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Eye-Tracking Evidence for the SNARC Effect: Unveiling Attentional Stages

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Abstract:

The Spatial Numerical Association of Response Codes (SNARC) effect, which involves the conjunction of spatial and numerical response coding, was initially identified through reaction time experiments involving numerical stimuli. Research has revealed a common tendency among individuals to associate smaller numbers with the left side and larger numbers with the right side. Furthermore, scholars have identified additional dimensions, such as the "up-down" and "near-far" associations, that contribute to the complexity of the SNARC effect. However, the universality of the SNARC effect and the underlying psychological and physiological mechanisms continue to be a topic of debate within the academic community. Various studies have proposed a range of interpretations and understandings of this effect. The present study delves into the cognitive mechanisms of the SNARC effect, employing eye-tracking technology to objectively quantify participants' responses. Utilizing the parity judgment task, a method frequently employed in SNARC effect research, in conjunction with eye-tracking, participants were instructed to judge the parity of numerical stimuli while directing their gaze to the left or right, and above or below the numbers as per the experimental requirements. Colored blocks were positioned around the numbers to serve as visual anchors, indicating the spatial directions of left/right and top/down. Data analysis revealed that when smaller numbers (1-4) were presented, participants exhibited a tendency to focus on the left color block adjacent to the number, characterized by a higher Total Fixation Duration (TFD) and a shorter Time to First Fixation (TFF). In contrast, when larger numbers (6-9) appeared, participants were more likely to focus on the right color block, indicating the presence of a SNARC effect in the horizontal dimension. However, no significant effect was observed in the vertical dimension. Additionally, this study innovatively employed a blank page in conjunction with a test page to differentiate between the early and late stages of participants' attentional processing. The examination of TFF and TFD data uncovered a two-stage processing mechanism associated with the SNARC effect. This experimental approach and methodological framework offer novel perspectives that contribute to the advancement of research in this domain.

Keywords: SNARC Effect, Numerical Cognition, Spatial-numerical Association, Eye-tracking

1. Introduction

Numerical cognition is a fundamental component of human cognition that is integral to daily activities and scientific comprehension. Galton (1880) initially observed that numerical cognition is not encoded as a discrete system within the human brain but is instead deeply integrated with spatial, visual, and other cognitive domains. This insight was later termed the "spatial bias in number processing" by Fischer and Shaki (2014). Dehaene (1993), through reaction time experiments, identified a sensitivity to smaller numerical values when participants used their left hand for responses, and a higher sensitivity to larger numerical values with the right hand. This phenomenon, known as the "Spatial Numerical Association of Response Codes" (SNARC) effect, has become a discovery of numerical cognition. Further research has revealed that individuals tend to associate smaller numbers with the left side and larger numbers with the right side. The SNARC effect has been observed not only with Arabic numerals but also with other symbolic representations, such as letters and Chinese numerals (Gevers, 2003; Pan, 2009).

The predominant explanation for the SNARC effect is the Mental Number Line (MNL) Theory, proposed by Dehaene (1993). The MNL Theory suggests that the human brain contains a mental number line that increases continuously from left to right. During numerical processing, smaller numbers are mentally represented on the left side of this line, while larger numbers are on the right. The theory posits that responses are facilitated when the spatial representation of numbers aligns with their position on the mental number line. This concept has been expanded to include not only the horizontal left-right dimension but also the vertical up-down and the near-far dimensions, suggesting a three-dimensional SNARC effect (Dehaene, 1997). Despite extensive engagement with the SNARC effect, there is inconsistency in the findings of experimental studies. For instance, Fischer et al. (2003) observed the SNARC effect within a specific numerical range, whereas Henik and Tzelgov (1982) did not find this effect within the same range. Additionally, there is ongoing debate regarding whether the SNARC effect occurs during the early or late stages of attentional processing (Gevers, 2006; Santens, 2008; Tzelgov, 1992).

