

The Dynamics and Internal Mechanisms of Digital Space Connectivity

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Date: 2021-07-27T00:00:00+00:00

Abstract

Numerical-spatial association has long been a focal topic in cognitive psychology research. An important index for exploring numerical-spatial association is the Spatial-Numerical Association of Response Codes (SNARC) effect (where left/right hand responds faster and more accurately to small/large numbers). Previous studies have verified the universality of the SNARC effect and its flexibility in direction, and have proposed multiple theoretical explanations. Additionally, the SNARC effect also demonstrates flexibility in processing stages, with possible reasons including: (1) misinterpretation of the additive factors method, (2) a singular observational perspective, (3) differences in observed criteria, and (4) differences in tasks employed. Integrating these factors, a two-stage processing model (spatial representation of numerical information, and from spatial representation to response selection) is proposed; different manipulative factors acting respectively on the two stages may constitute the core reason for the flexible variations in the SNARC effect. Future research could further validate the two-stage processing model by comparing task differences and introducing various interfering factors, and could reveal the underlying neural mechanisms of the flexibility of numerical-spatial association by integrating cognitive neuroscience techniques.

Full Text

The Flexibility of Spatial-Numerical Associations and its Internal Mechanism

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Abstract

Spatial-numerical associations (SNAs) have long been a focal topic in cognitive psychology research. A key experimental index for exploring SNAs is the spatial-numerical association of response codes (SNARC) effect, which manifests as faster and more accurate left-hand responses to small numbers and right-hand responses to large numbers. Previous studies have established both the universality of the SNARC effect and its flexibility in directional orientation, prompting multiple theoretical explanations. Moreover, the SNARC effect demonstrates flexibility in its processing stage, potentially arising from four sources: (1) misinterpretations of additive-factor logic, (2) reliance on single-perspective observations, (3) employment of different criterion measures, and (4) utilization of distinct experimental tasks. Integrating these considerations, we propose a dual-stage processing model encompassing (a) the spatial representation of magnitude information and (b) the translation from spatial representation to response selection. We suggest that differential manipulation factors acting upon these two stages constitute the core mechanism underlying the observed flexibility of the SNARC effect. Future research should further validate this dual-stage model by comparing task differences and introducing various interference factors, while incorporating cognitive neuroscience techniques to elucidate the underlying neural mechanisms of spatial-numerical association flexibility.

Keywords: SNARC effect, flexibility, spatial-numerical associations, dual-stage processing model

Classification Number: B842

1 Introduction

Numbers are integral to human society and essential tools for daily life. From primitive counting using stones or knots to modern applications in measuring height and weight, or composing unique identification numbers, humans employ numbers to describe, comprehend, and understand the world. Psychologists have long sought to understand how the brain represents and processes numerical information, investigating the mental processes underlying numerical comprehension, generation, and calculation (Dehaene, 1989, 1992; Moyer & Landauer, 1967). The association between numbers and space represents a crucial aspect of numerical processing, and studying this relationship helps illuminate the mechanisms of numerical cognition (徐晓东, 刘昌, 2006). Galton (1880) first identified the spatial characteristics of numbers through introspective reports, while Seron et al. (1992) found that most participants exhibited left-to-right mental representations of ascending numerical sequences. Beyond such introspective evidence, behavioral studies have also demonstrated spatial representations of numbers (Brysbart, 1995; Fias, Brysbart, Geypens, & d'Ydewalle, 1996; Ratinckx & Brysbart, 2002). A landmark development in this field was the discovery of the spatial-numerical association of response codes (SNARC) effect—where left-hand responses are faster and more accurate for

small numbers, while right-hand responses show superior performance for large numbers (Dehaene, Bossini, & Giraux, 1993). As an empirical indicator, the SNARC effect clearly demonstrates the existence of spatial-numerical associations, reflecting stronger connections between small numbers and left space, and large numbers and right space.

