Onset Stage of the Numerical SNARC Effect

Authors: Wang Chengcheng, Zhao Yufei, Sheng Yingying, Qingbai Zhao, Xiao Mengshi, Han Lei, Xiao Mengshi, Han Lei

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Abstract

Current findings regarding whether the numerical SNARC effect occurs in the early stimulus representation stage or the late response selection stage are inconsistent. The present study investigated its locus of occurrence through three experiments. Using a global-local paradigm, we constructed a composite experimental stimulus—an arrow composed of numbers—and employed it as experimental material, requiring participants to compare numerical magnitude (where the global precedence representation of arrow direction interferes with the spatial representation of numbers) and to judge arrow direction (where the arrow direction judgment task generates response competition with number processing at the response selection stage). The results revealed that interfering with the spatial representation of numbers in the horizontal direction impeded the generation of the numerical SNARC effect (Experiment 1a); interfering with the spatial representation of numbers in the vertical direction had no impact on the numerical SNARC effect (Experiment 1b); and interfering with the response selection stage impeded the generation of the numerical SNARC effect (Experiment 2). The experimental results demonstrate that both the stimulus representation stage and the response selection stage of number processing interference affect the generation of the numerical SNARC effect, supporting a dual-stage processing model of the numerical SNARC effect.

Full Text

Preamble

Occurrence Stage of the Digital SNARC Effect

WANG Chengcheng[1,2,3], ZHAO Yufei[1], SHENG Yingying[2,3], ZHAO Qingbai[2,3], XIAO Mengshi[1], HAN Lei[1]

([1] School of Psychology, Shandong Normal University, Jinan 250000, China)
([2] Key Laboratory of Adolescent Cyberpsychology and Behavior (CCNU), Min-

istry of Education; [3] Key Laboratory of Human Development and Mental Health of Hubei Province, School of Psychology, Central China Normal University, Wuhan 430079, China)

Abstract

Current research yields inconsistent findings regarding whether the digital SNARC effect occurs during early stimulus representation stages or late response selection stages. This study investigated its occurrence stage through three experiments. Using a global-local paradigm, we constructed a novel compound stimulus—arrows composed of numbers—and employed it as experimental material. Participants were asked to either compare numerical magnitudes (where the global precedence of arrow direction interferes with the spatial representation of numbers) or judge arrow direction (where arrow direction judgment competes with number processing during response selection). Results showed that horizontal interference with number spatial representation hindered the SNARC effect (Experiment 1a), vertical interference had no impact (Experiment 1b), and interference at the response selection stage blocked the SNARC effect (Experiment 2). These findings demonstrate that both stimulus representation and response selection stages influence the SNARC effect, supporting a dual-stage processing model.

Keywords: global-local paradigm, digital SNARC effect, early stimulus representation stage, late response selection stage

Dehaene et al. (1990) serendipitously discovered that when judging numerical magnitude, left-hand responses are faster for small numbers while right-hand responses are faster for large numbers. Dehaene et al. (1993) further investigated this phenomenon using a parity judgment task and found that the association between number magnitude and spatial location persisted even with crossed hands (i.e., when participants responded with left hand on right key and right hand on left key). They termed this association the Spatial-Numerical Association of Response Codes (SNARC) effect, which has since attracted considerable research attention and demonstrated broad universality (Xu & Liu, 2006; Kang et al., 2013; Yan et al., 2022).

However, the occurrence stage of the digital SNARC effect remains controversial. Some researchers argue it occurs during early stimulus representation stages (Fischer et al., 2004; Tlauka, 2002), others propose it emerges during late response selection stages (Gevers et al., 2005; Gevers, Ratinckx et al., 2006; Keus et al., 2005; Keus & Schwarz, 2005), while a third group suggests it occurs in both stages simultaneously (Nan et al., 2021; Xiang et al., 2022; Yan et al., 2022).