The aim of the current study is to investigate the SNARC effect using eye-tracking methodology. The parity judgment task, a common approach in SNARC research, was employed. Traditional response-time methods may not accurately discern the stage at which the SNARC effect manifests, and there can be a lag between cognitive processing and response that could influence behavioral test outcomes. Eye-tracking technology improves the accuracy via excluding the key press step. The results directly reflect the cognition process. Furthermore, this study introduces a novel experimental design by incorporating a blank page prior to the parity judgment task, which serves to segregate the stages of attentional processing. The use of an eye-tracker in this context allows for the collection of quantitative data that provides a more precise understanding of the attentional dynamics involved in the SNARC effect.

2. Methods

2. 1 Participants

Twenty-two participants, consisting of 9 males and 13 females with a mean age of 28.45 years (SD = 11.42), were randomly selected from a shopping mall in Shanghai, China. The eligibility criteria for the participants included being right-handed, having normal or corrected-to-normal vision, and lacking prior experience with similar experiments. Prior to their participation, all individuals were thoroughly informed about the study's procedures and potential risks associated with it. The research protocol was approved by the Ethics Review Committee of the respective institution, and written informed consent was obtained from each participant.

2. 2 Design

The current study utilized a two-factor, within-subjects experimental design with four levels. The factors were spatial orientation, with two conditions: horizontal (left-right) and vertical (up-down). The task involved parity judgment, where participants were required to make judgments of numbers presented on a screen.

In the vertical orientation, there are two groups in total. The parity judgment tasks have distinct instructions of these two groups. Group one was instructed to look at the upper part of the screen for odd numbers and the lower part for even numbers. Conversely, group two received the opposite instructions. Two color blocks, serving as visual response cues, were positioned above or below the number to indicate the 'upper' and 'lower' response areas, respectively. This design avoiding using Chinese characters aimed to mitigate the influence of verbal-spatial coding, as per Zhou (2015), while also providing a clear focal point for gaze, facilitating eye movement data collection. The horizontal orientation mirrored the vertical, with response locations being left and right. Participants were presented with four trial groups for each spatial orientation, resulting in a total of 32 parity judgment tasks (4 groups × 8 numbers). The numbers ranged from 1 to 4 (smaller numbers) and 6 to 9 (larger numbers), and were randomly presented in each trial to avoid predictability.

To identify the initial and final stages of attention allocation, the experiment introduced a blank screen, devoid of color blocks, which was displayed for 350 milliseconds before the number judgment screen. This brief exposure period corresponds to the subliminal perception stage of numbers, marking the early phase of the attentional response (Huo, 2011). The experimental design allows for the disentanglement of attentional phases by separating the blank and test screens as shown in Fig 1.

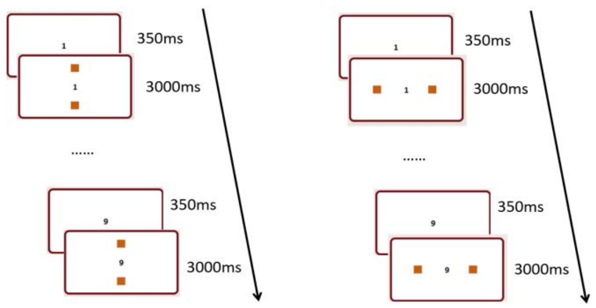

Fig 1. Task flowchart (vertical task & horizontal task examples)

2. 3 Procedure

Before commencing the experiment, participants were briefed on the study's rough objectives, procedures, and necessary precautions. Each participant provided voluntary consent to participate and signed an informed consent form. Throughout the experimental session, participants were seated in front of a monitor connected to the primary computing system with an eye-tracking device (Tobii 4C pro) positioned beneath the monitor. Successful completion of a five-point calibration was mandatory for participants to proceed with the experiment. During the trial they were tasked with making parity judgments on numbers centrally displayed on the screen and directing their gaze to corresponding color blocks.

The initial two tasks of each trial served as practice and were excluded from the final dataset. The duration of the entire experiment was approximately 10 minutes, and upon completion, participants received a gift. The regions corresponding to the color blocks (up-down, left-right) were designated as areas of interest (AOIs). Following the conclusion of the experiments for all participants, time to first fixation (TFF) and total fixation duration (TFD) metrics for each AOI were exported and analyzed.