2.1 The Universality of the SNARC Effect

Dehaene et al. (1993) first observed the SNARC effect in a parity judgment task using digits 0-9. Subsequent research has extensively investigated this phenomenon across various dimensions, including numerical range, experimental materials, sensory modalities, response modes, and dependent measures (康武 et al., 2013). Regarding numerical range, the SNARC effect has been documented not only for single digits (Dehaene et al., 1993; Moro, Dell' Acqua, & Cutini, 2018; Zhao et al., 2018) but also for double-digit numbers (Brybaert, 1995; Fitousi & Algom, 2020), negative numbers (韩萌 et al., 2017; Kong, Zhao, & You, 2012), number words (Nuerk, Wood, & Willmes, 2005; 乔福强 et al., 2016), and fractions (孙玉 et al., 2016). In terms of materials, the effect extends beyond digits to include letters (Gevers, Reynvoet, & Fias, 2003; Lonnemann, Linkersdorfer, Nagler, Hasselhorn, & Lindberg, 2013), musical notes (Prpic et al., 2016), pitch (Weis, Estner, van Leeuwen, & Lachmann, 2016), time (He et al., 2020; Zhao et al., 2018), logical reasoning (Prado, Van der Henst, & Noveck, 2008), and dimensions such as area and luminance (Fumarola et al., 2014; 胡林成, 熊哲宏, 2011). Regarding sensory modalities, Nuerk et al. (2005) required participants to judge the parity of numbers presented in four formats—dot arrays, Arabic digits, visually presented German number words, and auditorily presented German number words—observing SNARC effects across all conditions, thus demonstrating the effect in non-visual modalities. Additionally, Krause et al. (2014) documented SNARC effects in the tactile modality. Concerning response modes, the effect has been observed with bimanual responses (Rusconi, Bueti, Walsh, & Butterworth, 2011; Shaki & Gevers, 2011), crossed-hand responses (Dehaene et al., 1993; Viarouge, Hubbard, & Dehaene, 2014), unimanual responses (Riello & Rusconi, 2011), and foot pedals (Hartmann, Gashaj, Stahnke, & Mast, 2014). Finally, the SNARC effect appears not only in reaction times but also in eye movement trajectories (Myachykov, Cangelosi, Ellis, & Fischer, 2015; Pressigout, Charvillat, Mersad, & Dore-Mazars, 2019; 司继伟 et al., 2013), electrophysiological measures (Keus, Jenks, & Schwarz, 2005), functional magnetic resonance imaging (Tschentscher, Hauk, Fischer, & Pulvermuller, 2012; Weis, Estner, Krick, Reith, & Lachmann, 2015), and near-infrared spectroscopy (Cutini, Scarpa, Scatturin, Dell' Acqua, & Zorzi, 2014). For instance, Keus et al. (2005) observed that SNARC-incongruent trials elicited more negative lateralized readiness potentials (LRPs) at Cz and Pz electrodes compared to congruent trials during a parity judgment task. 韩萌 et al. (2017) found that SNARC-incongruent conditions for negative numbers evoked more negative P3 components, with source localization implicating frontal and parietal regions. Neuroimaging studies of numerical processing consistently show

activation of the intraparietal sulcus across visual and non-visual stimuli, as well as for both symbolic and non-symbolic numbers (Cohen & Walsh, 2009; Dehaene, Molko, Cohen, & Wilson, 2004). These findings collectively demonstrate the universality of the SNARC effect and the phenomenon of spatial-numerical associations.

2.2 The Flexibility of the SNARC Effect

Beyond its universality, the SNARC effect exhibits flexibility in both directional orientation and processing stage. Different manipulation factors influence the effect from various angles, producing changes in direction and processing locus that reveal its flexible nature. First, regarding directional flexibility, researchers have found that participants' reading habits (left-to-right vs. right-to-left), numerical range variations (1-9, 0-4, 4-9), representational formats (ruler vs. clock), working memory sequence positions, and comparison reference standards can all affect SNARC effect direction (Dehaene et al., 1993; Fias et al., 1996; Bächtold et al., 1998; Fias & van Dijck, 2016; Zhang, Cao, & Li, 2020). For example, Dehaene et al. (1993) observed classic SNARC effects in French participants (left-to-right readers) but reversed SNARC effects in Iranian participants (right-to-left readers). Second, concerning processing stage flexibility, researchers have attempted to localize the SNARC effect to either early stimulus representation or late response selection stages by examining its relationship with stage-specific criteria (Simon effect, Stroop effect, numerical distance effect, switch costs), its manifestation across response modes (bimanual vs. oculomotor responses), and its electrophysiological correlates. However, findings remain controversial (Nan, Yan, Yang, Liu, & Fu, 2021). Some studies support an early stimulus representation locus (Fischer, Warlop, Hill, & Fias, 2004; Mapelli, Rusconi, & Umiltà, 2003; Tlauka, 2002), others favor a late response selection stage (Daar & Pratt, 2008; Gevers, Caessens, & Fias, 2005; Gevers, Ratinckx, Baene, & Fias, 2006; Keus, Jenks, & Schwarz, 2005; Keus & Schwarz, 2005; Yan, Yang, Nan, Liu, & Fu, 2021), while recent work suggests flexible occurrence across both stages (Moro et al., 2018; Nan et al., 2021; Zhang et al., 2020). The following sections elaborate on these two forms of flexibility and summarize their underlying causes.