Current research primarily employs additive reaction time paradigms to investigate the SNARC effect's occurrence stage (Tlauka, 2002; Gevers et al., 2005; Nan et al., 2021). Based on Sternberg's (1969) additive factors logic, if two cognitive processes show an interaction, they occur in the same processing stage; if they are independent, they occur in different stages. The classic Stroop effect (Stroop, 1935) has been verified to occur during stimulus representation stages (Li et al., 2014; Scerrati et al., 2017), while the classic Simon effect (Simon & Rudell, 1967) occurs during response selection stages. Accordingly, if the SNARC effect is independent of the Stroop/Simon effect, it occurs during response selection/stimulus representation; if they interact, it occurs during stimulus representation/response selection. Tlauka (2002) presented numbers "1" and "100" (Experiment 1) and "100" and "900" (Experiment 2) on either side of the screen, requiring left/right key responses. Both SNARC and Simon effects were found and considered independent, leading to the conclusion that the SNARC effect occurs during stimulus representation. In contrast, Gevers et al. (2005) found interactions between SNARC and Simon effects in both magnitude-irrelevant (parity judgment; Experiment 1) and magnitude-relevant (magnitude comparison; Experiment 2) tasks, concluding that the SNARC effect occurs during response selection. Recent research increasingly points to dual-stage occurrence. For example, Nan et al. (2021) conducted two experiments based on additive factors logic and found interactions between SNARC and Stroop effects (Experiment 1) and between SNARC and Simon effects (Experiment 2), concluding that the SNARC effect exists in both stages. Xiang et al. (2022) conducted four experiments building on Nan et al. (2021) and Yan et al. (2021), finding that interference information magnitude relevance (introducing magnitude Stroop effect in parity judgment tasks) rather than quantity information task relevance (introducing parity Stroop effect in magnitude comparison tasks) was the key factor affecting the SNARC effect's occurrence stage, again supporting dual-stage processing.

Thus, while additive reaction time paradigms have yielded rich evidence, conclusions remain inconsistent. One possible reason is that different studies employ different stimuli and tasks while applying the same "golden rule" (additive factors logic). This singular approach neglects attention to specific processing components within particular experimental tasks, hindering comparison and integration across studies. The present study addresses this gap by using the global-local paradigm to innovatively construct compound stimuli—arrows composed of numbers—and manipulating attention toward local information (magnitude comparison task; Experiment 1) and global information (arrow direction judgment task; Experiment 2). This approach allows us to examine how interference with number processing at stimulus representation and response selection stages affects the SNARC effect, thereby identifying its occurrence stage.

Navon (1977) discovered that when intentionally perceiving local features, individuals are influenced by global features—a phenomenon termed global precedence. By using numbers as local information and arrows as global features in a magnitude comparison task, global precedence predicts that arrow direction will be preferentially represented, interfering with number spatial representation. This allows investigation of how stimulus representation stage interference affects the SNARC effect. Specifically, if the SNARC effect disappears under these conditions, it suggests that the stimulus representation stage plays a decisive role. Do both horizontal and vertical arrows interfere with number spatial representation? According to Dehaene et al.'s (1993) mental number line (MNL) theory, numbers are mentally represented along a left-to-right axis. Therefore, horizontal arrows can interfere with number spatial representation and affect the SNARC effect, whereas vertical arrows cannot interfere with horizontal spatial representation and thus cannot influence the SNARC effect. Experiments 1a and 1b tested this hypothesis. In Experiment 2, using number-composed arrows in a direction judgment task, numbers could be automatically processed and generate MNL representations (Dehaene & Akhavein, 1995; Gevers, Verguts et al., 2006; Casarotti et al., 2007; Yan et al., 2022), and unconscious information can have stimulus representation (Luo et al., 2018). Thus, numbers could be fully spatially represented unconsciously. However, because the task required arrow direction judgment, number processing and arrow direction processing would compete during response selection, allowing investigation of how response selection stage interference affects the SNARC effect. If the SNARC effect disappears under these conditions, it suggests that the response selection stage plays a decisive role.

Experiment 1a

2.1.1 Participants

Forty university students (27 female, 13 male) were recruited from Shandong Normal University. Ages ranged from 19 to 35 years (M = 22.03, SD = 2.93). All participants had normal or corrected-to-normal vision, no color blindness, no history of mental illness, were right-handed, ethnically Han Chinese, and had not participated in similar experiments previously. They received compensation upon completion.

2.1.2 Experimental Design

A within-subjects design with 2 (Number magnitude: small, large) × 3 (Arrow direction: left, right, left-right bidirectional) × 2 (Response hand: left, right) was employed. Small numbers were Arabic digits 1 and 2; large numbers were 8 and 9. Dependent variables were accuracy and reaction time.

2.1.3 Materials

Stimuli were arrows composed of Arabic digits 1/2/8/9. Materials were created using Photoshop CS6 with Times New Roman font, 48-point black digits presented at screen center. Participants sat 70 cm from the monitor with a visual angle of 10° × 6°. Screen resolution was 1024 × 768 pixels, black background, 60 Hz refresh rate. Materials are shown in Figure 1 [Figure 1: see original paper].

2.1.4 Procedure

The experiment was programmed in E-prime 2.0. Participants placed their left index finger on the "F" key and right index finger on the "J" key. Each trial began with a 500 ms fixation cross "+", followed by a number-composed arrow. Participants compared the constituent number to 5 and responded accordingly, followed by a 1500 ms blank screen before the next trial. The experiment comprised two blocks: in Block 1, "F" indicated numbers < 5 and "J" indicated numbers > 5; these mappings were reversed in Block 2. Block order was counterbalanced across participants. Each block included 12 practice trials and 144 experimental trials, with self-paced breaks between blocks (press "P" to continue). The entire experiment lasted approximately 16 minutes.

