study examined the effect of parity-response mapping on the SNARC effect. We first conducted four behavioral experiments that varied the time interval between two parity-to-response mappings to examine their impact on the SNARC and MARC effects. Contrary to the findings of Zohar-Shai et al. [10], we observed that, regardless of the time interval, left-to-right readers exhibited the SNARC effect, indicating that the SNARC effect dominated task execution throughout this study. While we found a MARC effect with a 10 minutes time interval in Experiment 2, this effect failed to replicate in Experiment 4 that also used a 10 minutes time interval. These results align with our hypothesis that cognitive control explains the interaction between the SNARC and MARC effects. When the two effects conflict, cognitive control suppresses the MARC effect by reallocating attention, leading to instability in its occurrence (as seen in Experiments 1, 2, 3, and 4). In contrast, the SNARC effect consistently emerged in all Experiments. Notably, our findings also highlight that, even when the MARC effect itself is nonsignificant, the different conditions of the MARC effect do influence the SNARC effect.

However, we found that these interactions mainly reflected the influences of the congruency of MARC effect on the SNARC effect. More specifically, although we observed a significant SNARC effect in parity judgment task, there was a stronger SNARC effect in congruent condition of MARC effect, and a weaker or reverse SNARC effect in incongruent condition. We proposed that the levels of cognitive conflict in different conditions might contribute to the changes of spatial-numerical associations; more conflict signal in current task would be transferred into more cognitive control to distribute more attention resource to the task-relevant dimensions, and then affected the spatial-numerical associations [20].

In addition, we conducted an ERP experiment to reveal the neural mechanism of the interactions between the SNARC and MARC effects. The ERP results offer evidence for the interactions between the SNARC and MARC effects, particularly in the amplitude of the P300 component. The significant SNARC effect observed in the congruent condition of the MARC effect, but not in the incongruent condition, highlights the critical role of cognitive conflict in shaping these interactions. This finding aligns with behavioral reaction time patterns, further supporting the notion that higher levels of cognitive conflict diminish the strength of the SNARC effect. Importantly, the absence of significant differences in P300 peak latency suggests that these interactions are not driven by temporal variations in processing but rather by differences in the allocation of cognitive resources, as reflected in P300 amplitudes. These results underscore the neural basis of how spatial-numerical and linguistic-spatial associations interact, reinforcing the idea that the resolution of cognitive conflict plays an important role in modulating these effects.

For the interactions between the SNARC and MARC effects, one could argue that reactions to numbers themselves caused the significant changes of SNARC effects in different conditions of MARC effect. More specifically, the same digit in different conditions of MARC effects (different parity-to-response mappings) belonged to congruent and incongruent condition of SNARC effect respectively. For instance, in the congruent MARC condition, digits 1, 3, 6, 8 belonged to the congruent condition of the SNARC effect (CC condition), but 2, 4, 7, 9 belonged to incongruent condition (CI condition), and it was reversed for these digits in incongruent condition of MARC effect (IC condition: 2, 4, 7, 9; II condition: 1, 3, 6, 8). One could argue that it was the reaction rule resulting in the significant difference or even reverse relationships between SNARC effects in different conditions of MARC effect. According to this viewpoint, we predicted that the same set of digits would show a similar reaction pattern for behavioral and ERP data. However, when we computed the congruency effect by comparing the CC to II conditions (digits: 1, 3, 6, 8), and comparing the IC to CI conditions (digits: 2, 4, 7, 9), we found that the behavioral and ERP results of two sets digits were inconsistent; there only was a significant difference between CC and II conditions (digits: 1, 3, 6, 8) in RTs [Mean = 22.78, t (21) = 1.99, p =.06, Cohen's d =.42], but only the significant difference between IC and CI conditions (digits: 2, 4, 7, 9) in amplitude of P300 component [Mean = -.73, t (21) = − 2.33, p =.03, Cohen's d =.50]. Based on these results, we could rule out this possibility.