3 The Directional Flexibility of the SNARC Effect and Theoretical Explanations

Dehaene et al. (1993) proposed the Mental Number Line hypothesis to explain the SNARC effect and its directional flexibility, though this account cannot fully explain all findings (Bächtold et al., 1998; van Dijck, Gevers, & Fias, 2009). Consequently, researchers have advanced alternative hypotheses including Polarity Coding Theory (Proctor & Cho, 2006), the Dual-Route Model (Gevers et al., 2006), Working Memory Sequence Position (Fias & van Dijck, 2016), Neural Network Models (Chen & Verguts, 2010), and Brain Hemisphere Lateralization (Vallortigara, 2017).

3.1.1 Mental Number Line Explanation

The Mental Number Line hypothesis posits that numbers are represented in the brain as a left-to-right vector, with small numbers on the left and large numbers on the right, thereby creating an intrinsic spatial attribute. The SNARC effect reflects compatibility between the spatial attributes of numbers and responses (Brysbaert, 1995; Dehaene, Dupoux, & Mehler, 1990; Vu & Proctor, 2001). When the left/right spatial attribute of a number aligns with the participant's left/right response, reaction times are faster; conversely, misalignment slows responses (Cutini et al., 2014; Dehaene et al., 1993; Fischer & Shaki, 2014; 康武 et al., 2013; Moro et al., 2018). Researchers have suggested that reading and writing habits contribute to the formation of the mental number line in long-term memory, with different habits producing distinct spatial-numerical association patterns (Dehaene et al., 1993; Fischer, Mills, & Shaki, 2010; 李雅君 et al., 2018; 刘雍江 et al., 2018). Dehaene et al. (1993) observed classic SNARC effects in French participants (left-to-right readers) but reversed effects in Iranian participants (right-to-left readers). Similar directional patterns consistent with reading habits have been found in vertical orientations (Gevers et al., 2006; Hung, Hung, Tzeng, & Wu, 2008; Schwarz & Keus, 2004; Seron et al., 1992). However, contradictory evidence exists: Ito and Hatta (2004) observed reversed spatial-numerical associations in Japanese participants (top-to-bottom readers). Dehaene et al. (1993) and Fias et al. (1996) demonstrated that numerical range can reverse SNARC effect direction—digit 4 is relatively large in 0-5 range (faster right-hand responses) but relatively small in 4-9 range (faster left-hand responses). Bächtold et al. (1998) showed that representational format alters SNARC direction: when participants (left-to-right readers) imagined numbers arranged as a ruler (small-left) versus a clock (small-right), classic and reversed SNARC effects emerged respectively. van Dijck et al. (2009) found that sequence position in working memory reverses the effect: when memorizing number sequences, early positions associate with left space and late positions with right space, regardless of numerical magnitude. Zhang et al. (2020) demonstrated that reference standards modulate direction: using 3 and 7 as reference cues, digits 4-6 were relatively large compared to 3 (showing classic SNARC) but relatively small compared to 7 (showing reversed SNARC). Thus, the long-term memory mental number line hypothesis cannot fully account for all spatial-numerical phenomena (Abrahamse, van Dijck, & Fias, 2016).

3.1.2 Polarity Coding Theory

Proctor and Cho (2006) proposed Polarity Coding Theory, which posits that semantic concept associations determine the SNARC effect. In binary classification tasks, stimuli and responses are typically coded as positive or negative polarity. In the SNARC context, “right,” “up,” and “large” share positive polarity, while “left,” “down,” and “small” share negative polarity. Response selection is faster when stimulus category (e.g., “large”) and response location (e.g., “right”) share congruent polarity. While this theory explains more findings than the

mental number line in binary classification tasks—particularly how relative magnitude coding accounts for numerical range effects (Dehaene et al., 1993; Zhang et al., 2020)—it cannot explain influences of representational format or working memory sequence position.

