The Online Construction of Numerical Spatial Representations: Evidence from the SNARC Effect in Interference Contexts

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Abstract

Although previous studies have found that numbers are spatially represented in the human memory system, how the human brain accomplishes this spatial representation of numbers remains controversial. This study conducted two experiments to investigate the characteristics and mechanisms of numerical spatial representation in mixed contexts of different proportions of numbers and letters (Experiment 1) and different proportions of numbers and Chinese characters (Experiment 2), providing an in-depth examination of the aforementioned controversy. The results revealed: (1) When the number-to-letter ratio was "one-to-one," no SNARC effect emerged in number processing. When the number-to-letter ratio was "one-to-six" and "six-to-one," a SNARC effect was observed in number processing. That is, the relationship between the number-to-letter ratio and the numerical SNARC effect followed an inverted "U-shaped" pattern. (2) In the mixed context of numbers and Chinese characters, the relationship between the number-to-Chinese-character ratio and the numerical SNARC effect also followed an inverted "U-shaped" pattern. The results indicate: (1) The mixed presentation of distractor stimuli with numbers can influence the numerical SNARC effect. (2) The influence of distractor stimulus processing on the numerical SNARC effect is modulated by the ratio of numbers to distractor stimuli and demonstrates stability across different distractor materials. The findings suggest that the spatial representation of numbers is constructed online by humans through statistical learning, supporting the working memory theory.

Full Text

Online Construction of Spatial Representation of Numbers: Evidence from the SNARC Effect in Interferential Situations

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Abstract

Although previous research has demonstrated that numbers are spatially represented in human memory systems, the mechanism by which the brain accomplishes this spatial representation remains controversial. This study investigated the characteristics and mechanisms of numerical spatial representation in mixed contexts with varying proportions of numbers and letters (Experiment 1) and numbers and Chinese characters (Experiment 2) to address this debate. The results revealed: (1) When the number-to-letter ratio was 1:1, no SNARC effect emerged in number processing. However, when the ratio was 6:1 or 1:6, the SNARC effect appeared in both cases, indicating an inverted U-shaped relationship between the alphanumeric ratio and the SNARC effect. (2) A similar inverted U-shaped relationship was observed between the number-to-Chinese character ratio and the SNARC effect. These findings demonstrate that (1) mixing interference stimuli with numbers affects the SNARC effect, and (2) this influence is moderated by the proportion of numbers to interference stimuli, showing stability across different interference materials. The results suggest that the spatial representation of numbers is constructed online through statistical learning, supporting the working memory account.

Keywords: SNARC effect, numbers, letters, spatial representation, mental number line, working memory

1. Introduction

Numbers serve not only as carriers of human civilization and information transmission but also as response identifiers for task completion, with widespread applications in human factors engineering (e.g., pressing numbers to reach specific floors). Investigating the encoding characteristics of numbers and their influence mechanisms on human behavioral responses provides a scientific basis for utilizing numbers in task design, thereby enhancing efficiency and user experience. Consequently, numerical cognition has become a prominent research area in psychology.

Dehaene et al. (1990; 1993) first documented the SNARC effect (Spatial-Numerical Association of Response Codes) when participants classified centrally presented Arabic digits using left/right key presses: small numbers elicited faster left-hand responses, while large numbers elicited faster right-hand responses. This effect generalizes across various symbolic numbers (e.g., Chinese, German) and non-symbolic magnitudes (e.g., brightness, area), and even extends to ordinal symbols, where earlier items in a sequence produce faster left-hand responses and later items produce faster right-hand responses (Fumarola et al., 2014; Fumarola et al., 2016; Kopiske et al., 2016; Nuerk et al., 2005; Prete, 2020; Wang et al., 2020; Wang et al., 2019; Zhang et al., 2016). The ubiquity of the SNARC effect demonstrates that number processing systematically influences human behavior.