The alternative argument was that the SNARC and MARC effects might share common processing mechanisms. Researchers hypothesized that numbers are spatially represented along a "mental number line" (MNL), on which numbers are spatially organized in accordance with their increasing magnitude [2]. Recently, some researchers have suggested that numbers are associated not only with spatial representations of a visuo-spatial nature (e.g., MNL metaphor) but also with a verbal nature [1, 3, 16, 63]. Additionally, van Dijck et al. [63] showed that numbers are associated with different types of spatial information, depending on the task. They suggested that the retrieval of parity status (conceptual number knowledge) would make conceptual spatial information (left/right) be retrieved during parity judgment and thus suggested that verbally mediated spatial representation was a crucial factor of the SNARC effect in parity judgment. More importantly, verbal coding is considered the dominant mechanism for the MARC effect [15, 64]; there are linguistic associations between the adjectives "odd" and "left" and between the adjectives "even" and "right". It could be argued that verbal coding might be the common processing mechanism for both SNARC and MARC effects, resulting in the interactions between them. We argued that if both effects shared a common processing mechanism, there would be a significant correlation between them at the individual level. Thus, we applied the correlation analysis on the behavioral experimental results by computing dRTs for each effect, to examine this argument. We found no significant correlation of the effect size between the SNARC and MARC effects (r =.08, p =.42). A BF_{10} of.16 also indicated that there was no correlation, which did not support the hypothesis of common processing mechanism between the SNARC and MARC effects.

Although we have discussed the cognitive control account for the interactions between the SNARC and MARC effects, it remains to be explained why the SNARC effect in the incongruent condition of MARC effect was sometime reversed significantly (e.g., the findings in Experiment 1, 3, and 4). The reverse SNARC effect seemed to indicate that there were privileged associations between small number and right-side response, large number and left-side response, which could not be explained by the MNL hypothesis [2]. We suggested that this phenomenon might be explained from the conflict-modulated Hebbian learning rule, which proposed that cognitive system would be based on the level of cognitive conflict to learn the task rule, and then meet the task demands [65]. In present study, the II condition was the high level cognitive conflict [66], which would strengthen the processing of goal-relevant information [20, 67], that is, the judgment of parity information. The mapping rule of parity-to-response might be applied to the spatial-numerical associations [68], leading to the significant reverse SNARC effect in the incongruent condition of MARC effect. Moreover, we further examined the correlation between MARC and map2-SNARC effects, finding that there was a significant correlation between MARC and map2-SNARC effects (r =.21, p =.03), and the BF_{10} of 1.21 also indicated that there was a correlation, supporting the cognitive control account again.

This study found that reaction times for even numbers were significantly faster than those for odd numbers, which may be related to the odd-number effect. Hines [69] proposed that the odd-number effect suggests that individuals are typically slower in judging odd numbers, possibly due to the linguistic markedness of odd numbers. According to the theory of linguistic markedness, "odd" is considered marked, while "even" is unmarked. Markedness reflects cognitive complexity or asymmetry: marked concepts are more specific, less frequently used, and therefore require more cognitive resources to process. However, we argue that the phenomenon observed in this study cannot be entirely attributed to the linguistic markedness of odd numbers. Our experimental results revealed a complex interaction pattern, which primarily reflects the dynamic regulation of the SNARC and MARC effects under different conditions. Notably, the interaction between these effects was particularly evident in Experiments 2 and 3, where different response sides significantly influenced reaction times in numerical magnitude processing tasks. In addition, we observed that reaction times increased progressively with the magnitude grouping, showing a significant linear growth pattern. This linear increase may reflect the magnitude effect [70], whereby "larger quantities elicit longer response times." However, in all experiments, we consistently observed a significant interaction between numerical magnitude and response side, consistently demonstrating the presence of the SNARC effect, indicating that response side played a critical role in our experimental setup. Although the magnitude effect and odd-number effect, along with their significant interaction ($p < 0.05$), were present in our study, these effects did not directly interfere with the core interaction between the SNARC and MARC effects. Our experimental design, which was 2 (response side: left vs. right) * 4 (magnitude bin: 1/2, 3/4, 6/7, 8/9) * 2 (parity: odd vs. even), ensured the generalizability of the SNARC and MARC effects across different magnitude and parity conditions. Furthermore, when analyzing the SNARC and MARC effects, we focused primarily on the patterns of the SNARC effect under different MARC conditions. The results showed that the SNARC effect exhibited a consistent pattern across the different MARC conditions, indicating that its repeatability was not significantly affected by the interaction between the magnitude and odd/even effects. While this study observed a significant interaction between the magnitude effect and the odd-number effect, our findings still support the interaction between the SNARC and MARC effects. Future research could further explore the mechanisms underlying these auxiliary effects and control for the influences of the magnitude and odd-number effects in experimental designs, in order to more precisely disentangle their impact on the SNARC and MARC effects.