3.1.3 Dual-Route Model Explanation

Verguts et al. (2005) proposed a connectionist model of numerical cognition to explain and integrate findings in the field, with position coding, linear scaling, and fixed variations of the mental number line as key features. Gevers et al. (2006) integrated and extended Polarity Coding Theory and the connectionist model to propose a computational dual-route model. This model posits that numerical processing involves two parallel pathways: an unconditional route and a conditional route. In the unconditional route, associations between numerical magnitude and spatial location in long-term memory are automatically activated. In the conditional route, numbers are encoded as task-relevant binary categories (e.g., parity) according to current task demands, with category-response mapping activated in working memory. The SNARC effect emerges from the congruence between activations in these two pathways. When task-relevant mapping rules align with long-term memory spatial-numerical associations, the pathways cooperate, yielding faster responses; otherwise, they compete, slowing responses. Consequently, changes in task-demanded representational format (ruler vs. clock) produce different SNARC effect directions (Bächtold et al., 1998).

3.2.1 Working Memory Explanation

Beyond early theories, researchers have introduced working memory sequence position to explain spatial-numerical associations (Abrahamse et al., 2016; Fias & van Dijck, 2016; van Dijck & Fias, 2011; van Dijck et al., 2009). This hypothesis proposes that spatial coding of sequence positions in working memory induces SNARC effects: early/late positions in a memorized sequence associate with left/right space, creating a temporary mental number line that may be stronger than the long-term memory representation. Consequently, only the short-term mental number line is observable experimentally, with its direction either matching or opposing the long-term representation. Lindemann et al. (2008), Herrera et al. (2008), and van Dijck et al. (2009) first confirmed the critical role of working memory mental number lines in SNARC effects. This working memory sequence position hypothesis extends earlier theories by explaining variations in SNARC effect direction (邓之君 et al., 2017).

3.2.2 Neural Network Model Explanation

Chen and Verguts (2010) extended the dual-route model by incorporating cultural and physiological factors (specifically the lateral intraparietal area, LIP) to propose a neural network model of spatial-numerical associations. This dual-source hypothesis suggests two origins of SNARC effects: (1) automatic

magnitude-response associations (small-left, large-right), and (2) number-space interactions in LIP where small numbers preferentially activate left spatial coding units, facilitating “left” responses, with large numbers showing the opposite pattern. This hypothesis has been supported by Gevers et al. (2010) and van Dijck et al. (2009), who demonstrated contributions from both linguistic-spatial and visuospatial response coding to the SNARC effect.

3.2.3 Biological Explanation via Brain Hemisphere Lateralization

Critically, spatial-numerical associations have been observed in populations without language capabilities, including patients with unilateral neglect (Zorzi, 2002), preschool children (van Galen & Reitsma, 2008), infants (Bulf, de Hevia, & Macchi Cassia, 2016), newborns (Giorgio et al., 2019), and animals (Drucker & Brannon, 2014). These findings challenge early theoretical explanations. Vallortigara (2017) proposed a theory based on brain hemisphere specialization for emotional valence: small/large quantities trigger negative/positive emotions that preferentially activate right/left hemispheres, causing left/right behavioral biases. Felisatti et al. (2020) advanced a biological mechanism based on asymmetric spatial frequency tuning in animal brains, where visual patterns containing few/many elements preferentially engage right/left hemispheres, producing left/right biases—an effect validated in newborns. Zhou et al. (2020) observed left-hand lateralization in semantic tasks (parity judgment, fruit-vegetable classification) but not in magnitude comparison tasks, suggesting this difference may relate to combined influences of brain hemisphere lateralization and task-relevance of spatial coding.

4 The Flexibility of SNARC Effect Processing Stage and Potential Causes

Beyond directional flexibility, the processing stage at which the SNARC effect occurs remains controversial. Information processing theory delineates sequential stages from stimulus presentation to response execution: stimulus representation, response selection, and response execution (Duncan, 1980; Marois, Larson, Chun, & Shima, 2006; Tombu et al., 2011). Researchers have proposed three main viewpoints: (1) the effect occurs at the stimulus representation stage (Tlauka, 2002), (2) it occurs at the response selection stage (Daar & Pratt, 2008; Yan et al., 2021), or (3) it occurs at both stages (Moro et al., 2018; Zhang et al., 2020; Nan et al., 2021).