2.2 Results and Analysis

Accuracy rates for each condition are shown in Table 1 . As the task was relatively simple, descriptive statistics showed accuracy > 95% across all conditions, so no further inferential analysis was conducted on accuracy. Error rates ranged from 0.35% to 14.93% (M = 4.31%, SD = 0.03%). Trials with incorrect responses, reaction times > 1000 ms, or RTs beyond 3 SD from the mean were excluded (4.94% of data). Remaining RTs are shown in Table 2 .

A three-way repeated-measures ANOVA on remaining RTs revealed no significant main effects of number magnitude, $F(1, 39) = 0.821$, $p = 0.370$, $^2p = 0.021$; arrow direction, $F(2, 78) = 2.429$, $p = 0.095$, $^2p = 0.059$; or response hand, $F(1, 39) = 0.079$, $p = 0.780$, $^2p = 0.002$. Critically, the Number magnitude × Response hand interaction was not significant, $F(1, 39) = 0.274$, $p = 0.604$, $^2p = 0.007$, indicating no SNARC effect. The three-way interaction was also non-significant, $F(2, 78) = 1.136$, $p = 0.326$, $^2p = 0.028$, suggesting the SNARC effect did not differ across arrow direction conditions.

The Arrow direction × Response hand interaction was significant, $F(2, 78) = 84.281$, $p < 0.001$, $^2p = 0.684$. As shown in Figure 2 [Figure 2: see original paper], simple effects analysis revealed that for left-pointing arrows, left-hand responses were significantly faster than right-hand, $F(1, 39) = 61.378$, $p < 0.001$, $^2p = 0.611$; for right-pointing arrows, right-hand responses were significantly faster than left-hand, $F(1, 39) = 34.228$, $p < 0.001$, $^2p = 0.467$; for bidirectional arrows, no difference emerged between hands, $F(1, 39) = 0.534$, $p = 0.469$, $^2p = 0.014$.

The Number magnitude × Arrow direction interaction was significant, $F(2, 78) = 4.234$, $p = 0.018$, $^2p = 0.098$. As shown in Figure 3 [Figure 3: see original paper], simple effects analysis indicated that for left-pointing arrows, responses to small numbers were faster than to large numbers, $F(1, 39) = 7.433$, $p = 0.010$, $^2p = 0.160$; no such differences appeared for right-pointing or bidirectional arrows (both ps > 0.05).

Bayes factors provide a method for model comparison and hypothesis testing in Bayesian statistics, simultaneously showing support for null (H_0) and alternative (H_1) hypotheses and enriching psychological research (Wang et al., 2023; Hu et al., 2018; Wu et al., 2018). Building on traditional hypothesis testing, we conducted Bayesian ANOVA using JASP to quantify evidence for H_0 and H_1.

Following established criteria for Bayes factor magnitude (Jeffreys, 1961; Wagenmakers et al., 2017), Bayesian three-way repeated-measures ANOVA showed moderate evidence against main effects of number magnitude (BF_{incl} = 0.269), arrow direction (BF_{incl} = 0.221), and response hand (BF_{incl} = 0.253). There was extreme evidence against the three-way interaction (BF_{incl} = 2.918×10^{-4}) and weak evidence for the Number magnitude × Arrow direction interaction (BF_{incl} = 1.967). Most importantly, there was extreme evidence for the Arrow direction × Response hand interaction (BF_{incl} = 1.867×10^{17}) and extreme evidence against the Number magnitude × Response hand interaction (BF_{incl} = 0.008), confirming absence of the SNARC effect.

2.3 Discussion

Experiment 1a failed to show a SNARC effect but demonstrated a Simon-like effect. According to global precedence theory (Navon, 1977), the global representation of horizontal arrow directions interfered with local number spatial representation, preventing SNARC effect emergence. This suggests the stimulus representation stage is decisive for SNARC effect generation. The left-right arrows preferentially activated left-right response codes that corresponded with left-right hand responses, producing a Simon-like effect (faster left-hand responses to left arrows and right-hand responses to right arrows).

Experiment 1a also revealed a Number magnitude × Arrow direction interaction, specifically that left arrows accelerated small number judgments or interfered with large number judgments. This indicates interactive processing between global and local information, jointly influencing responses. It supports our assumption that global processing affects local processing in early stages, consistent with He et al. (2015), who used local Arabic digits forming global Arabic digits in magnitude comparison tasks. They found no global processing advantage and proposed that global features may be processed early in perception, with local processing catching up later, potentially eliminating the global advantage by task completion.