In conclusion, we conducted a serial of experiments from cognitive behavior and neural levels to reveal the nature of interactions between the SNARC and MARC effects. We consistently found that the congruency of the MARC effect influenced the SNARC effect. From the point of view of cognitive control, we proposed that the changes of cognitive conflict levels in the task at hand might be the fundamental reason for the interactions between the

SNARC and MARC effects. It is recommended that future research manipulate different types of cognitive conflicts in task design (such as interference tasks or dual tasks) to observe their relative effects on the SNARC and MARC effects. This approach would further test our hypothesis that changes in cognitive conflict levels are the fundamental driving mechanism behind the interaction between the SNARC and MARC effects.

Abbreviations

SNARC	Spatial-numerical association of response codes
MARC	Linguistic markedness association of response codes
ERP	Event-related potentials
Map1	MARC-congruent conditions
Map2	MARC-incongruent conditions
CC	The congruent condition of SNARC effect in MARC-congruent conditions
CI	The incongruent condition of SNARC effect in MARC-congruent conditions
IC	The congruent condition of SNARC effect in MARC-incongruent conditions
II	The incongruent condition of SNARC effect in MARC-incongruent conditions

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Authors' contributions
Funding Acquisition, Q.C. and D.Z.; Conceptualization, Q.C. and D.Z.; Writing – Original Draft, Q.C. and D.Z.; Writing – Review & Editing, D.Z., Y.Z. and K.Q.; Data Curation, D.Z.; Formal Analysis, D.Z.; Methodology, D.Z.; Visualization, D.Z., Y.Z.; Software, D.Z.; Investigation, D.Z.; Project administration, Q.C. and D.Z.; Resources, Q.C. and D.Z.; Supervision, Q.C. and D.Z..

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Data availability
The data that support the findings of this study are available from the corresponding author D.Z, upon reasonable request.

Declarations

Ethics approval and consent to participate
Informed consent was obtained from all participants involved in the study. The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Henan Philosophy and Social Sciences Planning Annual Project(20220605002 and 2020.06).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Chen Q, Verguts T. Beyond the mental number line: a neural network model of number–space interactions. Cognitive Psychol. 2010;60(3):218–40. https://doi.org/10.1016/j.cogpsych.2010.01.001.
2. Dehaene S, Bossini S, Giraux P. The mental representation of parity and number magnitude. J Exp Psychol Gen. 1993;122(3):371–96.
3. Gevers W, Santens S, Dhooge E, Chen Q, Van den Bossche L, Fias W, Verguts T. Verbal-spatial and visuospatial coding of number–space interactions. J Exp Psychol Gen. 2010;139(1):180–90. https://doi.org/10.1037/a0017688.
4. Gevers W, Verguts T, Reynvoet B, Caessens B, Fias W. Numbers and space: a computational model of the SNARC effect. J Exp Psychol Human. 2006;32(1):32–44. https://doi.org/10.1037/0096-1523.32.1.32.
5. Fischer MH, Shaki S. Spatial associations in numerical cognition — from single digits to arithmetic. Q J Exp Psychol. 2014;67(8):1461–83. https://doi.org/10.1080/17470218.2014.927515.
