Studia Psychologica, Vol. 66, No. 4, 2024, 267-285
https://doi.org/10.31577/sp.2024.04.905

Encoding Numbers When Numbers Rotate to the Left or Right Space: Evidence from the Spatial-Numerical Association of Response Codes (SNARC) Effect

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Although previous studies have investigated the relationship between the SNARC effect and the Simon effect, the results of these previous studies are inconsistent. In addition, when spatial cues are not overly prominent or salient, how spatial cues influence the SNARC effect is still unknown. The present study rotated Arabic numbers 45° to the left or right and randomly and centrally presented these rotated numbers for participants to investigate the above questions in an orientation task (experiment 1), parity task (experiment 2), and magnitude task (experiment 3). The results revealed that 1) the SNARC effect was absent, but a Simon-like effect was present in the orientation classification task. 2) The SNARC effect was present only in the orientation-response consistent condition but was absent in the orientation-response inconsistent condition in the numerical parity task (experiment 2) and numerical magnitude classification task (experiment 3). From these results, it can be concluded that 1) rotating numbers to the left or right can substantially influence the SNARC effect and that 2) how rotated orientation influences the SNARC effect is moderated by the task performed when numbers are rotated to the left or right. These results imply that even when spatial cues are not overly prominent or salient, numerical spatial cues can also impede the role of numerical visuospatial coding and numerical verbal-spatial coding in individual responses.

Key words: SNARC effect, orientation spatial association, working memory theory, mental number line, cognitive tasks

Introduction

Dehaene et al. (1993) presented Arabic numbers ranging from 1 to 9 (except 5) in the center of a display and asked participants to press the left or right button to make a categorical response to the presented numbers depending on the numerical parity. Regardless of the parity of the numbers, the participants usually responded faster to small numbers when pressing the left button and more quickly to

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Received January 10, 2024

large numbers when pressing the right button. Dehaene et al. named this phenomenon in numerical parity classification the spatial-numerical association of response codes (SNARC) effect.

Since Dehaene et al. (1993) first discovered the SNARC effect in numerical cognition, many subsequent studies have demonstrated this phenomenon in the processing of other types of symbolic numbers (e.g., Chinese numerical words) and nonsymbolic numbers (e.g., dice dot patterns), and their results further extended the SNARC effect to the processing of both symbolic numbers (Liu et al., 2004; Nuerk et al., 2005; Wang et al., 2020) and nonsymbolic numbers (Nuerk et al., 2005; Prpic et al., 2023; Wang et al., 2021b). Several studies have even captured the SNARC-like effect in processing nonsymbolic dimensions such as luminance (Fumarola et al., 2014; Wang et al., 2022a), size (Prpic et al., 2020), and angle (Fumarola et al., 2016). Notably, although the SNARC effect could be present in both numerical and nonsymbolic number cognition, generally, the size of the SNARC effect in numerical cognition is greater than that in nonsymbolic number cognition (Macnamara et al., 2018; Wood et al., 2008).

The visuospatial coding model regards the origin of the SNARC effect as the visual spatial representation of numbers in long-term memory or working memory; small numbers are represented on the left of the mental number line, and as the numerical magnitude increases or the numerical ordinal sequence moves later, the numerical representation position on the mental number line tends to the right, which leads to the SNARC effect (Abrahamse et al., 2014; Abrahamse et al., 2016; Dehaene et al., 1993; Dollman & Levine, 2015; Fumarola et al., 2014; van Dijck & Fias, 2011). The verbal-spatial coding model regards the origin of the SNARC effect as the result of the binary coding of numbers and responses (Gevers et al., 2010; Proctor & Cho, 2006). For example, the polarity correspondence theory suggests that participants code small and left as negative polarity and large and right as positive polarity, which leads to the SNARC effect (Proctor & Cho, 2006). Notably, visuospatial coding and verbal-spatial coding play a role in the SNARC effect only when numerical semantic information is accessed (Gevers et al., 2010).

However, as research on the SNARC effect has advanced, an increasing number of studies have shown that the SNARC effect does not always robustly appear in number processing; in fact, sometimes this SNARC effect could be absent (Cleland et al., 2020; van Dijck & Fias, 2011; Wang et al., 2022a; Wang et al., 2023) or even reversed in numerical cognition (Bächtold et al., 1998; Mingolo et al., 2021; Wang et al., 2018). For example, when participants imagined numbers as numbers on a clock face and compared them with 6 o'clock, smaller numbers elicited faster keypress responses in the right hand, while larger numbers elicited faster keypress responses in the left hand (Bächtold et al., 1998). Similarly, when participants were asked to judge the parity of numbers after activating a temporary sequence of numbers by continuously presenting a series of numbers, numerical magnitude did not systematically affect people's keypress responses; however, the numerically presented order could (numbers laid at the front of the presented sequence were responded to more quickly with the left hand, while numbers laid at the back of the presented sequence were responded to more quickly with the right hand) (van Dijck & Fias, 2011). These findings of the reversal or disappearance of the SNARC effect in number processing suggest that there are factors that moderate the influence of visuospatial coding or verbal-spatial coding of numbers on individual responses and thus influence the SNARC effect.

The processing of magnitude or sequence cues can systematically influence individual responses, and the processing of spatial cues can also systematically influence individual responses (Simon & Small, 1969; Jin et al., 2017; Shi et al., 2020; Wang et al., 2021a). For example, processing the left side could induce a faster response for the left hand, and processing the right side could induce a faster response for the right hand (Simon & Small, 1969). Given that the spatial information of stimuli could substantially influence individual responses, it is easy for us to determine whether spatial cues are valuable factors that moderate the SNARC effect.