2. 4 Data analysis

The eye-tracking data were subjected to a data pre-processing phase to ensure the accuracy and reliability of the subsequent analysis. This process involved the exclusion of trials contaminated by excessive blinking, calibration inaccuracies, or outliers that deviated significantly. To evaluate the statistical significance of the observed differences in total fixation duration (TFD) and time to first fixation (TFF) across various experimental conditions, paired t-tests were employed. The numerical stimuli were grouped into two distinct categories for analysis: 'small numbers' ranging from 1 to 4 and 'large numbers' ranging from 6 to 9. Additionally, the data from the 'Blank Pages' and 'Test Pages' were analyzed independently to identify any potential effects of the initial and final stages of attention allocation.

3. Results

3.1 Paired T-test analysis from Blank Pages

As shown in Table 1, the analysis of the horizontal arrangement indicated that small numbers exhibited longer Total Fixation Durations (TFD) and shorter Time to First Fixations (TFF) when for the left side. Specifically, the mean TFD for small numbers was 0.18 seconds (SD=0.09), and the mean TFF was 135.49 milliseconds (SD=74.96). Conversely, larger numbers displayed a similar trend for the right, with a mean TFD of 0.25 seconds (SD=0.13) and a mean TFF of 111.61 milliseconds (SD=55.21). However, these differences were not statistically significant for either small numbers (TFD: t=-0.05, p>0.05; TFF: t=-0.85, p>0.05) or large numbers (TFD: t=0.40, p>0.05; TFF: t=0.97, p>0.05).

In the vertical arrangement, both small and large numbers were found to have longer TFD and shorter TFF for the upper part. The mean TFD for small numbers was 0.29 seconds (SD=0.14) with a mean TFF of 103.69 milliseconds (SD=87.98), while for large numbers, the mean TFD was 0.20 seconds (SD=0.09) and the mean TFF was 123.60 milliseconds (SD=88.04). These differences were statistically significant for small numbers (TFD: t=3.42, p<0.05; TFF: t=-2.73, p<0.05) and large numbers (TFD: t=2.55, p<0.05; TFF: t=-2.46, p<0.05).

3.2 Paired T-test analysis from Test Pages

As shown in Table 2, in the horizontal arrangement, similar to the findings on Blank Pages, small numbers for the left side were associated with both longer Total Fixation Durations (*M=0.99, SD=0.34*) and shorter Time to First Fixations (*M=135.44, SD=63.17*), compared to the right side (*TFD: M=0.93, SD=0.41; TFF: M=159.29, SD=70.78*). Conversely, larger numbers exhibited comparable trends on the right side (*TFD: M=0.98, SD=0.42; TFF: M=113.55, SD=68.45*) versus the left side (*TFD: M=1.00, SD=0.37; TFF: M=105.64, SD=67.04*). However, these differences were not statistically significant for either small numbers (*TFD: t=0.53, p>0.05; TFF: t=-1.18, p>0.05)* or large numbers *(TFD: t=-0.21, p>0.05; TFF: t(11)=0.38, p>0.05*).

In the vertical arrangement, a t-test indicated that both small and large numbers had longer TFD and shorter TFF for the upper of the screen. For small numbers, the TFD was longer for the upper part (*M=1.04, SD=0.46*) compared to the lower one (*M=0.84, SD=0.45*), and the TFF was shorter (*upper: M=107.58, SD=79.60; lower: M=145.39, SD=62.44*). For large numbers, similar patterns were observed with longer TFD for the upper part (*M=1.07, SD=0.40*) versus the lower one (*M=0.80, SD=0.48*), and shorter TFF (*upper: M=85.76, SD=62.61; lower: M=157.33, SD=83.92*). The differences in TFD for small numbers (t=1.45, p<0.05) and large numbers (*t=2.02, p<0.05*), as well as the differences in TFF for small numbers (*t=-1.73, p<0.05*) and large numbers (*t=-3.21, p<0.05*), were statistically significant.