6. Toomarian EY, Hubbard EM. On the genesis of spatial-numerical associations: evolutionary and cultural factors co-construct the mental number line. Neurosci Biobehav R. 2018;90:184–99. https://doi.org/10.1016/j.neubiorev.2018.04.010.
7. Wood G, Willmes K, Nuerk HC, Fischer MH. On the cognitive link between space and number: a meta-analysis of the SNARC effect. Psychol Sci. 2008;50(4):489–525.
8. Nuerk H, Iversen W, Willmes K. Notational modulation of the SNARC and the MARC (linguistic markedness of response codes) effect. Q J Exp Psychol Section A. 2004;57(5):835–63. https://doi.org/10.1080/02724980343000512.
9. Berch DB, Foley EJ, Hill RJ, Ryan PM. Extracting parity and magnitude from arabic numerals: developmental changes in number processing and mental representation. J Exp Child Psychol. 1999;74(4):286–308. https://doi.org/10.1006/jecp.1999.2518.
10. Zohar-Shai B, Tzelgov J, Karni A, Rubinsten O. It does exist! a left-to-right spatial-numerical association of response codes (SNARC) effect among native hebrew speakers. J Exp Psychol Human. 2017;43(4):719–28. https://doi.org/10.1037/xhp0000336.
11. Fischer MH, Castel AD, Dodd MD, Pratt J. Perceiving numbers causes spatial shifts of attention. Nat Neurosci. 2003;6(6):555–6. https://doi.org/10.1038/nn1066.
12. Fischer MH, Warlop N, Hill RL, Fias W. Oculomotor bias induced by number perception. Exp Psychol. 2004;51(2):91–7. https://doi.org/10.1027/1618-3169.51.2.91.
13. Shaki S, Fischer MH. Deconstructing spatial-numerical associations. Cognition. 2018;175:109–13. https://doi.org/10.1016/j.Cognition.2018.02.022.
14. Schwarz W, Müller D. Spatial associations in number-related tasks: a comparison of manual and pedal responses. Exp Psychol. 2006;53(1):4–15. https://doi.org/10.1027/1618-3169.53.1.4.
15. Nuerk H, Wood G, Willmes K. The universal SNARC effect the association between number magnitude and space is amodal. Exp Psychol. 2005;52(3):187–94. https://doi.org/10.1027/1618-3169.52.3.187.
16. Cho YS, Proctor RW. When is an odd number not odd? Influence of task rule on the MARC effect for numeric classification. J Exp Psychol Learn. 2015;33(5):832. https://doi.org/10.1037/0278-7393.33.5.832.
17. Gevers W, Ratinckx E, De Baene W, Fias W. Further evidence that the SNARC effect is processed along a dual-route architecture: evidence from the lateralized readiness potential. Exp Psychol. 2006;53(1):58–68. https://doi.org/10.1027/1618-3169.53.1.58.
18. Tzelgov J, Meyer J, Henik A. Automatic and intentional processing of numerical information. J Exp Psychol Learn Mem Cogn. 1992;18(1):166–79. https://doi.org/10.1037/0278-7393.18.1.166.
19. Roth L, Cipora K, Overlander A T, Nuerk H C, Reips U D. Shape of SNARC: how task-dependent are spatial-numerical associations? A highly powered online experiment. 2024; Preprint at: https://osf.io/4wpv6/.
20. Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. Conflict monitoring and cognitive control. Psychol Rev. 2001;108(3):624–52. https://doi.org/10.1037//0033-295X.I08.3.62/.
21. Zhang P, Cao B, Li F. The role of cognitive control in the SNARC effect: a review. PsyCh J. 2022;11(6):792–803. https://doi.org/10.1002/pchj.586.
22. Kiesel A, Steinhauser M, Wendt M, Falkenstein M, Jost K, Philipp AM, Koch I. Control and interference in task switching–a review. Psychol Bull. 2010;136(5):849–74. https://doi.org/10.1037/a0019842.