In fact, numerical spatial cues were activated by presenting numbers on the left or right side of the screen or by obvious left or right information (e.g., left-right hand) to investigate the above questions. The results showed that processing spatial cues can substantially moderate the influence of number coding on individual responses (Bächtold et al., 1998; Cleland et al., 2020; Mingolo et al., 2021; Wang et al., 2021b; Wang et al., 2023). For example, when participants were asked to classify a triangle's orientation (upward or downward), neither the triangle's magnitude nor its surface area elicited the SNARC effect (Cleland et al., 2020; Prpic et al., 2020). Similarly, this SNARC effect was also absent in Chinese finger numbers when participants were asked to judge in which hand (left or right) the Chinese finger numbers were expressed (Wang et al., 2021b). The absence or reversal of the SNARC effect when numerical spatial cues are activated suggests that space is an important factor that can influence the SNARC effect; however, few studies support this conclusion (Lammertyn et al., 2002; Mapelli et al., 2003). For example, Mapelli et al. (2003) presented numbers on the left or right side of the screen for participants, who were asked to classify numbers according to numerical parity, and the results showed that the SNARC effect coexisted with the Simon effect. Moreover, when spatial cues are not overly prominent or salient, how spatial cues influence the SNARC effect is still unclear. Researching the influence of spatial cues on the SNARC effect under conditions in which spatial cues are not salient or prominent would help reveal the mechanism by which numerical spatial cues and numerical magnitude cues interact in the SNARC effect. Therefore, the present study aimed to activate numerical spatial cues by rotating the number 45° to the left or right. In this condition, the rotated direction can also provide a spatial cue for participants, but the spatial cue provided by rotated direction is less salient than that provided by left or right location, as in the Simon paradigm. Then, we investigated how the direction of rotation of numbers influences the SNARC effect across cognitive tasks.

Specifically, in Experiment 1 Arabic numbers 1-9 (except 5) were rotated 45° to the left or right and then randomly presented to participants who were asked to judge whether the numbers were rotated to the left or to the right to investigate the influence of the numerical spatial cue on the SNARC effect in the orientation classification task. In Experiment 2, participants were randomly presented with these rotated numbers and asked to judge the rotated numerical parity to further examine the influence of the numerical spatial cue on the SNARC effect in the numerical parity classification task. In Experiment 3, participants were randomly presented with these rotated numbers but were asked to judge whether the rotated numbers were smaller or larger than 5 to further examine the influence of the numerical spatial cue on the SNARC effect in the numerical magnitude classification task.

Experiment 1

Participants were asked to classify rotated Arabic numbers according to orientation to investigate the influence of the numerical spatial cue on the SNARC effect in the orientation classification task.

Methods

Participants

The sample size was estimated by G*Power 3.1. Referring to previous studies, we set the effect size to 0.25 (Wang et al., 2021a; Wang et al., 2022a). The results indicated that a sample size of 24 participants was needed for a 2 × 2 within-participant design to detect a moderate effect size (f = 0.25) at an adequate power level (80%) when the α err probability was 0.05 (the next two experiments of the present study are the same). Thirty university students (18 females and 12 males) were recruited from Huzhou University to participate in this experiment. All students were native speakers of Chinese and read and wrote from left to right. The average age was 18.33 years (*SD* = 1.81), and the ages ranged from 15 to 22 years. All participants volunteered to participate in the experiment and had normal or corrected-to-normal vision.

Stimuli and Apparatus

Eight Arabic numerals ranging from 1 to 9 (except 5) rotated 45° to the left or right were used as experimental stimuli. Each number was inlaid on a white background picture with 121×121 pixels, and the number size was 72 dots (see Figure 1). The experimental stimuli were presented on a 19-inch screen with a resolution of 1280×1024 pixels and a refresh rate of 60 Hz.

Experimental Design

A 2 (magnitude-response consistency: consistent, inconsistent) × 2 (orientation-response consistency: consistent, inconsistent) within-participants design was used. Responses 1, 2, 3 and 4 issued with the left hand and responses 6, 7, 8, and 9 issued with the right hand are considered magnitude-response consistent. Responses 1, 2, 3, and 4 issued with the right hand and responses 6, 7, 8 and 9 issued with the left hand are considered magnitude-response inconsistent. The SNARC effect was reflected by the significant difference between the magnitude-response consistent condition and the magnitude-response inconsistent condition. Numbers rotated to the left that are responded to with the left hand, and numbers rotated to the right that are responded to with the right hand are defined as orientation-response consistent. Numbers rotated to the left that are responded to with the right hand, and numbers rotated to the right that are responded to with the left hand are defined as orientation-response inconsistent. The orientation spatial association effect (Simon-like effect) was reflected by the significant difference between the orientation-response consistent condition and the orien-

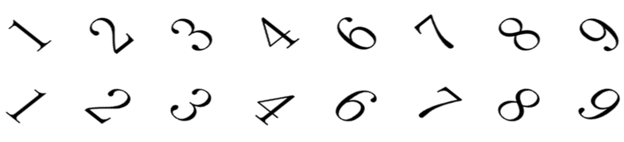

Figure 1 Rotated Arabic numbers used in the study. The numbers on the first line are rotated 45° to the left, and the numbers on the second line are rotated 45° to the right.

tation-response inconsistent condition. The dependent variables are response times (RTs) and error rate.