4.1 Evidence for the Stimulus Representation Stage

The first viewpoint holds that the SNARC effect occurs during stimulus representation (Fischer et al., 2004; Mapelli et al., 2003; Tlauka, 2002). Three lines of evidence support this claim. First, the SNARC effect shows no interaction with the Simon effect in reaction times (Mapelli et al., 2003; Tlauka, 2002). Since the classic Simon effect (faster left/right responses to left/right spatial stimuli)

has been localized to the response selection stage (De Jong, Liang, & Lauber, 1994; 金桂春 et al., 2017; Leuthold, 2011), additive-factor logic suggests that absence of interaction indicates different processing stages (Liu, Park, Gu, & Fan, 2010; Sternberg, 1969). Tlauka (2002) and Mapelli et al. (2003) simultaneously induced SNARC and Simon effects by presenting target digits on left/right screen locations requiring left/right keypresses, finding no interaction in reaction times, thus inferring an early stimulus representation locus for SNARC. Second, SNARC effects have been observed with central response modes lacking spatial differentiation (Fischer et al., 2004). Fischer et al. (2004) documented SNARC effects using central oculomotor responses (eye movements), suggesting an early stimulus-related rather than late response-related stage. Additionally, Pinto et al. (2019) used a go/no-go task and found that SNARC effects only emerged when spatial coding and magnitude coding at the stimulus representation stage were jointly engaged, supporting an early locus. Third, electrophysiological studies show early component modulations such as N1 and P1 (Gut, Szumska, Wasilewska, & Jaskowski, 2012; Schuller, Hoffmann, Goffaux, & Schiltz, 2014). Gut et al. (2012) simultaneously induced SNARC and Flanker effects using a numerical Flanker task, observing larger N1 amplitudes for SNARC-incongruent versus congruent trials, suggesting SNARC originates at the parieto-occipital N1 component. Schuller et al. (2014) found that digits as cues can direct attentional biases (small-left, large-right), with attentional effects also appearing in early P1 components.

4.2 Evidence for the Response Selection Stage

The second viewpoint argues that the SNARC effect occurs at the response selection stage (Daar & Pratt, 2008; Gevers et al., 2005; Gevers et al., 2006; Keus, Jenks, & Schwarz, 2005; Keus & Schwarz, 2005; Yan et al., 2021). Corresponding to the three evidence types above, first, SNARC and Simon effects do interact in reaction times (Gevers et al., 2005). Using additive-factor logic, Gevers et al. (2005) replicated Mapelli et al.'s (2003) design and observed a triple interaction among SNARC, Simon, and reaction time distribution, suggesting that as reaction times increase, SNARC and Simon effects interact, implying they share a common late response selection stage. Yan et al. (2021) also observed SNARC-Simon interactions in parity judgment tasks, supporting a late response selection locus. Second, SNARC effects appear only with left/right hand responses, not central response modes (Keus & Schwarz, 2005). Keus et al. (2005) manipulated stimulus position (lateral/central) and response mode (central verbal/left-right keypress), finding SNARC effects independent of stimulus position but present only in left-right keypress responses, not central verbal reports, suggesting a link to left-right spatial responses and thus a response selection stage. Third, electrophysiological studies show late component modulations including P300 and LRP (Keus et al., 2005; Gevers et al., 2006). Keus et al. (2005) found SNARC effects influenced the response-selection-related lateralized readiness potential (LRP). Gevers et al. (2006) replicated this and further showed that stimulus-locked LRP onset latency was earlier for SNARC-congruent than incongruent trials,

while response-locked LRP showed no difference, providing further evidence for a response selection locus.

Additionally, 徐晓东 and 刘昌 (2006) comprehensively reviewed behavioral and electrophysiological evidence, concluding that most findings support a response selection stage. Muller and Schwarz (2007) used a psychological refractory period paradigm with parity judgment and tone discrimination tasks, finding SNARC effects unaffected by stimulus onset asynchrony (SOA). Daar and Pratt (2008) employed a free-choice paradigm where participants freely pressed left/right keys to centrally presented digits, showing a tendency to press left for small numbers and right for large numbers, demonstrating a direct relationship between magnitude and response selection. Didino et al. (2019) used semantic and non-semantic tasks to test whether semantic processing affects SNARC, finding the effect unaffected by semantic processing but modulated by response latency—slower responses produced stronger effects. These studies collectively support a response selection stage.