Experiment 1b

3.1.1 Participants

Forty university students (25 female, 15 male) were recruited from Shandong Normal University. Ages ranged from 18 to 25 years (M = 20.58, SD = 1.81). All had normal or corrected-to-normal vision, no color blindness, no mental illness history, were right-handed, ethnically Han Chinese, and experiment-naive. They received compensation upon completion.

3.1.2 Experimental Design

A within-subjects design with 2 (Number magnitude: small, large) × 3 (Arrow direction: up, down, up-down bidirectional) × 2 (Response hand: left, right) was used. Small numbers were digits 1 and 2; large numbers were 8 and 9. Dependent variables were accuracy and reaction time.

3.1.3 Materials

Stimuli were arrows composed of Arabic digits 1/2/8/9. Created with Photoshop CS6 using Times New Roman font, 48-point black digits at screen center. Participants sat 70 cm from the monitor (visual angle: 4.4° × 9°). Screen resolution was 1024 × 768 pixels, black background, 60 Hz refresh rate. Materials are shown in Figure 4 [Figure 4: see original paper].

3.1.4 Procedure

Programmed in E-prime 2.0, the task and procedure matched Experiment 1a except for stimulus orientation. The experiment lasted approximately 16 minutes.

3.2 Results and Analysis

As shown in Table 3 , accuracy exceeded 97% across all conditions. Error rates ranged from 0.35% to 22.22% ($M = 4.01\%$, $SD = 0.05\%$). Trials with errors, RTs > 1000 ms, or RTs beyond 3 SD were excluded (4.64% of data). Remaining RTs are shown in Table 4 .

A three-way repeated-measures ANOVA revealed no significant main effects of number magnitude, $F(1, 39) = 0.581$, $p = 0.451$, ${}^2p = 0.015$, or arrow direction, $F(2, 78) = 0.609$, $p = 0.547$, ${}^2p = 0.015$. The main effect of response hand was significant, with right-hand responses faster than left-hand, $F(1, 39) = 7.028$, $p = 0.012$, ${}^2p = 0.153$. The Number magnitude × Arrow direction interaction was not significant, $F(2, 78) = 0.559$, $p = 0.574$, ${}^2p = 0.014$, nor was the three-way interaction, $F(2, 78) = 0.017$, $p = 0.983$, ${}^2p < 0.001$.

The Arrow direction × Response hand interaction was significant, $F(2, 78) = 4.258$, $p = 0.018$, ${}^2p = 0.098$. Simple effects analysis showed no difference between hands for up arrows, $F(1, 39) = 1.103$, $p = 0.300$, ${}^2p = 0.028$; significantly faster right-hand responses for down arrows, $F(1, 39) = 13.501$, $p = 0.001$, ${}^2p = 0.257$; and no difference for bidirectional arrows, $F(1, 39) = 2.144$, $p = 0.151$, ${}^2p = 0.052$.

Critically, the Number magnitude × Response hand interaction was significant, $F(1, 39) = 15.939$, $p < 0.001$, ${}^2p = 0.290$, indicating a robust SNARC effect. As shown in Figure 5 [Figure 5: see original paper], simple effects revealed faster left-hand responses to small numbers, $F(1, 39) = 19.019$, $p < 0.001$, ${}^2p = 0.328$, and faster right-hand responses to large numbers, $F(1, 39) = 9.055$, $p = 0.005$, ${}^2p = 0.188$.

Bayesian three-way ANOVA showed moderate evidence against number magnitude (BF_{incl} = 0.288) and arrow direction (BF_{incl} = 0.086) main effects, and moderate evidence for response hand (BF_{incl} = 4.686). There was moderate evidence against the Number magnitude × Arrow direction interaction (BF_{incl} = 0.120) and strong evidence against the three-way interaction (BF_{incl} = 0.082). Most importantly, there was very strong evidence for the Number magnitude × Response hand interaction (BF_{incl} = 64.391), confirming the SNARC effect, and weak evidence for the Arrow direction × Response hand interaction (BF_{incl} = 2.463).

3.3 Discussion

Experiment 1b demonstrated a clear SNARC effect, indicating that vertical arrow interference with number spatial representation does not affect the SNARC effect. This supports Dehaene et al.'s (1993) mental number line theory.

In Experiment 1a, the Arrow direction × Response hand interaction reflected a Simon-like effect. In contrast, Experiment 1b's interaction only showed a right-hand advantage for down arrows, suggesting that right-handedness primarily manifested when stimuli were downward-pointing, rather than reflecting a true Simon effect.