Procedure

The experimental program was written in E-prime 1.1. After the experiment started, a fixation point "+" appeared in the center of the display for 500 ms, followed by an Arabic number, ranged from 1-9 excluding 5 and rotated 45° to the left or right, at the position of the fixation point. When the numbers were presented, the participants were asked to judge whether the presented numbers were rotated to the left or to the right by pressing a button to respond as correctly and quickly as possible. After the participants responded, they were presented with a blank screen for 1500 ms and then entered the next trial. If the participants did not respond to the numbers within 3 s, the trial was considered an incorrect response and proceeded to the next trial after a blank screen for 1500 ms. The experiment consisted of two blocks. In one block, the participants were asked to press the left button with their left hand to respond to the numbers rotated to the left and to respond to the numbers rotated to the right by pressing the right button with their right hand. In the other block, the participants were asked to press the left button with the left hand to respond to the numbers rotated to the right and press the right button with the right hand to respond to the numbers rotated to the left. The order between the two blocks was balanced among the participants. Throughout the experiment, left rotated numbers and right rotated numbers were presented 6 times each, 3 times in each block, for a total of 96 times. There were 8 practice opportunities before the start of each block to help participants familiarize themselves with the experimental tasks. The entire experiment took approximately 10 minutes.

Results and Discussion

Error response and RT data beyond three standard deviations at each treatment level were excluded (4.55%), and repeated-measures ANOVA was performed on the remaining data. The results showed that the main effect of magnitude-response consistency was not significant, $F(1, 29) = 0.85$, $p = 0.36$, $\eta^2 = 0.029$, indicating that the SNARC effect was not elicited by numerical magnitude in the orientation classification task. The main effect of orientation-response consistency was significant, $F(1, 29) = 5.98$, $p = 0.02$, $\eta^2 = 0.171$. The responses in the orientation-response consistent trials (477 ± 16.18 ms) were significantly faster than those in the orientation-response inconsistent trials (516 ± 16.81 ms). This result indicates that the Simon-like effect was present in the rotated number orientation classification task (as shown in Figure 2). The interaction between magnitude-response consistency and orientation-response consistency was not significant, $F(1, 29) = 0.10$, $p = 0.75$, $\eta^2 = 0.003$, which indicates that the SNARC effect was not influenced by the Simon-like effect in the orientation classification task.

Both 3-second error response and no response trials were considered in the error rates. All trials were used to count the error rates (the following two experiments were the same). Repeated-measures ANOVA on the error rate revealed that the main effect of magnitude-response consistency was not significant, $F(1, 29) = 0.02$, $p = 0.90$, $\eta^2 = 0.001$, indicating that the SNARC effect could not be elicited by the numerical magnitude in the numerical orientation classification task. The main effect of orientation-response consistency was not significant, $F(1, 29) = 2.73$, $p = 0.11$, $\eta^2 = 0.086$, indicating that participants also did not associate orientation with response space in the orientation classification

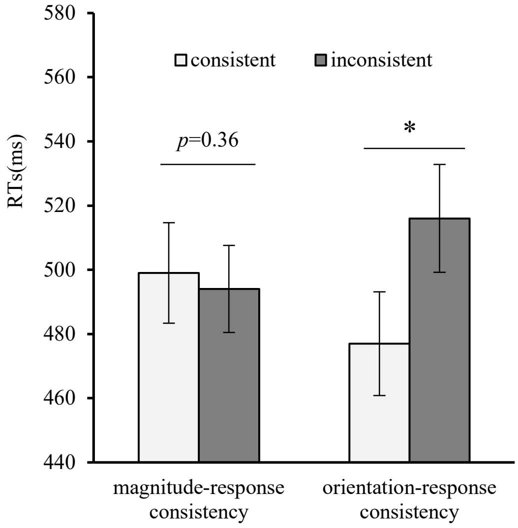

Figure 2 RTs and standard errors at each treatment level in the orientation classification task.

Table 1 *Error rate (%) and standard error at each treatment level in orientation classification*

	magnitude-response consistency	orientation-response consistency
consistent	2.8 ± 0.005	2.1 ± 0.005
inconsistent	2.8 ± 0.005	3.5 ± 0.007

task (as shown in Table 1). There was no significant interaction between magnitude-response consistency and orientation-response consistency, $F(1, 29) = 3.67$, $p = 0.07$, $\eta^2 = 0.112$, which indicates that the SNARC effect was not influenced by the Simon-like effect in the orientation classification task.

In Experiment 1, participants were asked to judge the rotated orientation to investigate the influence of the numerical spatial cue on the SNARC effect in an orientation classification task. In this task, participants paid direct attention to spatial cues; therefore, spatial cues of rotated numbers could be processed beforehand. The RT results revealed the Simon-like effect but not the SNARC effect in the orientation classification task. This result shows that when an additional spatial cue is provided for Arabic numbers, even when the spatial cue is not highly salient, the processing of an additional spatial cue can strongly inhibit the influence of numerical magnitude on individual responses when the spatial cue has been previously processed.

Experiment 2

The participants were asked to classify the rotated Arabic numbers depending on the numerical parity to investigate the influence of the numerical spatial cue on the SNARC effect in a numerical parity classification task.

Methods

Participants

Thirty-two students (25 females and 7 males) were recruited from Huzhou University to participate in this experiment. All students were native speakers of Chinese and read and wrote from left to right. The error rates of two participants exceeded 20%, so the data for these participants were excluded. There were 30 remaining valid participants. The average age was 19.75 years (*SD* = 1.95), and the age range was 18-24 years. All participants volunteered to participate in the experiment and had normal or corrected-to-normal vision.

Stimuli and Apparatus

The stimuli and apparatus were the same as those used in Experiment 1.

Experimental Design

A within-participants design of 2 (magnitude-response consistency: consistent, inconsistent) × 2 (orientation-response consistency: consistent, inconsistent) was used, and the dependent variables were RT and error rate. The definitions of magnitude-response consistency and orientation-response consistency in Experiment 2 were the same as those in Experiment 1.