4.3 Evidence for Occurrence at Both Stages

Beyond single-stage accounts, recent research increasingly supports a novel view: the SNARC effect may not be confined to one stage but occurs at both stimulus representation and response selection stages (Moro et al., 2018; Nan et al., 2021; Zhang et al., 2020). Moro et al. introduced the numerical distance effect (stimulus representation stage; van Opstal & Verguts, 2011) and switch costs (response selection stage; Hirsch, Nolden, & Koch, 2017) into SNARC paradigms, examining interactions among the three effects. They observed interactions between SNARC and switch costs (response selection) and a triple interaction among SNARC, distance effect (stimulus representation), and reaction time distribution. Zhang et al. (2020) similarly observed triple interactions among SNARC, response rules (response selection), and distance effects (stimulus representation). Nan et al. (2021) used a modified magnitude comparison task incorporating manual Stroop effects (stimulus representation; Li, Nan, Wang, & Liu, 2014) and Simon effects (response selection), finding SNARC interactions with both Stroop and Simon effects. These results support a dual-stage account. Electrophysiologically, 韩萌 et al. (2017) observed flexible SNARC occurrence across stages under different conditions within the same experiment. In a magnitude comparison task manipulating sign congruency between target and baseline numbers (± 5), they found that when signs matched, incongruent trials evoked more negative P300 (response selection stage); when signs differed and baseline was +5, incongruent trials evoked more negative N300 (stimulus representation stage); when baseline was -5, congruent trials evoked larger late positive potentials (LPP), suggesting response execution stage involvement.

4.4 Possible Reasons for Processing Stage Flexibility

Controversies regarding the SNARC effect's processing stage likely stem from four factors. First, misinterpretation of additive-factor logic leads to indirect

inferences. Most previous studies localized SNARC processing through its relationship with the Simon effect (Gevers et al., 2005; Mapelli et al., 2003; Scerrati, Lugli, Nicoletti, & Umiltà, 2017; Stroop, 1935). According to additive-factor logic, absence of SNARC-Simon interaction only indicates they occur at different stages; concluding that SNARC occurs at the stimulus representation stage constitutes an indirect inference. Direct inference requires comprehensive examination across stages, simultaneously introducing effects occurring at both stimulus representation and response selection stages (Moro et al., 2018; Nan et al., 2021; Yan et al., 2021) to directly determine processing locus. Recent dual-stage studies have adopted this logic.

Second, single-perspective observation leads to indirect inferences. Beyond SNARC-Simon studies, most research has examined the effect from only one angle. For example, Fischer et al. (2004) observed SNARC effects with central oculomotor responses, inferring an early stimulus-related stage; Schuller et al. (2014) used digits as attentional cues, finding attentional biases (small-left, large-right) and early P1 effects, concluding early-stage processing; Daar and Pratt (2008) found free-choice response biases linking magnitude directly to response selection; Keus et al. (2005) and Gevers et al. (2006) found late component modulations (P300, LRP). While supporting single-stage accounts, these studies share the limitation of demonstrating occurrence at one stage without excluding other stages.

Third, different types of Simon effects have been used as criteria, with distinct mechanisms causing divergent results. Simon effects are classified as visuomotor or cognitive based on how spatial attributes are perceived (王力 et al., 2013; Wang, Du, He, & Zhang, 2014; Wiegand & Wascher, 2005). These types differ in reaction time distribution analysis, hand-proximity effects, and LRP components. Visuomotor Simon effects, induced by transient visual position information, decrease, disappear, or reverse with longer reaction times, are modulated by hand proximity (larger when response hand is near the stimulus), and show early LRP deflections in incongruent conditions. Cognitive Simon effects, induced by cognitively coded spatial information, remain stable or increase with longer reaction times, are not modulated by hand proximity, and show no early LRP deflections (Wiegand & Wascher, 2005, 2007). Most SNARC-Simon studies have used visuomotor Simon effects that diminish over time, yielding inconsistent interactions (Gevers et al., 2005; Keus & Schwarz, 2005; Mapelli et al., 2003; Treccani, Milanese, & Umiltà, 2010), whereas studies using cognitive Simon effects have consistently observed SNARC-Simon interactions (Nan et al., 2021; Yan et al., 2021). Future research should employ cognitive Simon effects to clarify SNARC's processing stage.