Experiment 2

4.1.1 Participants

Forty university students (25 female, 15 male) were recruited from Shandong Normal University. Ages ranged from 18 to 27 years ($M = 21.20$, $SD = 1.99$). All had normal or corrected-to-normal vision, no color blindness, no mental illness history, were right-handed, ethnically Han Chinese, and experiment-naive. They received compensation upon completion.

4.1.2 Experimental Design

A within-subjects design with 3 (Local information: small number, large number, special character) × 2 (Arrow direction: left, right) × 2 (Response hand: left, right) was employed. Small and large number conditions used the same materials as Experiment 1; special characters were asterisks "*". Dependent variables were accuracy and reaction time.

4.1.3 Materials

For small and large number conditions, stimuli were left/right arrows composed of digits (Figure 1). For the special character condition, stimuli were arrows composed of asterisks (Figure 6 [Figure 6: see original paper]). Created with Photoshop CS6 using Times New Roman font, 48-point black characters at screen center. Participants sat 70 cm from the monitor (visual angle: 10° × 6°). Screen resolution was 1024 × 768 pixels, black background, 60 Hz refresh rate.

4.1.4 Procedure

Participants placed left and right index fingers on “F” and “J” keys, respectively. Each trial began with a 500 ms fixation cross “+”, followed by a number/character-composed arrow. Participants judged arrow direction and responded accordingly, followed by a 1500 ms blank screen. The experiment comprised two blocks: in Block 1, left arrows required “F” and right arrows “J”; these mappings were reversed in Block 2. Block order was counterbalanced. Each block included 10 practice trials and 100 experimental trials, with self-paced breaks between blocks. The experiment lasted approximately 12 minutes.

4.2 Results and Analysis

As shown in Table 5 , accuracy exceeded 97% across all conditions. Error rates ranged from 0% to 5.42% (M = 1.60%, SD = 0.01%). Trials with errors, RTs > 1000 ms, or RTs beyond 3 SD were excluded (2.47% of data). Remaining RTs are shown in Table 6 .

A three-way repeated-measures ANOVA revealed a significant main effect of local information, $F(2, 78) = 4.162$, $p = 0.019$, $^2p = 0.096$, with faster responses to large-number arrows than small-number arrows. Arrow direction main effect was not significant, $F(1, 39) = 2.169$, $p = 0.149$, $^2p = 0.053$. Response hand main effect was significant, with right-hand responses faster than left-hand, $F(1, 39) = 4.271$, $p = 0.045$, $^2p = 0.099$. No significant two-way or three-way interactions emerged (all ps > 0.05).

The Arrow direction × Response hand interaction was significant, $F(1, 39) = 58.512$, $p < 0.001$, $^2p = 0.600$. As shown in Figure 7 [Figure 7: see original paper], simple effects showed faster left-hand responses to left arrows, $F(1, 39) = 63.258$, $p < 0.001$, $^2p = 0.619$, and faster right-hand responses to right arrows, $F(1, 39) = 39.396$, $p < 0.001$, $^2p = 0.503$.

Bayesian three-way ANOVA showed weak evidence against local information (BF_{incl} = 0.676) and arrow direction (BF_{incl} = 0.566) main effects, and weak evidence for response hand (BF_{incl} = 1.336). There was strong evidence against the Local information × Arrow direction interaction (BF_{incl} = 0.087) and moderate evidence against the three-way interaction (BF_{incl} = 0.203). Critically, there was extreme evidence for the Arrow direction × Response hand interaction (BF_{incl} = 1.927×10^6), with extreme evidence for this interaction regardless of whether local information was numbers (BF_{incl} = 3.142×10^6) or special characters (BF_{incl} = 1.731×10^{15}).

4.3 Discussion

Experiment 2 showed that when using number-composed arrows in a direction judgment task, the SNARC effect disappeared, demonstrating that the response selection stage plays a crucial role in SNARC effect generation.

General Discussion

Previous research yields inconsistent results regarding whether the SNARC effect occurs in early stimulus representation or late response selection stages. Using the global-local paradigm, we constructed compound stimuli—arrows composed of numbers—and manipulated attention toward local information (magnitude comparison; Experiment 1) and global information (arrow direction judgment; Experiment 2) to examine how interference at stimulus representation and response selection stages affects the SNARC effect. This represents one of few studies investigating SNARC effect occurrence from specific cognitive processing perspectives. Results show that interference at both stages blocks the SNARC effect, supporting the dual-stage processing model (Yan et al., 2022). This model (Figure 8 [Figure 8: see original paper]) depicts task-relevant (Figure 8-A) and task-irrelevant (Figure 8-B) processing pathways, proposing that interference at any processing link affects SNARC effect generation. In Experiment 1a, we interfered with the pathway from magnitude to spatial representation in Figure 8-A; in Experiment 2, we interfered with the pathway from spatial representation to response in Figure 8-B. Both manipulations affected SNARC effect generation.