Procedure

The experimental task of Experiment 2 was different from that of Experiment 1; however, the other aspects of Experiment 2 were the same as those of Experiment 1. Specifically, participants were asked to judge whether the presented rotated numbers were odd or even in Experiment 2. The formal experiment also included two blocks. In one block, participants were asked to respond to odd numbers by pressing the left button with their left hand and responded to even numbers by pressing the right button with their right hand. In the other block, participants were asked to respond to even numbers by pressing the left button with their left hand and to respond to odd numbers by pressing the right button with their right hand. The order of the two blocks was balanced between participants.

Results and Discussion

Error responses and RTs beyond three standard deviations at each treatment level were excluded (5.14%), and repeated-measures ANOVA was performed on the remaining data. The results showed that the main effect of magnitude-response consistency was not significant, $F(1, 29) = 2.61$, $p = 0.12$, $\eta^2 = 0.083$, which indicates that the SNARC effect was not elicited by the numerical magnitude cue in the numerical parity classification task. The main effect of orientation-response consistency was not significant, $F(1, 29) = 1.12$, $p = 0.30$, $\eta^2 = 0.037$, indicating that the Simon-like effect was also not elicited by orientation in the numerical parity classification task. The interaction effect between magnitude-response consistency and orientation-response consistency was significant, $F(1, 29) = 6.16$, $p = 0.02$, $\eta^2 = 0.175$, which suggests that the SNARC effect may interact with the Simon-like effect in rotated numerical parity classification. Further simple effect analysis revealed that the simple main effect of magnitude-response consistency was significant in the orientation-response consistent trials, $F(1, 29) = 11.62$, $p = 0.002$, $\eta^2 = 0.286$. The RTs in the magnitude-response consistent trials (539 ± 10.22 ms) were significantly faster than those in the magnitude-response inconsistent trials (565 ± 13.13 ms), indicating that there was a

SNARC effect in numerical processing under conditions of orientation-response consistency. The simple main effect of magnitude-response consistency was not significant in the orientation-response inconsistent trials, $F(1, 29) = 0.35$, $p = 0.56$, $\eta^2 = 0.012$, indicating that the SNARC effect did not appear in the numerical processing in the orientation-response inconsistent trials (as shown in Figure 3).

We also analyzed the Simon-like effect in the magnitude-response consistent condition and magnitude-response inconsistent condition. The results showed that the simple main effect of orientation-response consistency was not significant in the magnitude-response consistent trials, $F(1, 29) = 1.55$, $p = 0.224$, $\eta^2 = 0.051$, indicating that there was no Simon-like effect in numerical processing under conditions of magnitude-response consistency. The simple main effect of orientation-response consistency was significant in the magnitude-response inconsistent trials, $F(1, 29) = 7.13$, $p = 0.012$, $\eta^2 = 0.197$, and the RTs in the orientation-response consistent trials (565 ± 13.13 ms) were significantly slower than those in the magnitude-response inconsistent trials (543 ± 10.95 ms), indicating that there was a reverse Simon-like effect in numerical processing under magnitude-response inconsistent conditions (as shown in Figure 4).

Repeated-measures ANOVA for the error rate revealed that the main effect of magnitude-response consistency was not significant, $F(1, 29) = 0.02$, $p = 0.89$, $\eta^2 = 0.001$, indicating that the numerical magnitude cue did not elicit the SNARC effect in the numerical parity classification task. The main effect of orientation-response consistency was not significant, $F(1, 29) = 0.00$, $p = 1.00$, $\eta^2 < 0.001$, indicating that the orientation spatial association effect was not present in the numerical parity classification task (as shown in Table 2). The interaction between magnitude-response consistency and orientation-response consistency was not significant, $F(1, 29) = 1.25$, $p = 0.27$, $\eta^2 = 0.041$, indicating that the SNARC effect was not influenced by orientation-re-

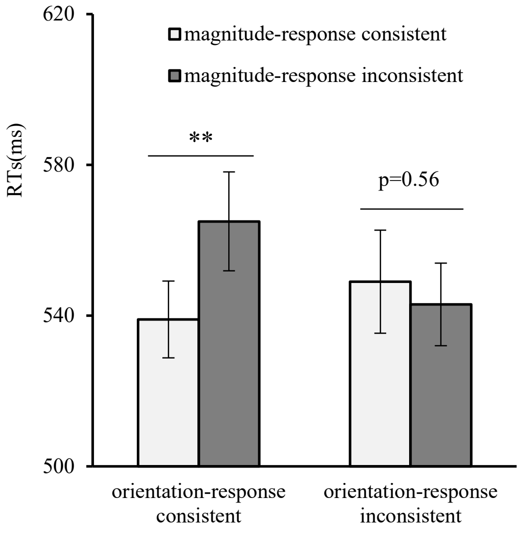

Figure 3 SNARC effect of orientation-response consistent and inconsistent conditions in numerical parity classification.

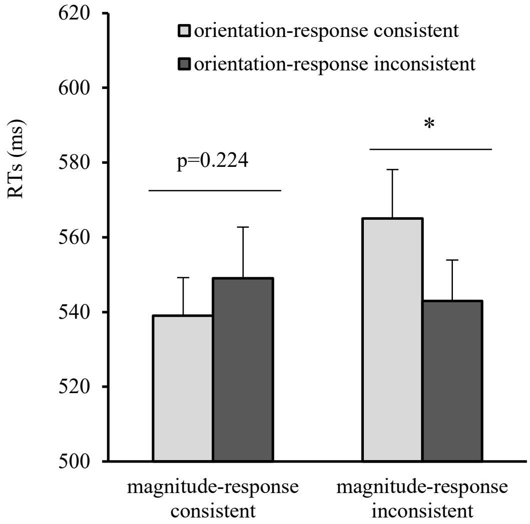

Figure 4 Simon-like effect of magnitude-response consistent and inconsistent condition respectively in numerical parity classification.

