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Brief article

Deconstructing spatial-numerical associations

Samuel Shaki[a,*], Martin H. Fischer[b]

[a] Ariel University, Israel
[b] University of Potsdam, Germany

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ABSTRACT

Spatial-numerical associations (SNAs) have been studied extensively in the past two decades, always requiring either explicit magnitude processing or explicit spatial-directional processing. This means that the typical finding of an association of small numbers with left or bottom space and of larger numbers with right or top space could be due to these requirements and not the conceptual representation of numbers. The present study compares explicit and implicit magnitude processing in an implicit spatial-directional task and identifies SNAs as artefacts of either explicit magnitude processing or explicit spatial- directional processing; they do not reveal spatial-conceptual links. This finding requires revision of current accounts of the relationship between numbers and space.

1. Introduction

Small numbers are associated with left space, larger numbers with right space – the study discovering this SNARC (spatial-numerical association of response codes) effect has since its discovery been cited 2200 times (citations for Dehaene, Bossini, & Giraux, 1993, on Google Scholar, January 22, 2018). Such interest in the SNARC effect reflects its importance for understanding numerical processing, cognition generally, and its practical implications. However, previous work on SNARC has two important limitations. First, it focused on assessments with spatially distributed stimuli or responses (see review by Fischer & Shaki, 2014). This assessment introduces spatial processing into the task and thereby contaminates the evidence. Secondly, almost all studies used magnitude classification or parity judgments. In magnitude classification, participants decide whether a number is larger or smaller than a standard, thus requiring explicit magnitude comprehension[1] which may bias number processing. Parity judgments require participants to decide whether a number is odd or even, thereby not demanding explicit magnitude activation. Implicit magnitude processing ensures that any magnitude effect on performance reflects obligatory semantic processing that was not merely instructed by the task.

Results from both explicit and implicit tasks yielded converging results, implying an inherently spatial mental number line where small numbers are cognitively represented to the left of larger numbers. Consequently, processing is more efficient whenever the side of the mental stimulus and the side of the response are horizontally aligned.

Here we wish to refute this widely held inference. Given that our argument has broader implications we consider the SNARC effect as one instance of spatial-numerical associations (SNAs) more generally (cf. Fischer & Brugger, 2011) and summarize the entire evidence regarding horizontal SNAs in a 2 × 2-Table with factors magnitude processing (explicit, implicit) and spatial-directional processing (explicit, implicit; see Table 1).

The original SNARC study (Dehaene et al., 1993) exemplifies implicit magnitude processing with explicit spatial-directional processing: participants classified digits by parity with lateralized keys. The study of Gevers et al. (2010, Experiment 1) raised the problem of spatial-directional response activation: participants said "left" or "right" to odd or even numbers. Facilitation of non-lateralized detection responses involves a spatial coding process for lateralized stimuli, either targets (Fischer, 2003; Ranzini, Dehaene, Piazza, & Hubbard, 2009) or inducers (Sallilas, El Yagoubi, & Semenza, 2008; Stoianov, Kramer, Umilta, & Zorzi, 2008). Therefore, all studies in this cell explicitly induced spatial-directional processing, thus perhaps artificially creating spatial-numerical associations.

Explicit magnitude processing with explicit spatial-directional processing is tapped when numbers are compared to a standard in single-number trials (magnitude classification) and when two different numbers are compared in each trial (magnitude comparison), with responses given on lateralized keys. Typical examples are Bächtold, Baumüller, and Brugger (1998) who showed how imagery instructions change SNAs, and Shaki and Petrusic (2005) who investigated negative

* Corresponding author.
E-mail address: samuel_shaki@hotmail.com (S. Shaki).

[1] A task variant with two simultaneously presented numbers (magnitude comparison task) yields similar results: Decisions are faster when the number is more remote from the standard.

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Table 1
Summary of existing literature on the SNARC effect, with sample references. For details, see text.

		Magnitude processing	
		Explicit	Implicit
Spatial-directional processing	Explicit	**Magnitude classification** (Bächtold et al., 1998) **Magnitude comparison** (Shaki & Petrusic, 2005) **Midpoint estimation** (Zorzi et al., 2002)	**Parity classification** (Dehaene et al., 1993; Gevers et al., 2010) **Detection** (Fischer, 2003; Stoianov et al., 2008)
	Implicit	Go/no-go task (Fischer & Shaki, 2016, 2017) Random Number Generation (Loetscher et al., 2010; Shaki & Fischer, 2014) **Calculation** (Hartmann et al., 2016; Holmes, Ayzenberg, & Lourenco, 2016)	[none]

numbers. In interval bisection (e.g., Zorzi, Priftis, & Umiltà, 2002) spatial processing is imposed per task instruction (use of "interval" and "midpoint") and in recent work of Ranzini et al. (2015) and Ranzini, Lisi, and Zorzi (2016) right-ward eye movements improved larger number processing. All studies in this cell may have artificially imposed spatial-numerical associations.