5.1 Stimulus Representation Stage in the SNARC Effect

Experiments 1a and 1b examined how horizontal versus vertical interference at stimulus representation affects the SNARC effect. Only horizontal interference blocked the SNARC effect; vertical interference did not. Bayesian analysis of the Number magnitude × Arrow direction interaction supported the alternative hypothesis for Experiment 1a (interaction exists) but the null hypothesis for Experiment 1b (no interaction), further supporting that horizontal but not vertical arrows influence number processing. Dehaene et al. (1993) adopted Restle's (1970) mental number line concept, proposing that numbers are mentally represented along a left-to-right axis, creating direct number-response correspondence (left hand faster for left-side small numbers, right hand faster for right-side large numbers). Our finding that only parallel (not perpendicular) interference affects the SNARC effect supports mental number line theory.

Neural dimensional overlap theory offers an alternative explanation. Fias et al. (2001) used numbers as task-irrelevant information while participants judged triangle orientation, digit color, line direction, or shape. They found that when target and distractor shared similar neural pathways, they competed for neural resources, reducing processing efficiency and revealing SNARC effects for irrelevant numbers. They extended Kornblum et al.'s (1990) dimensional overlap theory to the neural level, proposing that neural pathway similarity underlies task interference. In Experiment 1a, digits and arrows activated similar neural pathways and competed for resources. As distractors, arrows showed spatial effects while the SNARC effect disappeared.

Experiment 1a also provides indirect evidence regarding the spatial characteristics of ordinal information. Our Experiment 1 found no SNARC effect, while Shi (2010) found SNARC effects using number-composed letters in magnitude comparison tasks. This discrepancy may reflect letters' lack of spatial characteristics. When number-composed letters serve as stimuli, letters' global precedence does not interfere with number spatial representation, allowing SNARC effects to emerge. Dodd et al. (2008) provided supporting evidence using a target detection paradigm with numbers (1, 2, 8, 9), letters (a, b, y, z), days (Monday, Tuesday, Friday, Saturday), and months (January, February, November, December) as probes. Attentional SNARC effects only appeared for numbers, supporting that numbers have spatial characteristics while letters do not.

5.2 Response Selection Stage in the SNARC Effect

Experiment 2 found no SNARC effect. The global arrow direction may interfere with response selection in two ways. First, cognitive resource consumption at response selection may affect the SNARC effect. Consistent with our Experiment 2, Shi (2010) found no SNARC effect when using number-composed letters in vowel/consonant judgment tasks. When number-composed arrows/letters serve as stimuli in tasks unrelated to magnitude judgment, numbers can be automatically processed and spatially represented unconsciously (Dehaene & Akhavein, 1995; Gevers, Verguts et al., 2006). However, arrow/letter direction judgment consumes response selection resources, eliminating the SNARC effect. Future research could manipulate task difficulty levels to examine how response selection resource consumption affects the SNARC effect. For example, Wang et al. (2018) found that task switching suppressed the SNARC effect. Specifically, switch trials requiring two response standards (magnitude comparison for black digits, parity judgment for green digits) consumed more response selection resources than repeat trials, eliminating the SNARC effect. Wang et al. (2022) further manipulated switch frequency (1:1 ratio = high frequency/high resource consumption; 1:6 or 6:1 ratios = low frequency/low resource consumption). The SNARC effect appeared at low switch frequencies but disappeared at high frequency, supporting the cognitive resource consumption hypothesis.

Second, stimulus location attribute activation and response code competition may affect the SNARC effect. Unlike our Experiment 2, Fias et al. (2001) found SNARC effects using "triangles superimposed on digits" in upward/downward orientation judgments. This may occur because triangle orientation activated vertical response codes while digits activated horizontal response codes linked to left/right hands, preventing competition between relevant and irrelevant tasks' stimulus locations and response codes, thus revealing SNARC effects. However, in our Experiment 2, both left-right arrows and digits activated horizontal response codes, creating competition. Arrow direction codes were more strongly activated, producing Arrow direction × Response hand interaction but no SNARC effect. Future research should separate and test these hypotheses to clarify specific mechanisms.