Table 2 *Error rates and standard errors at each treatment level in the numerical parity classification*

	magnitude-response consistency	orientation-response consistency
consistent	3.4 ± 0.006	3.5 ± 0.007
inconsistent	3.5 ± 0.008	3.5 ± 0.006

sponse consistency in the numerical parity classification.

In Experiment 2, participants were asked to judge the rotated numerical parity to investigate the influence of the numerical spatial cue on the SNARC effect in a numerical parity classification task. In this task, participants paid direct attention to numerical parity, rather than processing both spatial cues and the magnitude of rotated numbers. According to the RT results, the SNARC effect was moderated by orientation-response consistency in the numerical parity classification task. This shows that when an additional spatial cue was provided for Arabic numbers, even when the spatial cue was not directly attended, the spatial cue could also be processed, and the processing of additional spatial cues could still vividly influence the SNARC effect.

Experiment 3

Participants were asked to classify the rotated Arabic numbers depending on the numerical magnitude to investigate the influence of the numerical spatial cue on the SNARC effect in a numerical magnitude classification task.

Methods

Participants

Thirty-two students (21 females and 11 males) were recruited from Huzhou University to participate in this experiment. All students were native speakers of Chinese and read and wrote from left to right. The average age was 19.59 years (*SD* = 1.54), and the age range was 18-23 years. All participants volunteered to participate in this experiment and had normal or corrected-to-normal vision.

Stimuli and Apparatus

The stimuli and apparatus were the same as those used in Experiment 1.

Experimental Design

A 2 (magnitude-response consistency: consistent, inconsistent) × 2 (orientation-response consistency: consistent, inconsistent) within-participants design was adopted in this experiment. The dependent variables are RT and error rate. The definitions of magnitude-response consistency and orientation-response inconsistency are the same as in Experiment 1.

Procedure

Although the experimental task of Experiment 3 was different from that of Experiment 1, the other aspects of Experiment 3 were the same as those of Experiment 1. In Experiment 3, participants were asked to judge whether the presented numbers were smaller or larger than 5. The formal experiment also included two blocks. In one block, participants were asked to press the left button with their left hand to respond to numbers smaller than 5 and press the right button with their right hand to respond to numbers larger than 5. In the other block, participants were asked to press the left button with their left hand to respond to numbers larger than 5 and pressed the right button with their right hand to respond to numbers smaller than 5. The sequence of the two blocks is balanced among the participants.

Results and Discussion

Error response and RT data beyond three standard deviations at each treatment level were excluded (6.15%), and repeated-measures ANOVA was performed on the remaining data. The results show that the main effect of magnitude consistency is significant, $F(1, 31) = 8.23$, $p = 0.007$, $\eta^2 = 0.21$. The responses in the magnitude-response consistent trials (463 ± 9.31 ms) were significantly faster than those in the magnitude-response inconsistent trials (491 ± 11.78 ms), indicating that the SNARC effect appears in the rotated numerical magnitude classification task. The main effect of orientation-response consistency was not significant, $F(1, 31) = 0.18$, $p = 0.675$, $\eta^2 = 0.006$, indicating that the Simon-like effect was not present in the rotated numerical magnitude classification task. There was a significant interaction between magnitude-response consistency and orientation-response consistency, $F(1, 31) = 7.09$, $p = 0.012$, $\eta^2 = 0.186$. Further simple effects analysis revealed that the magnitude-response consistency simple main effect was significant under conditions of orientation-response consistency, $F(1, 31) = 13.75$, $p = 0.001$, $\eta^2 = 0.307$. RTs in the magnitude-response consistent condition (457 ± 9.07 ms) were significantly faster than those in the magnitude-response inconsistent condition (495 ± 12.43 ms), indicating that the SNARC effect appeared in the numerical magnitude classification when the orientation was consistent with the response space. The simple main effect of magnitude-response consistency was not significant in the orientation-response inconsistency condition, $F(1, 31) = 2.81$, $p = 0.104$, $\eta^2 = 0.083$, indicating that the SNARC effect was not present in the numerical magnitude classification when the orientation was not consistent with the response space (as shown in Figure 5).

We also analyzed the Simon-like effect in the magnitude-response consistent condition and magnitude-response inconsistent condition. The results showed that the simple main effect of orientation-response consistency was marginally significant in the magnitude-response consistent trials, $F(1, 31) = 4.06$, $p = 0.053$, $\eta^2 = 0.116$, and the RTs in the orientation-response consistent trials (457 ± 9.07 ms) were significantly faster than those in the magnitude-response inconsistent trials (469 ± 10.43 ms), indicating that there was a Simon-like effect in numerical processing under magnitude-response consistent conditions. The simple main effect of orientation-response consistency was not significant in the magnitude-response inconsistent trials, $F(1, 31) = 2.06$, $p = 0.162$, $\eta^2 = 0.062$, indicating that there was no Simon-like effect in numerical processing under magnitude-response inconsistent conditions (as shown in Figure 6).