23. Wickens CD. Multiple resources and mental workload. Hum Factors. 2008;50(3):449–55. https://doi.org/10.1518/001872008X288394.
24. Egner T, Hirsch J. Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. Nat Neurosci. 2005;8(12):1784–90. https://doi.org/10.1038/nn1594.
25. Leth-Steensen C, Citta R. Bad–good constraints on a polarity correspondence account for the spatial–numerical association of response codes (SNARC) and markedness association of response codes (MARC) effects. Q J Exp Psychol. 2016;69(3):482–94. https://doi.org/10.1080/17470218.2015.1055283.
26. Adachi I. Spontaneous spatial mapping of learned sequence in chimpanzees: evidence for a SNARC-like effect. PLoS One. 2014;9:e90373. https://doi.org/10.1371/journal.pone.0090373.
27. Drucker C, Brannon EM. Rhesus monkeys (Macaca mulatta) map number onto space. Cognition. 2014;132:57–67. https://doi.org/10.1016/j.cognition.2014.03.011.
28. Rugani R, Vallortigara G, Priftis K, Regolin L. Numberspace mapping in the newborn chick resembles humans' mental number line. Science. 2015;347(6221):534–6. https://doi.org/10.1126/science.aaa1379.
29. Rugani R, Vallortigara G, Priftis K, Regolin L. Numerical magnitude, rather than individual bias, explains spatial numerical association in newborn chicks. eLife. 2020;9:e54662. https://doi.org/10.7554/eLife.54662.
30. Rugani R, de Hevia MD. Number-space associations without language: evidence from preverbal human infants and non-human animal species. Psychon Bull Rev. 2017;24(2):352–69. https://doi.org/10.3758/s13423-016-1126-2.
31. Hevia MD, de Veggiotti L, Streri A, Bonn CD. At birth, humans associate "few" with left and "many" with right. Curr Biol. 2017;27(24):3879–84. https://doi.org/10.1016/j.cub.2017.11.024.
32. Shaki S, Fischer MH, Petrusic WM. Reading habits for both words and numbers contribute to the SNARC effect. Psychon Bull Rev. 2009;16(2):328–31. https://doi.org/10.3758/PBR.16.2.328.
33. Hochman S, Havedanloo R, Heysieattalab S, Soltanlou M. How does language modulate the association between number and space? A registered report of a cross-cultural study of the spatial-numerical association of response codes effect. J Exp Psychol Gen. 2025;154(2):305–24. https://doi.org/10.1037/xge0001653.
34. Bulut M, Roth L, Bahreini N, Cipora K, Reips U D, Nuerk H C. One direction? Cultural aspects of the mental number line beyond reading/writing direction. Psychol Res. 2024; Preprint on OSF: https://doi.org/10.31234/osf.io/qcb6m.
35. Zebian S. Linkages between number concepts, spatial thinking, and directionality of writing: the SNARC effect and the REVERSE SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. J Cogn Cult. 2005;5:165–90.
36. Deng Z, Chen Y, Zhang M, Li Y, Zhu X. The association of number and space under different tasks: insight from a process perspective. Front Psychol. 2018;9:957. https://doi.org/10.3389/fpsyg.2018.00957.
37. Jiang J, Yang X, Qi Y, et al. How do symbolic and non-symbolic spatial-numerical associations develop? Evidence from the parity judgment task and the magnitude comparison task. Curr Psychol. 2024;43:16572–90. https://doi.org/10.1007/s12144-023-05571-4.
38. Meiran N. Reconfiguration of processing mode prior to task performance. J Exp Psychol Learn Mem Cog. 1996;22(6):1423–42. https://doi.org/10.1037/0278-7393.22.6.1423.
39. Gray HM, Ambady N, Lowenthal WT, Deldin P. P300 as an index ofattention to self-relevant stimuli. J Exp Soc Psychol. 2004;40(2):216–24. https://doi.org/10.1016/s0022-1031(03)00092-1.
40. Nieuwenhuis S, Aston-Jones G, Cohen JD. Decision making, the P3, and the locus coeruleus-norepinephrine system. Psychol Bull. 2005;131(4):510–32. https://doi.org/10.1037/0033-2909.131.4.510.
41. Leng Y, Zhou X. Modulation of the brain activity in outcome evaluation by interpersonal relationship: an ERP study. Neuropsychologia. 2010;48(2):448–55. https://doi.org/10.1016/j.neuropsychologia.2009.10.002.
42. Wu Y, Leliveld MC, Zhou X. Social distance modulates recipient's fairnessconsideration in the dictator game: an ERP study. Biol Psychol. 2011;88(2):253–62.
43. Deng L, Li Q, Zhang M, Shi P, Zheng Y. Distinct neural dynamics underlying riskand ambiguity during valued-based decision making. Psychophysiology. 2022;13:e14201.
44. Ludowicy P, Czernochowski D, Weis T, Haese A, Lachmann T. Neural correlates of feedback processing during a sensory uncertain speech-nonspeech discrimination task. Biol Psychol. 2019;144:103.
45. Liu S, Hu X, Mai X. Social distance modulates outcome processing when comparing abilities with others. Psychophysiology. 2021;58(5):e13798.
46. Roettger TB, Domahs F. Grammatical number elicits SNARC and MARC effects as a function of task demands. Q J Exp Psychol. 2015;68(6):1231–48. https://doi.org/10.1080/17470218.2014.979843.