Fourth, different experimental tasks engage distinct processing pathways for the SNARC effect, leading to divergent observations. Common paradigms include parity judgment and magnitude comparison tasks, which process magnitude information differently and thus produce different SNARC effect pathways (see Figure 1 [Figure 1: see original paper]) (Dehaene et al., 1993; Deng, Chen,

Zhang, Li, & Zhu, 2018; Deng, Chen, Zhu, & Li, 2017; Gevers, Lammertyn, et al., 2006). In parity judgment, participants process magnitude implicitly (task-irrelevant), with magnitude information automatically activating mental number line representations that conflict with current responses to produce SNARC effects. In magnitude comparison, magnitude is processed explicitly (task-relevant), with intentional top-down activation of mental number line representations. Deng et al. (2018) observed that SNARC effect magnitude fluctuates over time in parity tasks but emerges earlier and remains stable or increases in magnitude comparison tasks. Nan et al. combined SNARC, Simon (response selection), and Stroop (stimulus representation) effects, finding SNARC-Simon interactions in parity tasks (supporting response selection; Yan et al., 2021) but SNARC interactions with both Simon and Stroop in magnitude comparison tasks (supporting dual-stage occurrence; Nan et al., 2021).

4.5 The Dual-Stage Processing Model

Previous theories have not adequately explained the flexible processing stage of the SNARC effect. Therefore, this review proposes a conceptual dual-stage processing model (Figure 1) to address this issue. The model comprises three layers: an input layer receiving magnitude and parity information; a representation layer where input information undergoes magnitude and parity coding, with magnitude coding further generating spatial representations; and a response output layer that receives representational input and generates responses according to task demands. The dual-stage model posits that the SNARC effect occurs at both stimulus representation and response selection stages, specifically manifesting as (a) spatial representation of magnitude information and (b) translation from spatial representation to response selection. Any factor interfering with either stage will affect SNARC effect generation and magnitude, producing the varied forms and relationships observed across studies.

Figure 1 illustrates the dual-stage processing model for SNARC effects in magnitude comparison and parity judgment tasks. Solid lines indicate task-relevant processing pathways, dashed lines indicate task-irrelevant pathways, and lightning arrows indicate that interference at any point in the SNARC generation chain affects the effect. Panel A shows magnitude comparison tasks where magnitude is task-relevant and parity is irrelevant; Panel B shows parity judgment tasks where parity is task-relevant and magnitude is irrelevant.

We attribute different experimental findings to differential influences on the two SNARC stages: (1) Representation-related factors including long-term memory, working memory load, task type, and Stroop tasks affect the spatial representation of magnitude stage. Reading habits in long-term memory influence spatial coding of numerical information, producing left-to-right SNARC effects in left-to-right readers and reversed effects in right-to-left readers (Dehaene et al., 1993). Limited cognitive resources mean high working memory load disrupts magnitude-to-space translation, causing SNARC effects to disappear or reverse (van Dijck & Fias, 2011). Task type also affects this stage: in color judgment

tasks lacking deep numerical processing, insufficient magnitude-space representation prevents SNARC effects (Didino et al., 2019). Background Chinese characters “大小” (big-small) inducing Stroop effects provide additional magnitude information that impacts this stage, producing SNARC-Stroop interactions (Nan et al., 2021). (2) Response-related factors including Simon tasks and response rule switching affect the spatial-to-response selection stage. When digits appear on left/right screen locations, stimulus position influences spatial representation, further interfering with spatial-to-response translation and potentially eliminating SNARC effects (金桂春 et al., 2017). Response rule switching affects response selection, disrupting the spatial-to-response stage and producing SNARC-switch cost interactions (Moro et al., 2018; Zhang et al., 2020).

The dual-stage model distinguishes processing pathways for magnitude as task-relevant versus irrelevant information across different tasks, proposing that multiple manipulation factors affect SNARC’ s two stages from different angles, thereby comprehensively explaining the flexible phenomena observed in previous research.

5.1 Research Summary

The SNARC effect serves as a widely used empirical index demonstrating that numbers convey not only magnitude information but also spatial information (Gevers et al., 2005; Nuerk et al., 2005). Multiple studies have verified the effect’ s existence from various perspectives. However, the SNARC effect is flexible and susceptible to different manipulation factors (Dehaene et al., 1993; van Dijck & Fias, 2011). Concurrently, debate persists regarding its flexible localization to processing stages (stimulus representation vs. response selection). This review summarizes and compares previous theoretical hypotheses and models, proposing a dual-stage processing model where SNARC generation involves two key stages: spatial representation of magnitude information and translation from spatial representation to response selection, corresponding to early stimulus representation and late response selection stages in information processing. The dual-stage model suggests that different manipulation factors interfere with these two stages from different angles, producing the flexible phenomena observed across studies.

