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Brief article

Deconstructing spatial-numerical associations

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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

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[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

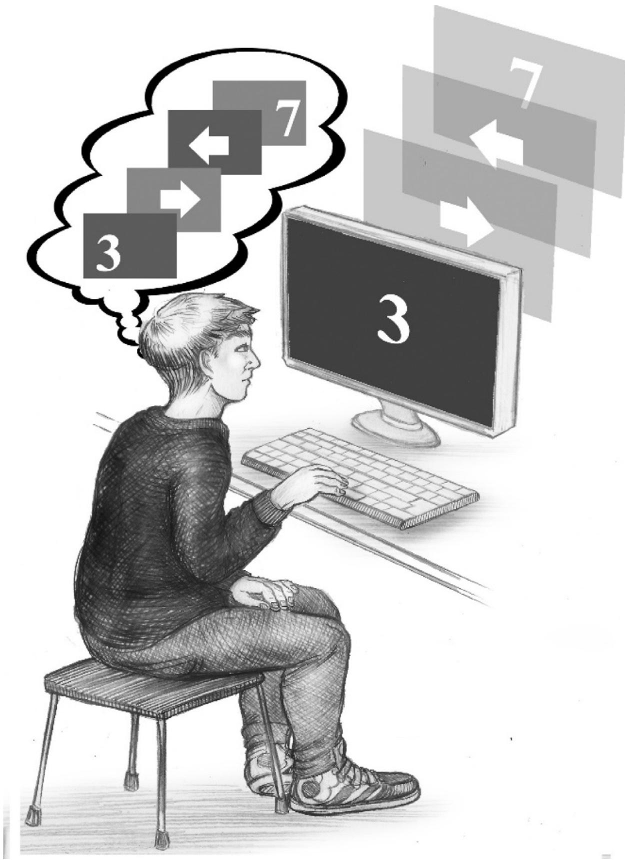

Fig. 1. Experimental set-up. For details see text.

(e.g., the rule "digits smaller than 5 or arrows facing left" would require responses to the first and third display shown in Fig. 1 above and only the first response would be analyzed here, as described below). Each trial showed a randomly selected stimulus at fixation until response (go trials, false alarms) or until 2000 ms had elapsed (no-go trials, misses). Response speed and accuracy were recorded, followed without feedback by the next trial. Data were collected in two 1-h sessions (for magnitude and parity tasks) a few days apart.

2.5. Analyses

Data from two Russian-speaking participants with > 15% errors were discarded; the remaining participants' error rate was too low for analysis (0.008% commissions, 0.003% omissions). We accepted correct reaction times to digits from 300 to 1500 ms (97.8%) for analysis. We computed congruity scores in each main condition (Magnitude task/Vertical orientation, Magnitude task/Horizontal orientation, Parity task/Vertical orientation, Parity task/Horizontal orientation). For horizontal arrows, we combined small numbers with left arrows and large numbers with right arrows into the congruent condition, and small numbers with right arrows and large numbers with left arrows into the incongruent condition. Similarly, for vertical arrow orientations, we combined small numbers with down arrows and large numbers with up arrows into the congruent condition, and small numbers with up arrows and large numbers with down arrows into the incongruent condition. Then we subtracted each participant's congruent mean from their incongruent mean to obtain congruity scores. On those congruity scores a repeated-measures ANOVA evaluated effects of arrow orientation (horizontal, vertical) and task (magnitude, parity).