Two competing theories have emerged to explain this phenomenon: the mental number line hypothesis and the working memory account. The mental number line hypothesis posits that cultural experiences, particularly reading and writing direction, lead to a stable spatial representation of numbers in long-term memory, organized from left to right (or right to left for opposite reading habits). This pre-existing spatial representation is thought to directly cause the SNARC effect (Dehaene et al., 1993; Gevers et al., 2003; Wang et al., 2019). However, van Dijck and Fias (2011) challenged this view by demonstrating that when numerical order information was primed through sequential presentation, participants showed ordinal position effects rather than magnitude-based SNARC effects, a finding incompatible with the mental number line hypothesis. Consequently, they proposed the working memory account, suggesting that the SNARC effect originates from spatial representations constructed online in working memory.

The spatial representation of numbers in long-term memory is shaped by early cultural experiences and potentially genetic factors (Bulf et al., 2016; Bulf et al., 2022; Dehaene et al., 1993; Shaki et al., 2009), whereas working memory representations are highly susceptible to situational factors such as priming order, interference stimuli, and task demands, exhibiting substantial context dependency and online construction (Abrahamse et al., 2014; Abrahamse et al., 2016; Guida & Campitelli, 2019; Guida & Lavielle-Guida, 2014; Guida & Maherault, 2021; Guida et al., 2018; van Dijck & Fias, 2011; Wang et al., 2021). This suggests that while mixing numbers with other stimuli should not affect their long-term mental number line representation, it may disrupt the online spatial construction in working memory. Furthermore, the degree of interference may be moderated by the proportion of numbers to other stimuli.

If the SNARC effect directly stems from long-term memory representation, it should persist regardless of stimulus mixture or ratio. Conversely, if it originates from working memory, mixing numbers with other stimuli could affect the SNARC effect through two potential pathways: (1) semantic processing of interference stimuli, or (2) task switching between number processing and interference stimulus processing. The semantic pathway would predict a linear relationship, where increasing proportions of interference stimuli progressively reduce the SNARC effect. The task-switching pathway would predict an inverted U-shaped relationship, with maximal interference (and minimal SNARC effect) when proportions are equal due to frequent switching, and reduced interference when proportions are skewed due to less frequent switching.

This study systematically investigated these possibilities using two experiments. Experiment 1 employed spatially-organized letters as interference stimuli, while Experiment 2 used non-spatial Chinese characters. By manipulating the ratio of numbers to interference stimuli (1:1, 6:1, and 1:6) and requiring participants to classify numbers by magnitude and interference stimuli by ordinal position or structural composition, we examined whether the SNARC effect exhibits context-dependent patterns consistent with the working memory account.

Experiment 1: Letter Interference

Experiment 1 investigated how spatially-organized letters interfere with the SNARC effect and whether this interference is moderated by the number-to-letter ratio.

2.1.1 Participants

Sample size was estimated using G*Power 3.1 with effect size f = 0.40 and α = 0.95, indicating a minimum of 27 participants needed for a 2$×$2 within-subjects design (applied to all subsequent experiments). Thirty university students (25 female, 5 male) participated, with a mean age of 19.43 years (SD = 0.86, range = 18-22). All had normal or corrected-to-normal vision.

2.1.2 Materials and Apparatus

Stimuli comprised digits 1, 2, 3, 5, 6, 7 and letters A, B, C, E, F, G. All stimuli were 72-point font presented on 70$×70*pixelwhitebackgrounds.TheexperimentranonaDellcomputerwitha*19−*inchmonitor*(1024×$768 resolution, 60 Hz refresh rate).

2.1.3 Design

A 2 (congruency: congruent, incongruent) × 2 (stimulus type: number, letter) within-subjects design was employed. Digits 1–3 were classified as small, 5-7 as large. Letters A, B, C were defined as early in the alphabet, and E, F, G as late. Following previous research (Shi et al., 2020; Wang et al., 2021), congruent trials required left-hand responses to small numbers/early letters and right-hand responses to large numbers/late letters. The reverse mapping defined incongruent trials. The dependent variable was response time.

2.1.4 Procedure

Programmed in E-Prime 1.1, each trial began with a 500 ms fixation cross, followed by a centrally presented stimulus. Participants judged whether the number was greater or less than 4, or whether the letter came before or after D in the alphabet. After responding, a 1500 ms blank screen preceded the next trial.