Consider now explicit magnitude processing and implicit spatial-directional processing. Fischer and Shaki (2016, 2017) modified the Implicit Association Test (Greenwald, McGhee, & Schwartz, 1998) to assess horizontal SNAs with go/no-go responses (Nosek & Banaji, 2001). They removed explicitly spatial features during number assessment by using only a single central response key and (in half of the trials) a single central number. Direction was implicit because participants remembered a go-nogo instruction; this instruction included a directional component which was not relevant for go-decisions on numbers. Nevertheless, a horizontal SNA was observed and therefore interpreted as purely conceptual. However, even this approach explicitly activated magnitude processing. Similarly, random number generation without spatial behavioural instructions (Loetscher, Bockisch, Nicholls, & Brugger, 2010) required participants to check each number word they produced for its acceptability with regard to the instructed magnitude range, hence triggering the magnitude meaning of numbers. Finally, calculation tasks (e.g., Hartmann, Mast, & Fischer, 2016; Holmes et al., 2016), where spontaneous eye movements reflect the current count, may also artificially elicit spatial-numerical associations via explicit magnitudes.

Implicit processing of both magnitude and spatial directionality constitutes the litmus test for the inherent spatial nature of number concepts because both ingredients of the association of interest (number magnitude and space) are generated internally by participants. Obtaining evidence for SNAs with both implicit magnitude and implicit spatial-directional processing is crucial because without such evidence we cannot know whether the number symbol by itself activates a spatial representation of number meaning. Crucially, there is almost no published work fitting this requirement. One possible exception concerns evidence from neglect patients (Priftis et al., 2008) who showed slower brain waves when hearing small than large number names but this evidence remained correlational, did not affect overt responding and was absent in control patients without spatial deficits. We report below the first assessment of horizontal SNAs with both explicit (magnitude classification) and implicit (parity judgment) tasks but without explicit spatial-directional behaviour, in order to obtain causal evidence for spatial-numerical associations. Only finding SNAs in the parity task with go/no-go responses establishes the inherently spatial nature of number knowledge.

SNAs also exist for vertical space and denote a preference to associate small numbers with the bottom and larger numbers with the top (Ito & Hatta, 2004; Winter, Matlock, Shaki, & Fischer, 2015). Vertical SNAs are interesting because most explanations for horizontal SNAs (hemispheric asymmetry: e.g., De Hevia, Veggiotti, Streri, & Bonn, 2017; Rugani, Vallortigara, Priftis, & Regolin, 2015; Rugani et al., 2017; reading direction: e.g., Fischer, Shaki, & Cruise, 2009; Göbel, McCrink, Fischer, & Shaki, 2018; Shaki, Fischer, & Petrusic, 2009; finger counting: e.g., Fischer & Brugger, 2011; serial working memory: e.g., Abrahamse, van Dijck, & Fias, 2016) cannot be extended to vertical SNAs. Instead, vertical SNAs may reflect universal physical laws ("more is up") and suggest an embodied origin of SNAs in sensory-motor experiences (Fischer, 2012; Lakoff & Nunez, 2000; Werner & Raab, 2014).

Evidence on vertical SNAs is mixed; given that all previous studies assessed vertical SNAs with explicit spatial-directional processing (cf. Table 1 in Winter et al., 2015), this inconsistency may reflect spatial biases imposed by the assessment methods used. We ask: Are there vertical SNAs when their assessment involves both implicit magnitude processing and implicit spatial-directional processing? Analogous to the horizontal dimension, we also compared explicit and implicit magnitude processing along the vertical dimension in an implicitly spatial-directional task. Again, only finding SNAs in the parity task with go/no-go responses establishes the inherently spatial nature of number knowledge.

2. Experiment 1

2.1. Participants

Thirty-three adults (21 native Russians, 12 native Germans) participated. Their average age was 25.7 years (range: 19–37). Two were left-handed and 5 male. All were naïve regarding our hypotheses.

2.2. Stimuli and apparatus

Stimuli were presented in black on white background on a 19″ monitor with 1280 × 1024 pixels resolution via PC. The space bar of a QWERTY keyboard recorded responses (Fig. 1). Four digits (1, 2, 8, 9; size 2.5 × 1.5 cm) and four arrows (pointing left, right, up, down; size 2.5 × 4 cm) appeared at fixation in structured blocks (see below).

2.3. Design

In separate blocks for magnitude and parity tasks the 4 digits were randomly mixed with four arrows: either horizontal or vertical arrows of different shapes (two pointing in each direction). This resulted in 16 blocks with different response rules (e.g., in the parity task, responded to "even + left" stimuli in one block, to "odd + down" stimuli in another block, etc.). These pairings constitute the key logic of our method: Combining number-related with arrow-related instructions, we show digits non-spatially and record implicitly spatial responses for them while at the same time measuring a spatial congruency effect for each digit with the instructed spatial rule-component. Thus, we introduced direction as a task feature but it was not explicitly induced during numerical trials. There were 56 trials per block (7 repetitions per stimulus); block order was counterbalanced by task.

2.4. Procedure

Participants sat 55 cm from the screen and were instructed to "respond fast and accurately only in trials where a stimulus matches the current response rule" (i.e., in 14 number trials and 14 arrow trials, yielding 50% go trials). Blocks began by displaying the response rule