5.3 SNARC Effect Occurs in Both Stages

Few studies have simultaneously examined both processing stages and their continuous cognitive sequence. Our results suggest stimulus representation and response selection stages are not entirely independent but interconnected. In Experiment 1a, the Arrow direction × Response hand interaction (Simon-like effect) was significant, while Experiment 1b showed no such effect. Researchers have demonstrated Simon effects for both visual and auditory stimuli when stimulus location corresponds with response location (Simon, 1968; Simon & Small, 1969; Craft & Simon, 1970; Hedge & Marsh, 1975). Because arrows convey spatial location information (left arrows point left, right arrows point right), left-hand responses are faster to left arrows and right-hand responses to right arrows, showing Simon-like effects (Luo & Proctor, 2021). Dimensional overlap theory proposes that Simon effects arise from mapping between stimulus location attributes and response codes, with stimulus locations automatically activating ipsilateral responses (Kornblum et al., 1990). In Experiment 1a, global precedence caused left-right arrows to be preferentially represented and activate left-right response codes, competing with the left-right codes required for magnitude comparison. However, because arrow direction interfered with number spatial representation on the mental number line, numbers failed to activate corresponding response codes. Thus, despite requiring magnitude judgments, strong evidence supported absence of the SNARC effect but presence of the Arrow direction × Response hand interaction (Simon-like effect). In Experiment 1b, vertical arrows did not interfere with horizontal mental number line representation, allowing numbers to activate response codes and produce the SNARC effect. This suggests that stimulus representation spatial strength may influence response code activation strength at response selection, and their joint interaction may contribute to SNARC effect occurrence.

5.4 Limitations and Future Directions

Most previous research used single-digit Arabic numbers, whereas we innovatively used compound stimuli, providing a new approach for investigating SNARC effect occurrence stages. However, limitations remain. First, this behavioral study used reaction time as the primary measure, lacking more precise cognitive process measurement. Numerous studies have provided more precise evidence from electrophysiological perspectives, such as eye-tracking (Schwarz & Keus, 2004) and ERP research (Salillas et al., 2008; Gevers, Ratinckx et al., 2006). However, these studies still primarily use single-digit numbers. Future research could innovate materials and tasks for electrophysiological studies to investigate SNARC effect mechanisms across levels and better understand its nature. Second, Experiment 2 used only one task type, finding that response selection interference affects the SNARC effect. Future research should further examine specific mechanisms of response selection stage influence.

Conclusion

Using the global-local paradigm with number-composed arrows, three experiments investigated SNARC effect occurrence stages. Key findings: (1) Interference with number processing at the stimulus representation stage blocks SNARC effect generation, but only when interference occurs horizontally (not vertically); (2) Interference at the response selection stage blocks SNARC effect generation, with cognitive resource consumption and stimulus location attribute activation/response code competition as two possible explanatory mechanisms. These results support the dual-stage processing model of the SNARC effect.

References

Casarotti, M., Michielin, M., Zorzi, M., & Umiltà, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition, 102*(1), 101–117.

Craft, J. L., & Simon, J. R. (1970). Processing symbolic information from a visual display: Interference from an irrelevant directional cue. *Journal of Experimental Psychology, 83*, 415–420.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and levels of representation in number processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*(2), 314–326.

Dehaene, S., Bossini, S., & Giraus, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology General, 122*(3), 371–396.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of experimental psychology: Human perception and performance, 16*(3), 626–641.

Dodd, M. D., Stigchel, S. V. D., Leghari, M. A., Fung, G., & Kingstone, A. (2008). Attentional SNARC: there's something special about numbers (let us count the ways). *Cognition, 108*(3), 810–818.

Fias, W., Lauwereyns, J., & Lammertyn, J. (2001). Irrelevant digits affect feature-based attention depending on the overlap of neural circuits. *Cognitive Brain Research, 12*(3), 415–423.

Fischer, M. H., Warlop, N., Hill, R. L., & Fias, W. (2004). Oculomotor bias induced by number perception. *Experimental Psychology, 51*(2), 91–97.

Gevers, W., Caessens, B., & Fias, W. (2005). Towards a common processing architecture underlying Simon and SNARC effects. *European Journal of Cognitive Psychology, 17*(5), 659–673.

Gevers, W., Ratinckx, E., De Baene, W., & Fias, W. (2006). Further evidence that the SNARC effect is processed along a dual-route architecture. *Experimental Psychology, 53*(1), 58–68.

Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: A computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance, 32*(1), 32–44.

He, H., Yu, H. H., & Liu, J. P. (2015). Study on number processing with Global-Local aspects of compound visual stimulations. *Psychological Exploration, 35*(6), 499–501.

Hedge, A., & Marsh, N. W. A. (1975). The effect of irrelevant spatial correspondences on two-choice response-time. *Act Psychologica, 39*, 427–439.

Hu, C. P., Kong, X. Z., Wagenmakers, E.-J., Ly, A., & Peng, K. P. (2018). The Bayes factor and its implementation in JASP: A practical primer. *Advances in Psychological Science, 26*(6), 951–965.

Jeffreys, H. (1961). *Theory of probability* (3rd Ed.). Oxford, UK: Oxford University Press.