Two blocks were administered. In Block 1, participants used the left hand (F key) for small numbers/early letters and right hand (J key) for large numbers/late letters. Block 2 used the opposite mapping. Block order was counterbalanced across participants. The number-to-letter ratio was 1:1, with each stimulus presented 16 times for 192 total trials. Each block included 12 practice trials requiring $ $80% accuracy to proceed. The experiment lasted approximately 15 minutes.

2.1.5 Results

Trials with incorrect responses or response times exceeding 3 SDs from each condition' s mean were excluded (6.15% of data). A repeated-measures ANOVA revealed no significant main effect of congruency, $F(1, 29) = 1.46$, $p = 0.24$, $^{2} = 0.05$, suggesting no SNARC effect emerged. The main effect of stimulus type was significant, $F(1, 29) = 77.87$, $p < 0.001$, $^{2} = 0.73$, with faster responses to numbers (487.06 ± 10.24 ms) than letters (513.30 ± 11.53 ms). The interaction between congruency and stimulus type was not significant, $F(1, 29) = 2.56$, $p = 0.12$, $^{2} = 0.08$.

Despite the non-significant interaction, separate analyses were conducted to ensure the mixed analysis did not mask effects. Simple main effects showed no significant congruency effect for numbers, $F(1, 29) = 0.43$, $p = 0.52$, $^{2} = 0.02$, or letters, $F(1, 29) = 2.22$, $p = 0.15$, $^{2} = 0.07$, confirming the absence of SNARC effects in both tasks (see Figure 1).

Figure 1. Mean reaction times and standard errors for congruent and incongruent trials in number magnitude and letter order classification tasks at a 1:1 number-to-letter ratio.

2.2.1 Participants

Thirty-two university students (25 female, 7 male) participated, with a mean age of 19.94 years (SD = 2.06, range = 18–27). All had normal or corrected-to-normal vision.

2.2.3 Design

The design was identical to Experiment 1a: 2 (congruency) × 2 (stimulus type) within-subjects, with response time as the dependent variable.

2.2.4 Procedure

The procedure matched Experiment 1a except for the 6:1 number-to-letter ratio. Each number was presented 36 times and each letter 6 times, totaling 252 trials.

The experiment lasted approximately 15 minutes.

2.2.5 Results

After excluding errors and outliers (5.17% of data), a repeated-measures ANOVA revealed a significant main effect of congruency, $F(1, 31) = 15.04$, $p = 0.001$, $^2 = 0.33$, with faster responses in congruent (535.75 ± 12.44 ms) than incongruent trials (573.87 ± 16.48 ms), indicating a SNARC effect. The stimulus type main effect was significant, $F(1, 31) = 176.70$, $p < 0.001$, $^2 = 0.85$, with faster number responses (496.17 ± 10.43 ms) than letter responses (613.45 ± 17.55 ms). The interaction was significant, $F(1, 31) = 10.75$, $p = 0.003$, $^2 = 0.26$.

Simple effects analysis showed significant congruency effects for both numbers, $F(1, 31) = 7.90$, $p = 0.009$, $^2 = 0.20$ (congruent: 485.81 ± 9.43 ms; incongruent: 506.53 ± 12.49 ms), and letters, $F(1, 31) = 15.79$, $p < 0.001$, $^2 = 0.34$ (congruent: 585.69 ± 16.06 ms; incongruent: 641.20 ± 21.35 ms), confirming SNARC effects in both tasks (see Figure 2).

Figure 2. Mean reaction times and standard errors for congruent and incongruent trials in number magnitude and letter order classification tasks at a 6:1 number-to-letter ratio.

2.3.1 Participants

Thirty-two university students (26 female, 6 male) participated, with a mean age of 19.56 years (SD = 1.56, range = 18–24). All had normal or corrected-to-normal vision.

2.3.3 Design

The design remained 2 (congruency) × 2 (stimulus type) within-subjects, with response time as the dependent variable.

