AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: General

ISSN: 0096-3445

2024, Vol. 153, No. 1, 171–183
https://doi.org/10.1037/xge0001493

How Do Numbers Shift Spatial Attention? Both Processing Depth and Counting Habits Matter

Samuel Shaki[1] and Martin H. Fischer[2]
[1] Department of Psychology, Ariel University
[2] Division of Cognitive Sciences, Department of Psychology, University of Potsdam

There have been inconsistent reports about whether seeing small versus large numbers (e.g., 1 or 2 vs. 8 or 9) automatically shifts an observer's attention into left versus right hemispace. We report four visual detection experiments ($N = 162$) where centrally presented uninformative number cues were followed by lateralized targets that required go/no-go responses. Processing depth was manipulated by requiring observers to either distinguish numbers from other symbols (Experiment 1) or to classify numbers by either parity (Experiment 2) or magnitude (Experiments 3 and 4). Attention shifts occurred only after magnitude processing. Importantly, their direction depended on observers' directional preferences for object counting, which was separately assessed in all experiments. These results clarify the mechanism by which abstract concepts activate their inherent spatial associations and lead to spatial attention shifts. They also demonstrate the feasibility of attentional probing to study mechanisms of symbol comprehension in various contexts, ranging from mental arithmetic to language processing.

Public Significance Statement

There is considerable interest in understanding how number symbols become associated with space. The present work demonstrates that, in addition to the depth of number processing, directional object-counting habits contribute to spatial–numerical associations in healthy adults by influencing their deployment of spatial attention.

Keywords: attention shift, conceptual cueing, spatial–numerical associations, numerical cognition

A foundational feature of human cognition is the use of symbols, such as words and numbers. Consequently, a longstanding research question has been how we deploy our cognitive resources to understand symbols. One particularly influential method to measure the allocation of attentional resources in response to visual symbols was developed by Posner (1978) who compared two conditions of a speeded target detection task: In each experimental trial, observers were first shown a symbolic cue (a left- or right-pointing arrow at display center) to manipulate their spatial attention deployment in the direction of the arrow.[1] When the target subsequently appeared on the display side indicated by the arrow cue, this constituted a "valid" condition, whereas the target appearing on the other side defined an "invalid" condition. The effect of arrow symbols on attention allocation was measured by comparing the speed of pressing a response button in both conditions: targets were typically detected faster in valid than invalid conditions, presumably because faster target detection indicated allocation of attention at the target location, compared to

[1] The term "attention" here refers to *covert* attention, that is, spatial deployment of a cognitive resource in the absence of overt movements of the eyes or the body.

This article was published Online First October 5, 2023.
Martin H. Fischer https://orcid.org/0000-0003-3818-7272
This work was supported by Israel Science Foundation_2215/20 "How does language affect attention? Deconstructing cue-probe relationships" to Samuel Shaki and partially supported by Deutsche Forschungsgemeinschaft (German Research Foundation) FI/1915/8-1 "Heuristics and biases in mental arithmetic" to Martin H. Fischer. We thank Thomas Faulkenberry and Alex Miklashevsky for their constructive comments. Both authors declare that they have no competing interests. Prior dissemination: These results were presented at the 65th Annual Meeting of experimentally working psychologists (TeaP) in Trier/Germany on March 28, 2023: https://conference-service.com/teap-2023-trier/xpage.html?xpage=264&lang=en. Raw data from all experiments are available at https://osf.io/y6exq/. All procedures of this study were in accordance with the ethical standards of the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Ethical approval was obtained through the Institutional Ethics Committee for Non-Clinical Studies in Humans at Ariel University (AU-SOC-SS-20190204-1).

Samuel Shaki served as lead for conceptualization, data curation, funding acquisition, project administration, resources, software, and supervision and contributed equally to validation. Martin Fischer served in a supporting role for conceptualization, funding acquisition, project administration, and validation. Samuel Shaki and Martin Fischer contributed equally to formal analysis, methodology, visualization, writing–original draft, writing–review and editing, and investigation.