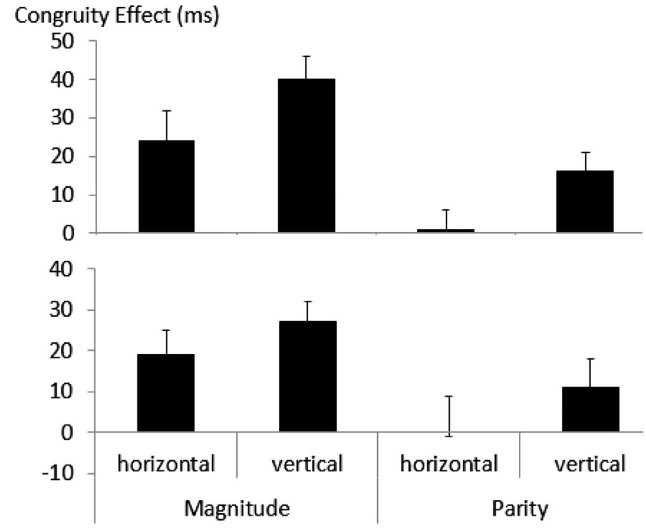

Fig. 2. Spatial congruity effect. Upper panel: Experiment 1 (using arrows). Lower panel: Experiment 2 (using colours).

2.6. Results

We found a reliable main effect of arrow orientation, $F(1, 30) = 8.62$, $p = .006$, partial eta^2 = .22. The congruity effect was larger with vertical than horizontal arrows. We also obtained a reliable main effect of task, $F(1, 30) = 15.21$, $p = .001$, partial eta^2 = .37. The congruity effect was larger for magnitude compared to parity tasks. There was no reliable interaction, $F < 1$.

Separate *t*-tests evaluated the reliability of the congruity effect in each of the four experimental conditions (Fig. 2, upper panel). In the magnitude task the horizontal congruity effect was 24 ms (SEM = 8.1 ms), $t(30) = 2.9$, $p = .006$, Cohen's d = 0.53; the vertical congruity effect was 40 ms (SEM = 5.5 ms), $t(30) = 7.2$, $p = .001$, d = 1.31. In the parity task, the horizontal congruity effect was 1 ms (SEM = 5 ms), $t(30) = 0.2$, $p = .80$, d = 0.04. This result is remarkable because it constitutes the standard SNARC assessment. Finally, the vertical congruity effect was 16 ms (SEM = 5 ms), $t(30) = 3.9$, $p = .002$, d = 0.57.

3. Experiment 2

A possible objection to Experiment 1 concerns the fact that terms "left" and "right" were explicit parts of the response rules, thus introducing indirectly an explicit spatial bias into number trials. Although the well-established implicit association test (Greenwald et al., 1998) argues against this, we conducted a second experiment to replicate our novel finding with a new response rule that contained no spatial terminology: We replaced the black arrows with red and green arrows while leaving other aspects of the task unchanged; participants were instructed to respond on the basis of colour instead of direction.

3.1. Participants

Twenty-four adults (all Hebrew speakers[2]) participated. Their average age was 23.6 years (range: 20–28). Three were left-handed and 5 male; all were naïve regarding our hypotheses.

[2] In response to a reviewer, we tested Hebrew speakers to extend the generality of findings. Note that only adults who prefer to count from left to right were examined here because counting direction preference influences spatial-numerical mappings; cf. Fischer & Shaki, 2017).

3.2. Stimuli and apparatus

These were similar to Experiment 1 with the following exceptions: Eight digits (1, 2, 3, 4, 6, 7, 8, 9[3]) and sixteen colored arrows (pointing left, right, up, down; each either empty or filled in either green or red) were presented at fixation in specifically structured blocks.

3.3. Design and procedure

In separate blocks for magnitude and parity tasks, the eight digits were randomly mixed with either four horizontal or four vertical arrows of different filling. Arrow colors were fixed for each participant (e.g. red left arrows and green right arrows) to support identical between-block analyses as before. This resulted in 16 blocks with different response rules (e.g., in the magnitude task: "smaller + red"). There were 48 trials per block (4 repetitions per stimulus). Block order was counterbalanced by task. The procedure of Experiment 1 was repeated.

3.4. Analyses

Error rates were too low for analysis (0.37% commissions, 0.2% omissions). We accepted correct reaction times from 300 to 1500 ms (99.6%) for analysis as in Experiment 1.