3.3 Paired T-test analysis from Total Pages

As detailed in Table 3, the horizontal direction analysis using a t-test revealed that for the left, small numbers had larger Total Fixation Durations (*M=1.17, SD=0.41*) and shorter Time to First Fixations (*M=270.93, SD=105.05*), compared to the right (*TFD: M=1.11, SD=0.50; TFF: M=314.62, SD=123.36*). The t-test indicated that the difference in TFF was statistically significant (*t=-1.26, p<0.05*), while the difference in TFD was not (*t=0.43, p>0.05*). For large numbers, the right was associated with larger TFD (*M=1.23, SD=0.53*) and shorter TFF

($M=225.16$, $SD=110.79$), but these differences did not reach statistical significance (*TFD:* $t=-0.07$, $p>0.05$; *TFF:* $t=0.81$, $p>0.05$).

In the vertical direction, the t-test showed that when participants looked upwards, both small and large numbers were associated with larger TFD and shorter TFF compared to when they looked downwards. For small numbers, the upper position showed a TFD of M=1.33 ($SD=0.59$) and a TFF of M=211.27 ($SD=151.28$), while the bottom position had a TFD of M=0.99 ($SD=0.65$) and a TFF of M=328.56 ($SD=151.28$). For large numbers, the top position exhibited a TFD of M=1.27 ($SD=0.48$) and a TFF of M=209.36 ($SD=138.24$), and the bottom position had a TFD of M=0.92 ($SD=0.57$) and a TFF of M=352.45 ($SD=163.23$). The differences in TFD for small numbers ($t=1.93$, $p<0.05$) and large numbers ($t=2.19$, $p<0.05$), as well as the differences in TFF for small numbers ($t=-2.57$, $p<0.05$) and large numbers ($t=-3.13$, $p<0.05$), were statistically significant.

Table1: TFD and TFF for Blank Pages					
Small		TFD (s)		TFF (ms)	
		Big	Small	Big	
Horizontal	Left	0. 18	0. 25	135. 49	111. 61
	Right	0. 18	0. 24	155. 33	91.77
Vertical	Top	0. 29	0. 20	103. 69	123. 60
	Bottom	0. 16	0. 12	183. 17	195. 12

Table2: TFD and TFF for Test Pages					
Small		TFD (s)		TFF (ms)	
		Big	Small	Big	
Horizontal	Left	0. 99	0. 98	135. 44	113. 55
	Right	0. 93	1. 00	159. 29	105. 64
Vertical	Top	1. 04	1. 07	107. 58	85.76
	Bottom	0. 84	0. 80	145. 39	157.33

Table3: TFD and TFF for Total Pages					
Small		TFD (s)		TFF (ms)	
		Big	Small	Big	
Horizontal	Left	1. 16	1. 22	270. 93	225. 16
	Right	1. 11	1. 24	314. 62	195. 41
Vertical	Top	1. 33	1. 27	211. 27	209. 36
	Bottom	0. 99	0. 92	328. 56	352. 45

4. Discussion

In this study, the SNARC effect was investigated in both vertical and horizontal dimensions using eye-tracking methodology integrated with a parity judgment task. The analysis of eye-tracking data, including Time to First Fixation (TFF) and Total Fixation Duration (TFD), revealed the presence of a horizontal SNARC effect, while no vertical SNARC effect was discerned. The findings on TFF and TFD from both blank and test pages substantiated the dual-stage processing model of the SNARC effect.

The TFF, which denotes the latency to the initial fixation on a target stimulus post its appearance, was observed to be shorter for small numbers on the left and for large numbers on the right. This finding suggests a directional gaze shift consistent with the left-to-right SNARC effect, indicating a spatial-numerical association for small and large numbers. Conversely, TFD, reflecting the cumulative attention allocated to a stimulus, was longer for small numbers on the left and large numbers on the right, further supporting the SNARC effect's spatial-numerical association. In the vertical dimension, the TFF and TFD data indicated a preference for the upper position for both small and large numbers, with no significant up-down or down-up SNARC effect observed. This outcome aligns with previous horizontal SNARC effect findings from behavioral studies employing paradigms such as size judgment, parity judgment, midpoint finding, and gaze-square (Dehaene, 1992; Dehaene et al., 1993; Fischer, 2003).