Correspondence concerning this article should be addressed to Martin H. Fischer, Division of Cognitive Sciences, Department of Psychology, University of Potsdam, Karl-Liebknecht-Strasse 24-25, 14476 Potsdam, OT Golm, Germany. Email: martinf@uni-potsdam.de

slower detection indicating the need to shift attention across space into the hemifield containing the target. This well-known validity effect indicates that symbols with explicit spatial meaning can push attention into our visual periphery to improve cognitive processing of objects of interest (for review, see Chapter 7 of Gazzaniga et al., 2019).

More broadly, the attentional cueing method has been influential because it suggested a general mechanism for symbol comprehension in various domains. In the language domain, a validity effect indicated that some words direct attention to the space they explicitly denote (e.g., "left" and "right": Hommel et al., 2001) or to the space their referents would typically occupy (e.g., upper or lower visual space for "hat" and "boot," respectively: Estes & Barsalou, 2018; for review, see Shaki & Fischer, 2023). But also abstract concepts like "yesterday," "god," or "nine" direct our attention across space, presumably in preparation of associated actions such as referential movements (for time: Weger & Pratt, 2008; reviews by Bonato et al., 2012; von Sobbe et al., 2019; for religious terms: Chasteen et al., 2010; for numbers and pointing movements: Fischer, 2003).

Given the wide support for spatial attention shifts being related to symbol comprehension, it is surprising to witness the current debate about the attention-shifting capacity of number symbols. Next, we will first describe the pervasive evidence for an association between numbers and space and review an influential demonstration of attention shifts induced by number viewing. Then we will discuss possible reasons for recent failures to replicate this seminal finding that have informed our own study.

Numbers are systematically associated with space—this can be observed in many speeded choice tasks, for example, when observers classify visually presented numbers as odd or even (parity task) or as larger or smaller than five (magnitude classification) by using left and right response buttons. Left responses are faster for small numbers (such as 1 or 2) and right responses are faster for larger numbers (such as 8 or 9). This association is known as the spatial–numerical association of response codes (SNARC) effect (Dehaene et al., 1993). Several studies documented versions of the SNARC effect, as well as extensions and limitations (reviews in Fischer & Shaki, 2014, 2018; Toomarian & Hubbard, 2018; Winter et al., 2015; Wood et al., 2008). This pervasive spatial–numerical association led to the idea that our number knowledge is cognitively represented on a spatially oriented "mental number line" along which we internally shift our attention to the left or right side during subtraction or addition, respectively (Glaser & Knops, 2020; McCrink et al., 2007; Shaki et al., 2018). The dynamics of this attention allocation process can be studied with mouse tracking (e.g., Faulkenberry et al., 2016). More broadly, theoretical interpretations of attentional effects induced by symbol processing can reveal the cognitive mechanisms involved in activating and representing our knowledge (Borghi et al., 2022).

In an influential study of attentional mechanisms involved in number comprehension, Fischer et al. (2003) measured the speed of detecting targets that were randomly shown on the left or right side of a computer screen (cf. Posner, 1978). In each experimental trial, initially, a task-irrelevant number symbol (1, 2, 8, or 9) appeared at a central fixation point. Observers responded to the subsequently appearing targets with speeded button presses. As per convention, faster target detection indicates allocation of attention at the target location, compared to slower detection indicating the need to shift attention into the hemifield containing the target. Two experiments showed that the mere viewing of small numbers shifted attention into the observers' left visual hemifield, while seeing larger numbers shifted attention into their right visual hemifield. The attention shift was inferred from observing faster average detection times in SNARC-congruent conditions (small numbers followed by left targets; large numbers followed by right targets) compared to SNARC-incongruent conditions (small numbers followed by right targets; large numbers followed by left targets). This validity effect was termed attentional SNARC (att-SNARC; e.g., Fattorini et al., 2015; He et al., 2020; Pellegrino et al., 2019).