Repeated-measures ANOVA for error rates revealed a significant main effect of magnitude-response consistency, $F(1, 31) = 8.95$, $p = 0.005$, $\eta^2 = 0.224$. The error rate in the magnitude-response consistent condition (2.9% ± 0.005) was significantly lower than that in the magnitude-response inconsistent condition (5.8% ± 0.009), indicating the presence of the SNARC effect in the numerical magnitude classification task. The main effect of orientation-response consistency was not significant, $F(1, 31) = 0.023$, $p = 0.881$, $\eta^2 = 0.001$, indicating that there was no Simon-like effect in the numerical magnitude classification task (as shown in Table 3). There was a significant interaction effect between magnitude-response consistency and orientation-response consistency, $F(1, 31) = 6.80$, $p = 0.014$, $\eta^2 = 0.18$. Further simple effect analysis revealed that under orientation-response consistent conditions, the simple main effect of magnitude-response consistency was significant, $F(1, 31) = 14.47$, $p = 0.001$, $\eta^2 = 0.303$. The error rate in the magnitude-response consistent condition (1.7% ± 0.005) was significantly

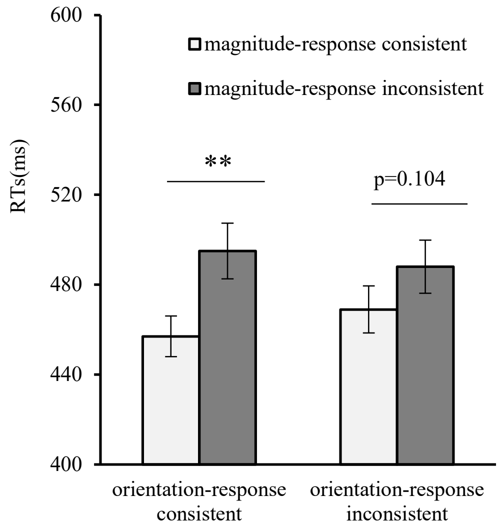

Figure 5 SNARC effect of orientation-response consistent and inconsistent conditions in numerical magnitude classification.

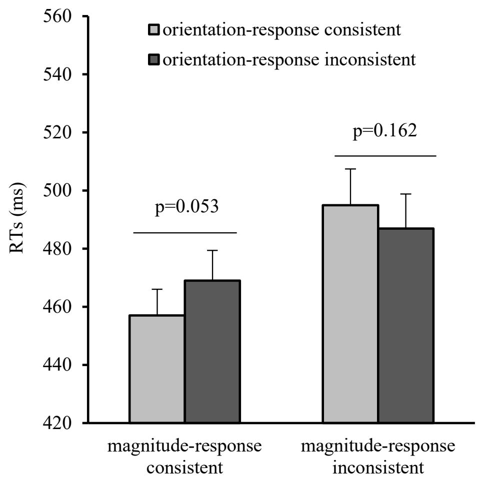

Figure 6 Simon-like effect of magnitude-response consistent and inconsistent condition respectively in numerical magnitude classification.

Table 3 *SNARC effect of orientation-response consistent and inconsistent conditions in numerical magnitude classification*

	orientation-response consistent	orientation-response inconsistent
magnitude-response consistent	1.7 ± 0.005	4.2 ± 0.008
magnitude-response inconsistent	7.2 ± 0.015	4.4 ± 0.009

lower than that in the magnitude-response inconsistent condition (7.2% ± 0.015). This finding indicated that the SNARC effect was present in the orientation-response consistent condition. The simple main effect of magnitude-response consistency was not significant under orientation-response is inconsistent conditions, $F(1, 31) = 0.04$, $p = 0.84$, $\eta^2 = 0.001$, indicating that the SNARC effect was not present in the orientation-response inconsistent condition (see Table 3).

Under magnitude-response consistent conditions, the orientation-response consistency simple main effect was significant, $F(1, 31) = 8.00$, $p = 0.008$, $\eta^2 = 0.205$. The error rate in the orientation-response consistent condition (1.7% ± 0.005) was significantly lower than that of the orientation-response inconsistent condition (4.2% ± 0.008). The Simon-like effect was present in the magnitude-response consistent condition. The simple main effect of magnitude-response consistency was not significant in the magnitude-response inconsistent condition, $F(1, 31) = 2.75$, $p = 0.107$, $\eta^2 = 0.082$, indicating that the Simon-like effect was not present in the magnitude-response inconsistent condition (see Table 4).

In Experiment 3, participants were asked to judge the rotated numerical magnitude to investigate the influence of the numerical spatial cue on the SNARC effect in a numerical magnitude classification task. In this task, participants were asked pay direct attention to numerical magnitude, allowing the magnitude of rotated numbers to be processed beforehand. Both the RT and error rate results revealed that the SNARC effect was moderated by orientation-response consistency in the numerical magnitude classification task. This shows that when an additional spatial cue is provided for Arabic numbers, even when the numerical magnitude is directly attended, the spatial cue can be processed; moreover, the processing of an additional spatial cue can still strongly influence the SNARC effect.

To further compare the SNARC effect sizes among the three experiments, we first quantified the size of the SNARC effect by the difference in RTs between the magnitude-response inconsistent and magnitude-response consistent conditions according to previous studies (Wang et al., 2022b; Wang et al., 2021a). That is, the magnitude-response inconsistency was subtracted from the magnitude-response inconsistency in each experiment (size of SNARC effect = inconsistent RTs-consistent RTs). Then, we performed a one-way analysis of variance, in which we took the SNARC effect size as the dependent variable and task as the independent variable. The results revealed that there

Table 4 *Simon-like effect of magnitude-response consistent and inconsistent condition in numerical magnitude classification*

	magnitude-response consistent	magnitude-response inconsistent
orientation-response consistent	1.7 ± 0.005	7.2 ± 0.015
orientation-response inconsistent	4.2 ± 0.008	4.4 ± 0.009