2.3.4 Procedure

The procedure matched Experiment 1a except for the 1:6 number-to-letter ratio. Each number was presented 6 times and each letter 36 times, totaling 252 trials. The experiment lasted approximately 15 minutes.

2.3.5 Results

After excluding errors and outliers (6.05% of data), a repeated-measures ANOVA revealed a significant main effect of congruency, $F(1, 31) = 18.67$, $p < 0.001$, $^2 = 0.38$, with faster responses in congruent (550.80 ± 11.11 ms) than incongruent trials (598.20 ± 13.12 ms). The stimulus type main effect was significant, $F(1, 31) = 52.91$, $p < 0.001$, $^2 = 0.63$, with faster letter responses (548.76 ± 9.20 ms) than number responses (600.24 ± 13.25 ms). The interaction was not significant, F(1, 31) = 0.24, p = 0.63, ^{2} = 0.01.

Given the significant stimulus type effect, separate analyses were conducted. Simple main effects revealed significant congruency effects for numbers, F(1, 31) = 10.26, p = 0.003, ^{2} = 0.25 (congruent: 577.52 ± 13.47 ms; incongruent: 622.72 ± 16.39 ms), and letters, F(1, 31) = 26.88, p < 0.001, ^{2} = 0.46 (congruent: 523.85 ± 9.50 ms; incongruent: 573.68 ± 11.19 ms), confirming SNARC effects in both tasks (see Figure 3).

Figure 3. Mean reaction times and standard errors for congruent and incongruent trials in number magnitude and letter order classification tasks at a 1:6 number-to-letter ratio.

Summary of Experiment 1

Experiment 1 examined letter interference on the SNARC effect across three number-to-letter ratios (1:1, 6:1, and 1:6). The critical finding was that at a 1:1 ratio, no SNARC effect emerged despite robust activation of numerical magnitude and letter order information. However, at both 6:1 and 1:6 ratios, significant SNARC effects appeared in both number and letter tasks. This demonstrates that mixing numbers with letters substantially impacts the SNARC effect, with the degree of interference moderated by the numerical ratio.

To visualize this relationship, we calculated SNARC effect magnitude as the difference between incongruent and congruent trial reaction times (following Shi et al., 2020; Wang et al., 2021) and plotted it against number-to-letter ratio. Figure 4 clearly shows an inverted U-shaped relationship: interference was maximal and SNARC effect magnitude minimal at the 1:1 ratio, decreasing as ratios became more extreme. Notably, number processing also interfered with letter processing, showing a parallel inverted U-shaped pattern.

Figure 4. SNARC effect magnitude in number and letter processing across different number-to-letter ratios.

Experiment 2: Chinese Character Interference

Experiment 2 extended these findings using non-spatial Chinese characters as interference stimuli to test whether the interference pattern generalizes beyond spatially-organized materials.

3.1.1 Participants

Thirty university students and graduate students (24 female, 6 male) participated, with a mean age of 20.67 years (SD = 3.63, range = 17-34). All had normal or corrected-to-normal vision.

3.1.2 Materials and Apparatus

The apparatus was identical to Experiment 1a. Number stimuli were 1, 2, 3, 5, 6, 7. Chinese character stimuli were 校, 困, 床, 较, 应, 园. Font and size matched Experiment 1a.

3.1.3 Design

A 2 (congruency: congruent, incongruent) × 2 (stimulus type: number, Chinese character) within-subjects design was used. Number-response congruency was defined as in Experiment 1a. Since Chinese characters lack inherent spatial properties, we operationally defined congruency based on structural composition: characters containing the "木" radical required left-hand responses and those without it required right-hand responses for congruent trials, with the reverse mapping for incongruent trials. This definition was applied consistently across Experiments 2a, 2b, and 2c.

3.1.4 Procedure

The procedure matched Experiment 1a except that participants judged whether numbers were greater or less than 4, or whether Chinese characters contained the "木" radical. The number-to-character ratio was 1:1, with each stimulus presented 16 times for 192 total trials. The experiment lasted approximately 15 minutes.