The basic att-SNARC was replicated both with and without success in a number of studies (discussed in Fischer & Knops, 2014; Fischer et al., 2020). Prominent among several replication failures of the original att-SNARC is a recent multilab registered replication of the original study by Colling et al. (2020) which included over 1,100 observers and 17 laboratories from around the world. The authors followed closely the original protocol and also collected several potential "participant-level moderators (finger-counting habits, reading and writing direction, handedness, and mathematics fluency and mathematics anxiety)" (Colling et al., 2020, p. 143). While the att-SNARC was numerically present in half of these studies, its size was negligible throughout and there were no substantial moderating effects, indicating a clear replication failure.

Why is the att-SNARC so difficult to find with the original number cueing method in the Posner detection task? Two important points help to answer this question. First, processing requirements for the number cues are a crucial component of successful replications: While the att-SNARC tended to elude researchers who left the numbers task-irrelevant, it tended to replicate when these cues were task-relevant (e.g., Casarotti et al., 2007: report the number; Zanolie & Pecher, 2014: classify the number by magnitude; Fattorini et al., 2016; Pinto et al., 2018: imagine the number). For example, consider Casarotti et al. (2007), where participants reported the perceived temporal order of peripherally presented stimuli after a centrally presented digit. There was no effect of the central digit when it was task-irrelevant, but an att-SNARC was obtained when participants named the digit after each trial: Small numbers made left-side stimuli appear earlier while large numbers made right-side stimuli appear earlier, indicating that attention had been allocated in accordance with SNARC. Importantly, and consistent with the original report by Fischer et al. (2003), number processing was neither controlled nor manipulated in Colling et al.'s (2020) failed registered replication.

Therefore, the present study manipulated the semantic processing depth of numbers to establish its key role in attentional shifts. Observers performed either shallow, intermediate, or deep processing of the number cues in order to decide whether to respond to targets in a go/no-go task. This task was chosen to avoid lateralized response keys while at the same time enabling a manipulation of processing depth per response instruction (Fischer & Shaki, 2016, 2017; Shaki & Fischer, 2018). Specifically, in the first experiment, observers performed a superficial visual analysis to decide whether centrally presented cues were numbers or other symbols. Only numbers required a detection response to the subsequently presented targets. In the second experiment, observers classified numbers as odd or even. In separate blocks, either odd or even number cues required a target detection response. This analysis required retrieval of conceptual knowledge about number cues without tapping into their quantity meaning. Finally, in the third and fourth experiments, observers decided whether to respond after understanding the quantity meaning of the number symbol relative to the reference number 5, so that in separate blocks either smaller or larger number cues required a target detection response.

As a second important point, it is likely that individual differences between and within observer samples contribute to the fragility and variability of the att-SNARC (see effect size distribution plots in Fattorini et al., 2015). However, it is currently unclear precisely which "participant-level moderators" (Colling et al., 2020, p. 143) may be important for obtaining the att-SNARC. Contrary to a prediction of spatial–numerical associations from habitual finger counting (Fischer, 2008), the att-SNARC was not moderated by finger-counting habits in Colling et al.'s (2020) replication study (see also Pellegrino et al., 2021).

Here we considered directional preference for object counting (DPOC) as a moderator variable because it was recently shown to systematically affect spatial–numerical associations. Specifically, observers who preferred to enumerate a series of four linearly arranged objects left-to-right had typical spatial–numerical associations while those who preferred to count the objects right-to-left had reverse spatial–numerical associations (Fischer & Shaki, 2016, 2017). DPOC also determined the spatial mapping of nonsymbolic quantities onto space more generally by modulating the general underestimation of visual lengths or haptic weights in the left space and their overestimation in the right space (Shaki & Fischer, 2021).