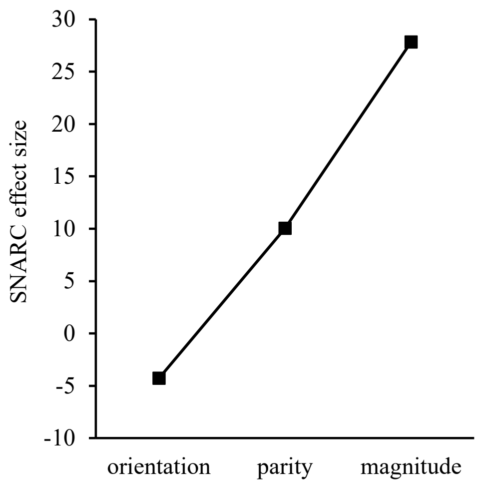

Figure 7 The SNARC effect size of the different tasks.

was a significant difference in the SNARC effect among tasks, $F(2, 91) = 4.91$, $p = 0.01$, and the SNARC effect sizes of numerical orientation, parity, and magnitude classification were -4.26, 10.05 and 27.84, respectively, indicating that the SNARC effect on numerical cognition was moderated by task. Furthermore, post hoc tests revealed that the SNARC effect on numerical magnitude classification was significantly larger than that on numerical orientation classification ($p = 0.002$) and marginally significantly larger than that on numerical parity classification ($p = 0.087$); moreover, the difference in the SNARC effect between numerical parity and numerical orientation classification was not significant ($p = 0.174$). The change trends of the SNARC effect with task performance are shown in Figure 7.

Discussion

Previous studies found that when people are asked to process a set of numbers and respond to them by pressing the left or right key, they associate specific numbers with specific response spaces, leading to the occurrence of the SNARC effect in numerical cognition (Abrahamse et al., 2014; Abrahamse et al., 2016; Dehaene et al., 1993; van Dijck & Fias, 2011). Previous studies have used visuospatial coding models (Dehaene et al., 1993; van Dijck & Fias, 2011) and verbal-spatial coding models (Gevers et al., 2010; Proctor & Cho, 2006); however, how numerical spatial cues influence the role of numerical visuospatial coding or numerical verbal-spatial coding on individual responses when spatial cues are contained in numbers has been undetermined. In addition, when spatial cues are not overly prominent or salient, how they influence the SNARC effect is still unclear; therefore, the present study aimed to provide additional spatial cues for numbers by rotating Arabic numbers 45° to the left or right and then systematically investigated the above questions.

The first experiment presented rotated Arabic numbers to participants who were asked to classify the rotated numbers according to orientation. The results revealed that the SNARC effect was absent in this experimental context; in contrast, the Simon-like effect was present. Previous studies found that the SNARC effect can stably and automatically survive in processing numbers even when the cognitive task is irrelevant to the numerical magnitude (Dehaene et al., 1993). Experiment 1 also explored Arabic numbers as experimental stimuli and found that the SNARC effect was absent in the orientation classification task. Obviously, the results of experiment 1 were different from those of previous studies (Dehaene et al., 1993). Compared with previous studies, the largest difference was that Experiment 1 provided additional spatial cues for Arabic numbers. The SNARC effect was absent in this experimental context, implying that even when the spatial cue was not overly prominent or salient, additional spatial cues can also impede the SNARC effect in the processing of Arabic numbers, when the numerical spatial cue is related to the cognitive task.

Most previous studies have shown that activating spatial cues on numbers can impede the SNARC effect (Bächtold et al., 1998; Jin et al., 2017; Mingolo et al., 2021). The first experiment of the present study activated numerical spatial cues by rotating the numbers to 45 degrees to the left or right and then investigated the SNARC effect in a numerical rotated direction classification task. The results showed that the SNARC effect was absent under these conditions. This result confirmed the conclusions of previous studies on the processing of numbers containing spatial cue (Bächtold et al., 1998; Jin et al., 2017; Mingolo et al., 2021) and further stressed that the spatial cues provided by numbers can substantially influence the SNARC effect.

Lammertyn et al. (2002) explored the SNARC effect as an extrinsic indicator deducing how numbers were processed to investigate how feature-based attention modulates visual processing. In their study, the authors presented upright numbers or numbers tilted 10 degrees to the right for participants who were asked to judge whether the probe number was upright or tilted; they also captured the SNARC effect in the processing of numbers. The first experiment of the present study rotated the numbers 45 degrees to the left or right, and the results revealed that the SNARC effect was absent in the numerical orientation classification. This gives the illusion that the results of the two studies are contradictory. In fact, in the present study, the numbers were rotated to the left or right, and thus led to the numbers containing left and right direction cues. Lammertyn et al. (2002) tilted numbers only 10 degrees to right; in this condition, the numbers did not contain either left or right direction cues. Therefore, the results of these two studies are not contradictory.

Previous studies regarded the origin of the SNARC effect to be numerical visuospatial coding (Dehaene et al., 1993; van Dijck & Fias, 2011) or to be explained by the verbal-spatial coding model (Gevers et al., 2010; Proctor & Cho, 2006). The first experiment of the present study presented numbers with spatial cue and asked participants to perform a space classification task; the results showed that the SNARC effect was absent. Combined with the results of the first experiment of the present study, it can be inferred that strongly activating spatial cues can impede the role of numerical visuospatial coding and numerical verbal-spatial coding in individual responses. In addition, when the numbers were rotated 45 degrees to the left or right, both the left-right spatial cue and magnitude cue were contained in the rotated numbers. Only the Simon-like effect was present in the rotated number rotation direction classification task, suggesting that the influence of spatial cue coding on individual responses was greater than the influence of numerical visuospatial coding and verbal-spatial coding on individual responses.