3.1.5 Results

After excluding errors and outliers (7.97% of data), a repeated-measures ANOVA revealed no significant main effect of congruency, $F(1, 29) = 1.43$, $p = 0.24$, $^2 = 0.05$, indicating no SNARC effect. The stimulus type main effect was significant, $F(1, 29) = 100.38$, $p < 0.001$, $^2 = 0.78$, with faster number responses (625.53 ± 16.55 ms) than character responses (698.63 ± 16.72 ms). The interaction was not significant, $F(1, 29) = 1.03$, $p = 0.32$, $^2 = 0.03$.

Separate analyses confirmed no significant congruency effects for numbers, $F(1, 29) = 2.18$, $p = 0.15$, $^2 = 0.07$, or characters, $F(1, 29) = 0.35$, $p = 0.56$, $^2 = 0.01$, confirming the absence of SNARC effects (see Figure 5).

Figure 5. Mean reaction times and standard errors for congruent and incongruent trials in number magnitude and Chinese character structure classification tasks at a 1:1 ratio.

3.2.1 Participants

Thirty university students and graduate students (27 female, 3 male) participated, with a mean age of 20.30 years (SD = 2.49, range = 18-27). All had normal or corrected-to-normal vision.

3.2.3 Design

The design was 2 (congruency) × 2 (stimulus type) within-subjects, with response time as the dependent variable.

3.2.4 Procedure

The procedure matched Experiment 2a except for the 6:1 number-to-character ratio. Each number was presented 36 times and each character 6 times, totaling 252 trials. The experiment lasted approximately 15 minutes.

3.2.5 Results

After excluding errors and outliers (6.35% of data), a repeated-measures ANOVA revealed a significant main effect of congruency, $F(1, 29) = 5.83$, $p = 0.02$, $^2 = 0.17$, with faster congruent (670.59 ± 18.13 ms) than incongruent responses (699.87 ± 22.73 ms). The stimulus type main effect was significant, $F(1, 29) = 155.69$, $p < 0.001$, $^2 = 0.84$, with faster number responses (543.98 ± 12.69 ms) than character responses (826.48 ± 29.45 ms). The interaction was not significant, $F(1, 29) = 0.60$, $p = 0.45$, $^2 = 0.02$.

Simple effects analysis revealed a significant congruency effect for numbers, $F(1, 29) = 6.86$, $p = 0.014$, $^2 = 0.19$ (congruent: 533.57 ± 12.38 ms; incongruent: 554.38 ± 14.17 ms), but not for characters, $F(1, 29) = 3.03$, $p = 0.09$, $^2 = 0.09$ (see Figure 6).

Figure 6. Mean reaction times and standard errors for congruent and incongruent trials in number magnitude and Chinese character structure classification tasks at a 6:1 ratio.

3.3.1 Participants

Thirty-two university students (26 female, 6 male) participated, with a mean age of 20.21 years (SD = 2.24, range = 18–25). All had normal or corrected-to-normal vision.

3.3.3 Design

The design was 2 (congruency) × 2 (stimulus type) within-subjects, with response time as the dependent variable.

3.3.4 Procedure

The procedure matched Experiment 2a except for the 1:6 number-to-character ratio. Each number was presented 6 times and each character 36 times, totaling 252 trials. The experiment lasted approximately 15 minutes.

3.3.5 Results

After excluding errors and outliers (6.56% of data), a repeated-measures ANOVA revealed no significant main effect of congruency, F(1, 31) = 1.67, p = 0.21, ^{2} = 0.05. The stimulus type main effect was significant, F(1, 31) = 79.51, $p < 0.001$, ^{2} = 0.72, with faster character responses (615.66 ± 12.59 ms) than number responses (704.19 ± 16.62 ms). The interaction was significant, F(1, 31) = 16.13, $p < 0.001$, ^{2} = 0.34.

Simple effects analysis revealed a significant congruency effect for numbers, F(1, 31) = 5.95, p = 0.02, ^{2} = 0.16 (congruent: 681.82 ± 18.80 ms; incongruent: 726.56 ± 19.16 ms), but not for characters, F(1, 31) = 0.40, p = 0.53, ^{2} = 0.01 (see Figure 7).