It is plausible that DPOC varied unsystematically within and between previous studies that either did or did not replicate the att-SNARC. This variable has not been considered in previous att-SNARC replication attempts because its role was only recently discovered. Little is known today about the distribution and reliability of DPOC among adult populations.

In summary, the present study had two objectives. First, to demonstrate that the att-SNARC depends on processing depth for the number cues. And second, to document the important influence of DPOC for the assessment of att-SNARC. If number magnitude is responsible for shifting attention across space, then the direction of the resulting effect should depend on the individual observer's preferred mapping of numbers into space. For this reason, we recorded our participants' DPOC as a covariate in all experiments.

Experiment 1: Numbers Versus Other Symbols

The purpose of Experiment 1 was to determine whether the mere classification of a cue stimulus as a number, without determination of its magnitude, would be sufficient to induce an attentional asymmetry.

Participants

Twenty-eight students (seven male and 21 female) from Ariel University participated. This sample size was in the upper range of sample sizes of previous studies reporting attentional asymmetries as a consequence of number processing.[2] Participants' average age was 22.4 years (range = 19–27) and three reported to be left-handed. Here and in all further experiments, participants were naïve with regard to the purpose of this experiment and received course credit for their participation.

Apparatus

The experiment was conducted in a quiet room on a desktop computer under the Windows 10 operating system, using SuperLab software for stimulus presentation and response collection. Visual stimuli were presented on a 19-in. monitor with 1,280 × 1,024 pixels screen resolution. Responses were collected to the nearest millisecond on the space bar of a standard QWERTY keyboard that was centered on a table below the screen.

Stimuli

The cue set consisted of the Arabic number symbols 1, 2, 8, and 9 and the symbols @, #, $, and %. The target stimulus was a small asterisk, which was presented in one of two locations 150 pixels to the left or right side of a central fixation point (a dot of 20 pixels in diameter). At a viewing distance of 60 cm, these values correspond to 3.15° of visual angle for target eccentricity and 0.42° of visual angle for the fixation point diameter. No lateralized placeholder boxes were presented at the target locations. All stimuli were black on a white background.

Design

Three types of trials were constructed: a number cue followed by the target; a non-number cue followed by the target; and catch trials in which no target followed a number cue. This factor *trial type* was fully crossed with the factor *target side*. As a result, an experimental block consisted of 20 randomly intermixed trials: eight number-cue trials (One of the Four Numbers × Two Lateral Target Locations), eight nonnumber cue trials (One of the Four Nonnumber Symbols × Two Lateral Target Locations), and four catch trials (one of the four numbers without target). Note that we implemented catch trials only for the number-cue condition because our instructions (see below) required participants to withhold their responses for nonnumber cues.