5.2 Future Directions

Several issues warrant further exploration in SNARC effect research. First, investigating task differences is crucial. Common SNARC-inducing tasks—parity judgment and magnitude comparison—process magnitude information differently (see Figure 1). In parity tasks, SNARC effects arise from automatic processing of task-irrelevant magnitude information that generates spatial codes influencing response selection. In magnitude comparison, magnitude is task-relevant and processed intentionally. Nan et al.’ s combined SNARC-Simon-Stroop design found SNARC-Simon interactions only in parity tasks (Yan et

al., 2021) but SNARC interactions with both Simon and Stroop in magnitude comparison tasks (Nan et al., 2021). Future research should further explore these task differences.

Second, the processing stage of SNARC effects requires clarification. Despite extensive investigation, disagreements persist without sufficient empirical resolution. This review proposes a dual-stage model suggesting SNARC occurs at both early stimulus representation and late response selection stages, with any interference at either stage affecting the effect. Future studies could validate this model by: (1) manipulating input information load to alter representational demands, such as adding color information to increase processing load; (2) manipulating response selection demands, such as increasing from two to four response keys; (3) combining SNARC with other conflict tasks occurring at different stages, such as Flanker or Stroop effects that involve both stimulus and response conflicts (唐丹丹 et al., 2020; 唐丹丹 et al., 2018; Treccani, Cubelli, Della Sala, & Umiltà, 2009); and (4) employing alternative validation methods beyond additive-factor logic, such as conflict adaptation (Yang, Nan, Zheng, Wu, Li, & Liu, 2017) or proportion congruency effects (Spinelli & Lupker, 2020), to examine SNARC's relationship with other conflict effects from multiple perspectives.

Third, the relationship between SNARC and the Linguistic Markedness of Response Codes (MARC) effect warrants attention. Numbers contain both magnitude and parity information. Previous research has found MARC effects similar to SNARC: left-hand responses are faster to odd numbers, right-hand to even numbers (Nuerk, Iversen, & Willmes, 2004). Like SNARC, MARC effects can be decomposed into two processing stages (Figure 2 [Figure 2: see original paper]). Introducing interference factors at both stages may similarly modulate MARC effects. Parity and magnitude representations may influence each other, with potentially different representational strengths. In Figure 2, MARC and SNARC effects are not independent but share the spatial-to-response selection process. Future research should examine whether MARC effects follow the dual-stage model and compare MARC-SNARC relationships to further explore the internal mechanisms of spatial-numerical association flexibility.

Fourth, the controversy regarding long-term versus working memory contributions to SNARC effects requires resolution. The relationship between these memory systems remains a research focus. Oberauer et al. (2017) proposed that information exchange between long-term and working memory is controlled by a gate that protects working memory contents but can receive long-term information when needed. Early research emphasized reading and cultural factors, suggesting long-term memory representations underlie SNARC effects (Dehaene et al., 1993; Fischer & Shaki, 2014; Ginsburg & Gevers, 2015; Shaki, Fischer, & Petrusic, 2009; Toomarian & Hubbard, 2018). Others argue that temporary spatial associations formed by sequence positions in working memory are critical (Fias & van Dijck, 2016; Fischer & Shaki, 2016; van Dijck & Fias, 2011; van Dijck et al., 2009). Abrahamse et al. (2016) theoretically analyzed memory re-

search and denied long-term memory contributions, arguing that only working memory matters. Future empirical work must investigate whether both memory systems contribute to spatial-numerical associations and whether they operate at different processing stages.

Fifth, the neural mechanisms of SNARC effects require further elucidation. Gut et al. (2012) observed SNARC effects in N1 components, suggesting early occurrence, while Keus et al. (2005) and Gevers et al. (2006) found stimulus-locked LRP onset latency differences but no response-locked differences, suggesting late occurrence. Additionally, spatial-numerical associations in non-linguistic populations (newborns, animals) have prompted biological explanations (Felisatti et al., 2020; Vallortigara, 2017). Current research on SNARC's relationship with other effects remains primarily behavioral (Mapelli et al., 2003; Nuerk et al., 2004). Future studies should employ EEG, fMRI, and fNIRS technologies combined with biological factors to investigate neural mechanisms, localize specialized brain regions for numerical processing, and identify relevant functional connectivity to determine the neural basis of flexibility.

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

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