Figure 7. Mean reaction times and standard errors for congruent and incongruent trials in number magnitude and Chinese character structure classification tasks at a 1:6 ratio.

Summary of Experiment 2

Experiment 2 replicated the interference pattern using non-spatial Chinese characters. At a 1:1 ratio, no SNARC effect emerged. However, at 6:1 and 1:6 ratios, significant SNARC effects appeared in number processing tasks. This demonstrates that mixing numbers with non-spatial stimuli also produces context-dependent interference moderated by stimulus ratio.

Figure 8 illustrates the inverted U-shaped relationship between number-to-character ratio and SNARC effect magnitude: maximal interference and minimal SNARC magnitude occurred at the 1:1 ratio, decreasing as ratios became more extreme. These findings replicate Experiment 1' s pattern, indicating that interference generalizes across spatial and non-spatial materials and is unlikely to result from processing stimulus-specific information.

Figure 8. SNARC effect magnitude in number and Chinese character processing across different number-to-character ratios.

4. General Discussion

While research has established that number processing systematically influences behavior through spatial representation, debate persists regarding whether this originates from long-term memory or working memory. This study addressed this controversy by examining numerical encoding mechanisms in mixed stimulus contexts with manipulated proportions.

Experiment 1 used spatially-organized letters as interference stimuli across three ratios. Remarkably, despite robust activation of magnitude and order information, the 1:1 ratio completely eliminated SNARC effects. This stands in stark contrast to decades of research consistently finding SNARC effects across various symbolic and non-symbolic materials (Gevers et al., 2003; Prete, 2020; Wang et al., 2019; Wang et al., 2020). The sole distinguishing feature was the 1:1 mixed presentation context, indicating that this specific ratio critically disrupts SNARC effects.

Two potential interference pathways exist: semantic processing of letters and task switching between number and letter classification. In random mixed contexts, a 1:1 ratio maximizes switch frequency, whereas extreme ratios minimize it. For instance, a 1:9 ratio requires only one switch, while a 1:1 ratio necessitates multiple switches. The observed inverted U-shaped relationship between ratio and SNARC magnitude aligns precisely with the task-switching account, not the semantic interference account. This conclusion is further supported by previous research demonstrating task-switching effects on the SNARC effect (Wang et al., 2018).

Experiment 2 extended these findings to non-spatial Chinese characters, replicating the identical interference pattern. The cross-material consistency suggests that interference stems from task-switching demands rather than stimulus-specific spatial properties. This also rules out alternative explanations based on processing spatial characteristics of interference stimuli.

Theoretical implications are clear. Long-term memory representations, shaped by cultural and genetic factors (Bulf et al., 2016; Bulf et al., 2022; Dehaene et al., 1993; Shaki et al., 2009), should be impervious to contextual manipulations of stimulus ratio. In contrast, working memory representations are inherently context-dependent and constructed online (Abrahamse et al., 2014; Abrahamse et al., 2016; Guida & Campitelli, 2019; Guida & Lavielle-Guida, 2014; Guida & Maherault, 2021; Guida et al., 2018; Wang et al., 2021). Our finding that SNARC effects vary systematically with interference context and stimulus ratio provides strong support for the working memory account.

Yan et al. (2022) proposed a dual-stage processing model to explain the flexibility of spatial-numerical associations, suggesting that SNARC effects can arise during either the spatial representation stage or the response selection stage, with interference at any stage modulating the effect. Our manipulations, while not affecting long-term mental number line representations, clearly disrupted the online spatial construction of magnitude information in working memory—that is, the spatial representation stage. The context-dependent SNARC effects we observed align perfectly with this model and deepen understanding of how spatial representations are formed during number processing.

5. Conclusion

This study demonstrates that (1) mixing numbers with other stimuli interferes with the SNARC effect through task-switching mechanisms, and (2) this interference is moderated by the proportion of numbers to interference stimuli, showing stable patterns across different interference materials. These findings support the working memory account and suggest that spatial representations of numbers are constructed online through statistical learning.

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