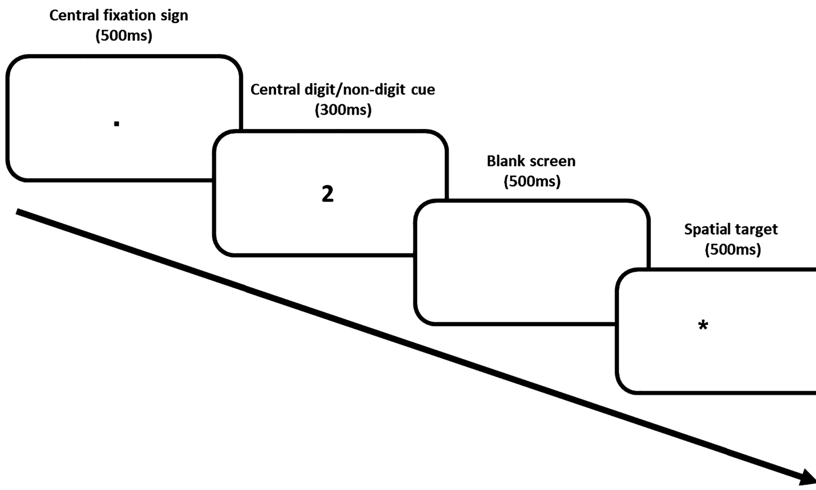
Procedure

Each participant was tested individually after providing informed consent. Participants were seated ∼60 cm from the monitor. The trial sequence is shown in Figure 1. It began with a central fixation sign that was presented for 500 ms and then replaced by a randomly chosen number or nonnumber symbol for 300 ms. This was followed by a 500 ms blank screen before the spatial target appeared in 80% of trials randomly on the left or right side. This resulted in a stimulus onset asynchrony (SOA) of 800 ms between cue and target, which was similar to the effective SOA in Fischer et al. (2003). The target remained on screen until a response was registered on the keyboard. The reaction time (RT) from target onset to button response was recorded as a dependent measure of interest.

Participants were instructed to maintain fixation at the center of the screen throughout the experiment. They were informed that the cue stimuli did not predict the target location and were irrelevant to the detection task. More importantly, participants were instructed to respond as fast as possible by pressing the space bar with their preferred hand when they detected the asterisk target but only when it was preceded by a number.

[2] The att-SNARC was discovered with underpowered experiments ($n = 14$ and 10, respectively, in Fischer et al., 2003), but "…true effects that are detected tend to have inflated effect sizes (i.e., a true effect is only significant in an underpowered study when the effect obtained in the study is larger than the effect at the population level)" (Brysbaert, 2019, p. 1). We opted for larger sample sizes to address this concern (see also van Dijck et al., 2014).

Figure 1
Schematic of Trial Sequence in All Experiments



Note. Not to scale.

Each participant first received a short practice of eight trials, followed by three experimental blocks of 20 trials, resulting in 68 trials total. At the end of the experiment, each participant's DPOC was assessed with four black circles (180 pixels diameter, 50 pixels separation) displayed horizontally, simultaneously, and continuously across the middle of the screen. The participant was invited to count these aloud by pointing at each of them. The order of pointing (left-to-right or right-to-left) was recorded. The duration of the entire experiment, including time for welcome, consenting, instructions, and debriefing, was approximately 15 min.

Transparency and Openness

We did not use data, program code, and other methods developed by others. Data from all experiments are available at https://osf.io/y6exq/?view_only=af0ddb982e3f43229720fb4201cdc221. The materials reported in our Methods section, and the computer code or syntax needed to reproduce our analyses, are available from the authors upon request. Our reporting of design and analyses aims to be consistent with the American Psychological Association Style Journal Article Reporting Standards.

Results and Discussion

Practice trials were removed from all analyses. All RTs faster than 150 ms and slower than 900 ms were excluded from the analysis because they were deemed anticipations and procrastinations, respectively (1.8% of trials). There were 1.8% response omission errors, 7.9% commission errors (responses to targets after nonnumber cues), and 0.8% commission errors (responses without targets). This amount of errors was deemed too small for statistical analysis.

The counting preference assessment revealed that 17 participants counted left-to-right while the remaining 11 participants preferred to count right-to-left. This information was entered as between-participant factor into a 2 × 2 × 2 mixed-factors analysis of variance (ANOVA) on mean RT with number size (small: 1, 2; large: 8, 9), target side (left, right), and counting preference (left–right, right–left) as factors. We report two-tailed p values throughout.

Average RT was 492 ms ($SE = 11$ ms) and there were no significant main effects or interactions, all p values $> .33$. The crucial interaction between number size and target side was not significant, $F(1, 26) < 1$, and also not modulated by counting preference, $F(1, 26) < 1$. Means of all conditions appear in Table 1, and the Appendix contains further statistical analyses. These results indicate the absence of att-SNARC when numbers were merely distinguished from other symbols.

Experiment 2: Odd Versus Even Numbers

The purpose of Experiment 2 was to determine whether the classification of a number as odd or even, without determination of its magnitude being required, would be sufficient to induce an attentional asymmetry.

Participants

Thirty new students (13 male and 17 female) from Ariel University participated. Their average age was 22.1 years (range = 20–25) and four reported to be left-handed.