In the first experiment, an additional spatial cue was provided for Arabic numbers, and when participants were asked to directly process the additional spatial cue, strongly activated spatial cues impeded the numerical visuospatial coding and numerical verbal-spatial coding of individual responses; however, unfortunately, this finding was based only on the results of the spatial cue-relevant cognitive task. When a task involves irrelevant numerical spatial cues, can numerical spatial cues also impede the effects of numerical visuospatial coding and numerical verbal-spatial coding on individual responses? Therefore, experiments 2 and 3 of the present study further investigated the influence of the additional spatial cue of Arabic numbers on the SNARC effect in numerical parity classification and numerical magnitude classification tasks, respectively. Both experiment 2 and experiment 3 revealed that the SNARC effect and Simon-like effect interacted with each other. This finding is different from the results of experiment 1, which showed that only the Simon-like effect was present and that there was no interaction between the SNARC effect and the Simon-like effect. Obviously, when the cognitive task was irrelevant to the numerical spatial cue, the influence of the numerical spatial cue on the SNARC effect based on the numerical visuospatial coding and numerical verbal-spatial coding was different from that in the numerical spatial cue relevant task. To further establish whether the cognitive tasks can moderate the influence of the numerical spatial cue on the SNARC effect, we compared the size of the SNARC effect among different cognitive tasks and we found that the size of the SNARC effect was different from the cognitive tasks. Specifically, the size of SNARC effect is the largest in the numerical magnitude classification task, the second in the numerical parity classification task, and the smallest in the orientation classification task. These results imply that the way numerical visuospatial coding and numerical verbal-spatial coding influence individual responses when a spatial cue is contained in a number is moderated by the cognitive task.

To further analyze how numerical spatial cues influence numerical visuospatial coding and numerical verbal-spatial coding, when interactions between the SNARC effect and Simon-like effect were captured, we further analyzed the SNARC effect in the Simon consistent condition and Simon inconsistent condition. Similarly, we further analyzed the Simon-like effect in the SNARC-consistent condition and the SNARC-inconsistent condition. In experiment 2, the SNARC effect was present in the Simon-like consistent condition but absent in the Simon-like inconsistent condition. The Simon-like effect was absent in the SNARC consistent condition but reversed in the SNARC-inconsistent condition. In experiment 3, the results showed that the SNARC effect was also present in the Simon-like consistent condition but absent in the Simon-like inconsistent condition. The Simon-like effect was present in the SNARC consistent condition but absent in the SNARC-inconsistent condition. Several previous studies suggested that the Simon effect and SNARC effect do not interact with each other (Jin et al., 2017; Mapelli et al., 2003), as also suggested by the first experiment of the present study. However, when the task was changed to classify the numerical parity and numerical magnitude, the SNARC effect and Simon-like effect interacted. The tasks were different, but the stimuli were the same among these three experiments in the present study. Furthermore, the tasks of the current study and the studies of Mapelli et al. (2003) and Jin et al. (2017) were the same, but the stimuli differed between these studies and experiment 2 of the present study. The difference in the results among these studies implies that the relationship between the SNARC effect and the Simon effect is very flexible. The task, stimuli and nature of the spatial cue might influence the relationship between the SNARC effect and the Simon effect.

Numbers contain both semantic information and other features, such as fonts, colors, and spatial cues. Previous studies suggested that the SNARC effect occurs because of numerical visuospatial coding (Dehaene et al., 1993; van Dijck & Fias, 2011) or numerical verbal-spatial coding (Gevers et al., 2010; Proctor & Cho, 2006). Moreover, only numerical semantic information has been accessed, and the role of visuospatial coding and verbal-spatial coding in the SNARC effect has come into play (Gevers et al., 2010). The present study rotated the numbers 45 degrees to the left or right, and the results showed that the direction of numerical rotation could influence the SNARC effect across all of the tasks; in addition, they showed how the direction of numerical rotation influence the SNARC effect was moderated by the cognitive task. These results similarly imply that individuals can process numerical space while processing numerical semantics and that numerical space and numerical semantics compete for cognitive resources. Even when the cognitive task was directly related to the numerical space, numerical spatial cues could be previously accessed by the agent cognitive system and thus were first processed by individuals. The previous processing of numerical spatial cues could lead to numerical semantic information not being accessed and processed by individuals in a timely manner, thus impeding the influence of numerical visual spatial representation on individual responses. This result means that when the processing path of numerical semantic information is blocked, visual spatial coding and semantic spatial coding may be affected, thus inhibiting the SNARC effect in the processing of numbers. This also explains the flexibility of the SNARC effect.

Conclusion

How numerical spatial cue (e.g., Location) influences the SNARC effect is a research hotspot in the field of number cognition. Although previous studies have investigated the relation between the SNARC effect and the Simon effect, the results of these previous studies are inconsistent. In addition, no study investigated how spatial cues influence the SNARC effect when spatial cues are not overly prominent or salient. The present study investigated the relationship between the SNARC effect and the Simon-like effect under the condition of the numerical spatial cue being prominent or salient. The following conclusions can be drawn from the research: 1) rotating numbers can vividly influence the SNARC effect in the processing of numbers, and 2) how rotated orientation influences the SNARC effect is moderated by the task performed when numbers are rotated to left or right. These results imply that even when spatial cues are not overly prominent or salient, numerical spatial cues can also impede the role of numerical visuospatial coding and numerical verbal-spatial coding in individual responses. The result firstly reveals the relation between the SNARC effect and Simon-like effect under the condition of the numerical spatial cue being prominent or salient.

Acknowledgement

This research was supported by the Project of Zhejiang Province Philosophy and Social Science under Grant (23NDJC046Z).

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