Kang, W., Yang, M., & Wang, L. (2013). SNARC Effect: Current Research, Theories and Suggestions. *Journal of Psychological Science, 36*(5), 1242–1248.

Keus, I. M., Jenks, K. M., & Schwarz, W. (2005). Psychophysiological evidence that the SNARC effect has its functional locus in a response selection stage. *Cognitive Brain Research, 24*(1), 48–56.

Keus, I. M., & Schwarz, W. (2005). Searching for the functional locus of the SNARC effect: Evidence for a response-related origin. *Memory and Cognition, 33*(4), 681–695.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility-a model and taxonomy. *Psychological Review, 97*(2), 253–270.

Li, Q., Nan, W., Wang, K., & Liu, X. (2014). Independent processing of stimulus-stimulus and stimulus-response conflicts. *PLoS ONE, 9*(2), e89249.

Luo, T., Qiu, R. Y., Chen, B., & Fu, S. M. (2018). The stimulus representation of unconscious information and its temporal characteristics. *Acta Psychologica Sinica, 50*(5), 473–482.

Luo, C., & Proctor, R. W. (2021). Word-and arrow-based Simon effects emerge for eccentrically presented location words and arrows. *Psychological Research, 85*, 816–827.

Nan, W. Z., Yan, L. Z., Yang, G. C., Liu, X., & Fu, S. M. (2021). Two processing stages of the SNARC effect. *Psychological Research, 86*, 375–385.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9*(3), 353–383.

Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology, 83*(2), 274–278.

Salillas, E., Elyagoubi, R., & Semenza, C. (2008). Sensory and cognitive processes of shifts of spatial attention induced by numbers: An ERP study. *Cortex, 44*(4), 406–413.

Scerrati, E., Lugli, L., Nicoletti, R., & Umilta, C. (2017). Comparing Stroop-like and Simon effects on perceptual features. *Scientific Reports, 7*(1), 17815.

Schwarz, W., & Keus, I. M. (2004). Moving the eyes along the mental number line: Comparing SNARC effects with saccadic and number responses. *Perception and Psychophysics, 66*(4), 651–664.

Shi, X. L. (2010). *Spatial representations of numbers in paradigm of Global-Local processing* (Unpublished master's thesis). Soochow University.

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology, 51*(3), 300–304.

Simon, J. R. (1968). Effect of ear stimulated on reaction time and movement time. *Journal of Experimental Psychology, 78*, 344–346.

Simon, J. R., & Small, A. M., Jr. (1969). Processing auditory information: Interference from an irrelevant cue. *Journal of Applied Psychology, 53*, 433–435.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30*, 276–315.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662.

Tlauka, M. (2002). The processing of numbers in choice-reaction tasks. *Australian Journal of Psychology, 54*, 94–99.

Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., … van Doorn, J. (2017). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review, 25*, 58–76.

Wang, Q. Q., Shi, W. D., & Ye, J. (2018). The impact effect of the task switch on the SNARC effect. *Chinese Journal of Applied Psychology, 24*(3), 271–279.

Wang, Q. Q., Zhang, Q., Shi, W. D., Wang, Z. W., & Zhang, P. C. (2022). Online construction of spatial representation of numbers: Evidence from the SNARC effect in number processing in interferential situations. *Acta Psychologica Sinica, 54*(7), 761–771.

Wang, Y. H., Bergh, D., Aust, F., Ly, A., Wagenmakers, E.-J., & Hu, C. P. (2023). The Implementation of Bayesian ANOVA in JASP: A Practical Primer. *Psychology: Techniques and Applications, 11*(9), 528–541.

Wu, F., Gu, Q., Shi, Z. H., Gao, Z. F., & Shen, M. W. (2018). Striding over the "Classical Statistical Inference Trap"—Application of Bayes Factors in Psychological Studies. *Chinese Journal of Applied Psychology, 24*(3), 195–202.

Xu, X. D., & Liu, C. (2006). The spatial character of number. *Advances in Psychological Science, 14*(6), 851–858.

Xiang, X. R., Yan, L. Z., Fu, S. M., & Nan, W. Z. (2022). Processing stage flexibility of the SNARC effect: Task relevance or magnitude relevance? *Frontiers in psychology, 13*, 1022999.

Yan, L. Z., Yang, G. C., Nan, W. Z., Liu, X., & Fu, S. M. (2021). The SNARC effect occurs in the response-selection stage. *Acta Psychologica, 215*, 103292.

Yan, L. Z., Chen, Y. X., Liu, X., Fu, S. M., & Nan, W. Z. (2022). The flexibility of spatial-numerical associations and its internal mechanism. *Advances in Psychological Science, 30*(1), 51–64.

Note: Figure translations are in progress. See original paper for figures.