3.5. Results

We found no reliable main effect of arrow orientation, $F(1, 23) = 1.73$, $p = .202$, partial eta$^2 = .07$: The congruity effect was not larger with vertical than horizontal arrows. Importantly, we obtained again a reliable main effect of task, $F(1, 23) = 6.80$, $p = .016$, partial eta$^2 = .23$: The congruity effect was larger for magnitude compared to parity tasks. There was no reliable interaction, $F < 1$.

Separate *t*-tests evaluated the reliability of the congruity effect in the main conditions (Fig. 2, lower panel). In the magnitude task the horizontal congruity effect was 19 ms (SEM = 5.7 ms), $t(23) = 3.4$, $p = .003$, d = 0.68; the vertical congruity effect was 27 ms (SEM = 4.9 ms), $t(23) = 5.6$, $p = .000$, d = 1.13. In the parity task, the horizontal congruity effect was −0.1 ms (SEM = 9.1 ms), $t(23) = -0.01$, $p = .98$, d = 0, again illustrating a complete absence of SNAs in the standard SNARC condition. Finally, the vertical congruity effect was 11 ms (SEM = 6.7 ms), $t(23) = 1.6$, $p = .13$, d = 0.33.

4. General discussion

Having identified essential gaps in the literature on horizontal and vertical spatial-numerical associations (SNAs), we studied them with implicit spatial-directional processing and either explicit or implicit magnitude processing. Across two experiments we found evidence for the importance of activating at least one of the two components of spatial-numerical associations: magnitude or space. These results have profound theoretical implications.

Observing horizontal SNAs with explicit magnitude processing replicates Fischer and Shaki (2016, 2017), establishing the reliability of this method. Moreover, this observation agrees with a large literature on SNARC. Importantly, the absence of SNAs in the parity tasks of both experiments challenges received interpretations of SNAs and is consistent with observations by Priftis et al. (2006; see also Zorzi et al., 2012) of task-specific associations. The differences between explicit and implicit horizontal magnitude processing with implicitly spatial assessment suggest that all previous studies reporting horizontal SNAs (including our own work) introduced spatial features by activating spatial cognitive representations (such as stimulus or response codes), or by activating the magnitude meaning of numbers directly while assessing SNAs. Without such explicit activation of "spatial" or "magnitude" features we do not associate numbers with horizontal space. This insight reflects the key logic of our method: Combining number-related and arrow-related instructions before the assessment of SNAs, we can measure spatial-numerical associations without explicit spatial features or explicit magnitude-related features present during the numerical trials. Thus, the horizontal SNARC effect is an artefact of its measurement and number concepts are not inherently associated with horizontal space. The presence of horizontal SNAs (e.g., Sella, Bertelletti, Lucangeli, & Zorzi, 2017) requires contextual priming.

Our results for the vertical dimension are the first evidence for a purely conceptual SNA in this dimension and largely support our theoretical interpretation. All previous evidence of vertical SNAs relied on explicit processing of magnitude (through explicit number processing) or by imposing spatial processing requirements. Once these inducers are removed, the vertical SNA is not consistently observed – it was statistically reliable only in the first experiment. This observation reflects the current debate about the importance of vertical compared to horizontal SNAs. On one hand, Holmes and Lourenco (2012) argued for a negligible role of vertical space for the mapping of number as a result of direct comparisons of their relative strength. On the other hand, embodied cognition proponents argue for a primacy of vertical over horizontal SNAs because the former reflect universal experiences of "more is up" (Fischer, 2012; Lakoff & Johnson, 1980), whereas the latter are largely culturally mediated (but see De Hevia et al., 2017; Rugani et al., 2015, 2017). More work is needed to decide between these views.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2018.02.022.

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[3] In response to a reviewer, we used this wider range of single digits. Given that our proposal is mute with regard to the discrete or continuous nature of the mapping we did not add a more detailed analysis.

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