47. Zhou D, Luo J, Yi Z, Li Y, Yang S, Verguts T, Chen Q. The hand-lateralization of spatial associations in working memory and long-term memory. Q J Exp Psychol. 2020;73(8):1150–61. https://doi.org/10.1177/1747021819899533.
48. Faul F, Erdfelder E, Lang AG, Buchner A. G * power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39(2):175–91.
49. Aleotti S, Di Girolamo F, Massaccesi S, Priftis K. Numbers around descartes: a preregistered study on the three-dimensional SNARC effect. Cognition. 2020;195:104–11. https://doi.org/10.1016/j.cognition.2019.104111.
50. Cipora K, Göbel S M. Number-space associations: just how reliable is the SNARC effect [poster presentation]. 16th European Workshop on Cognitive Neuropsychology. 2013; https://osf.io/nx6vq/.
51. Georges C, Hoffmann D, Schiltz C. The SNARC effect and its relationship to spatial abilities in women [poster presentation]. 18th Conference of the European Society for Cognitive Psychology, Budapest, Hungary. 2013; http://hdl.handle.net/10993/13012.
52. Hedge C, Powell G, Sumner P. The reliability paradox: why robust cognitive tasks do not produce reliable individual differences. Behav Res Methods. 2018;50(3):1166–86. https://doi.org/10.3758/s13428-017-0935-1.
53. Roth L, Jordan V, Schwarz S, Willmes K, Nuerk HC, van Dijck JP, Cipora K. Don't SNARC me now! Intraindividual variability of cognitive phenomena – insights from the Ironman paradigm. Cognition. 2024;248:105781. https://doi.org/10.1016/j.cognition.2024.105781.
54. Viarouge A, Hubbard EM, McCandliss BD. The cognitive mechanisms of the SNARC effect: an individual differences approach. PloS One. 2014;9(4):e95756. https://doi.org/10.1371/journal.pone.0095756.
55. Tzelgov J, Zohar-Shai B, Nuerk HC. On defining quantifying and measuring the SNARC effect. Front Psychol. 2013;4:3–5. https://doi.org/10.3389/fpsyg.2013.00302.
56. Prpic V, Basamh YA, Goodridge CM, Agostini T, Murgia M. Contrasting symbolic and non-symbolic numerical representations in a joint classification task. Psychon Bull Rev. 2023;30(4):1422–30.
57. Prpic V, Felisatti A, Aagten-Murphy D, Lugli L, Fischer HM. Investigating numerical signatures with hierarchical Navon stimuli[abstract]. European Conference on Visual Perception (ECVP) 2024. Perception. 2024;181. https://journals.sagepub.com/page/pec/collections/ecvp-abstracts/index/ecvp-2024.
58. Cipora K, Soltanlou M, Reips UD, Nuerk HC. The SNARC and MARC effects measured online: large-scale assessment methods in flexible cognitive effects. Behav Res Methods. 2019;51(4):1–17.
59. Cipora K, van Dijck JP, Georges C, Masson N, Goebel SM, Willmes K, Pesenti M, Schiltz C, Nuerk HC. A minority pulls the sample mean: on the individual prevalence of robust group-level cognitive phenomena – the instance of the SNARC effect. PsyArXiv. 2019. https://doi.org/10.31234/osf.io/bwyr3.
60. Kok A. On the utility of P3 amplitude as a measure of processing capacity. Psychophysiology. 2001;38(3):557–77.
61. Polich J. Updating P300: an integrative theory of P3a and P3b. Clin Neurophysiol. 2007;118:2128–48. https://doi.org/10.1016/j.clinph.2007.04.019.
62. Keus IM, Jenks KM, Schwarz W. Psychophysiological evidence that the SNARC effect has its functional locus in a response selection stage. Cognitive Brain Res. 2005;24:48–56. https://doi.org/10.1016/j.cogbrainres.2004.12.005.
63. van Dijck JP, Gevers W, Fias W. Numbers are associated with different types of spatial information depending on the task. Cognition. 2009;113(2):248–53. https://doi.org/10.1016/j.cognition.2009.08.005.
64. Proctor RW, Cho YS. Polarity correspondence: a general principle for performance of speeded binary classification tasks. Psychol Bull. 2006;132(3):416–42. http://doi.apa.org/getdoi.cfm?doi=10.1037/0033-2909.132.3.416.

65. Verguts T, Notebaert W. Hebbian learning of cognitive control: dealing with specific and nonspecific adaptation. Psychol Rev. 2008;115(2):518. https://doi.org/10.1037/0033-295X.115.2.518.
66. Zhang P, Cao B, Li F. SNARC effect modulated by central executive control: revealed in a cue-based trisection task. Psychol Rev. 2021;85(6):2223–36. https://doi.org/10.1007/s00426-020-01407-z.
67. Braver TS. The variable nature of cognitive control: a dual mechanisms framework. Trends Cogn Sci. 2012;16(2):106–13. https://doi.org/10.1016/j.tics.2011.12.010.
68. Notebaert W, Gevers W, Verguts T, Fias W. Shared spatial representations for numbers and space: the reversal of the SNARC and the Simon effects. J Exp Psychol Human. 2006;32(5):1197. https://doi.org/10.1037/0096-1523.32.5.1197.
69. Hines TM. An odd effect: lengthened reaction times for judgments about odd digits. Mem Cogn. 1990;18:40–6. https://doi.org/10.3758/BF03202644.
70. Moyer RS, Landauer TK. Time required for judgements of numerical inequality. Nature. 1967;215(5109):1519–20.

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