The current findings are congruent with the writing habits of the Chinese participants, who typically write from left to right. It has been posited that writing habits influence the directionality of the SNARC effect, with Chinese subjects exhibiting a left-to-right tendency, contrasting with Japanese subjects who may show a right-to-left inclination (Zebian, 2005). However, the influence of writing habits is not invariant, as the SNARC effect can be modulated by various factors. Some studies with subjects from similar cultural backgrounds have reported divergent results (Zhang & Wang, 2005), suggesting that the SNARC effect's manifestation is not solely determined by writing habits. In this study, despite the left- right and up-down writing conventions of the Chinese participants, the vertical SNARC effect was not observed, underscoring the complexity of factors influencing the SNARC effect.

The absence of the SNARC effect in the vertical dimension in the current study may be attributed to the task-dependency of the SNARC effect. Qiao (2016) demonstrated that the SNARC effect in the vertical dimension was not observed when using pure numbers as experimental stimuli, but was evident in other conditions involving different materials. This suggests that the manifestation of the SNARC effect is contingent upon various experimental factors, including the nature of the stimuli, the context of the experiment, and the type of task employed.

The timing of the SNARC effect within the attentional process has been a contentious issue. Fischer (2004) suggests that the SNARC effect emerges during the early stages of attention as an outcome of initial digit processing and spatial associations. Conversely, EEG studies, such as that by Keus and Schwarz (2005), have indicated that the SNARC effect unfolds during the later stages of attention, encompassing advanced digit processing and response decision-making. The present study aimed to delineate the stages of digit perception and response selection by introducing a brief blank page prior to the test page, thereby identifying the phase at which the SNARC effect materializes. Analysis of the eye-tracking parameters TFF and TFD on both the blank and test pages revealed consistent digit-spatial preferences across both phases. The brief presentation of the blank page, as referenced by Huo (2011), was deemed too short to facilitate decision-making, thus the eye-tracking metrics from this phase represent the early stages of attentional engagement, specifically the perception and preliminary processing of digits, akin to the TFF indicator. In contrast, the test page was displayed sufficiently long for decision-making processes to progress smoothly, with the TFD analysis reflecting the participants' performance during the later stages of attentional processing. The presence of the SNARC effect on both page types and across both eye-movement metrics—TFF and TFD—suggests that the effect happens in both early and late stages of attention, corroborating the dual-processing stage model of the SNARC effect proposed by Proctor and Cho (2006).

The study has several limitations that could be improved in future research. Firstly, the modest sample size of this experiment suggests the need for larger participant cohorts to enhance the generalizability of the findings. Additionally, the homogeneity of the subject pool, being exclusively Chinese, calls for investigations into the influence of cultural factors on the SNARC effect, given the potential impact of writing habits and other cultural nuances on the outcome. Furthermore, the current study uses numerical stimuli invites exploration of the SNARC effect using diverse stimuli, such as letters, images, or auditory signals, to broaden the understanding of this phenomenon.

5. Conclusion

The present study aims to validate the SNARC effect using a parity judgment task coupled with eye-tracking technology. To identify the stage of the SNARC effect's emergence, a design was implemented that included a blank page before the test page. The data analysis revealed a significant SNARC effect in the horizontal dimension, while no such effect was observed in the vertical dimension. Furthermore, the examination of the two eye movement parameters, Total Fixation Duration (TFD) and Time to First Fixation (TFF), on both the blank and test pages indicated that the SNARC effect occurs during both the early and late stages of attentional processing. This finding supports the dual-stage processing model of the SNARC effect. The innovation of this study lies in its approach to disentangling the early and late stages of attentional processing. By employing eye-tracking instruments, the study was able to obtain more precise measurements than traditional behavioral studies. The experimental design and methodology utilized in this research offer novel insights that could inform future investigations in this area.

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