Apparatus and Stimuli

The cue set consisted of the Arabic numbers 1, 2, 8, and 9. No symbol cues were used because the task instruction was changed from number classification to parity classification. All other aspects of stimuli and apparatus were identical to Experiment 1.

Design

Two types of trials were constructed: target trials in which each number cue was followed by the target; and catch trials in which no target followed a number. This factor *trial type* was again fully crossed with the factor *target side*, so that an experimental block consisted of 10 randomly intermixed trials: eight number-target trials (one of the four Numbers × Two lateral target locations) and two catch trials (one randomly selected small number and one randomly

Table 1
Overview of Results From the Four Experiments of the Present Study

	Left-to-right counters					Right-to-left counters				
	Left targets		Right targets			Left targets		Right targets		
Experiment/Task	Small numbers	Large numbers	Small numbers	Large numbers	Att-SNARC effect	Small numbers	Large numbers	Small numbers	Large numbers	Att-SNARC effect
1/Discrimination	476 (20)	482 (17)	484 (18)	476 (16)	+7	507 (25)	488 (21)	519 (23)	503 (20)	−2
2/Parity	481 (20)	480 (17)	493 (17)	489 (16)	+2	494 (21)	494 (18)	493 (19)	478 (17)	−7
3/Magnitude	463 (11)	463 (10)	475 (10)	455 (9)	+10	459 (12)	446 (12)	459 (11)	460 (10)	−7
4/Magnitude	457 (13)	463 (15)	464 (13)	450 (14)	+10	474 (15)	467 (16)	464 (14)	474 (15)	−9

Note. Values are mean RTs (*SE*s in brackets) in milliseconds. Att-SNARC effects were computed by assuming the canonical congruency relationship between numbers and space (details in the main text). Att-SNARC = attentional spatial–numerical association of response codes; RT = reaction time.

selected large number without target). The design also included an instruction manipulation: In one condition block, participants were required to respond when they detected the asterisk target only if it was preceded by an even number. In the complementary condition block, they were instructed to respond only when the target was preceded by an odd number. Order of instructions was counterbalanced across participants.

Procedure

The procedure was very similar to Experiment 1: A central fixation sign was presented for 500 ms and then replaced by a randomly chosen number for 300 ms. This was followed by a 500 ms blank screen before the spatial target appeared in 80% of trials randomly on the left or right side, yielding an 800 ms SOA. The target remained on screen until a response was registered on the keyboard. Participants had to respond as fast as possible by pressing the space bar with their preferred hand. For each response instruction (respond to odd vs. even numbers), they received six practice trials followed by five experimental blocks of 10 trials, resulting in 56 trials per instruction and 112 trials total per participant. This was again followed by the DPOC assessment. The overall experiment lasted approximately 20 min.

Results and Discussion

Practice trials were removed from all analyses. RTs faster than 150 ms and slower than 900 ms were again excluded from the analysis because they were deemed anticipations and procrastinations, respectively (2.3% of trials). There were 0.6% omission errors, 0.9% commission errors (responses after "no-go" number cues), and 0.7% commission errors (button presses without targets). This amount was deemed too small for statistical analysis.

The counting preference assessment revealed that 16 participants counted left-to-right while the remaining 14 participants preferred to count right-to-left. This information was entered as between-participant factor into a $2 \times 2 \times 2$ mixed-factors ANOVA on mean RT with number size (small: 1, 2; large: 8, 9), target side (left, right), and counting preference (left–right, right–left) as factors.

Average RT was 487 ms ($SE = 11$ ms) and there were no significant main effects or interactions, all p values $> .14$. The crucial interaction between number size and target side was not significant, $F(1, 28) < 1$, and also not modulated by counting preference, $F(1, 28) < 1$. Means of all conditions appear in Table 1, and the Appendix contains further statistical analyses. These results indicate the absence of an attentional cueing effect of numbers even when they were classified by their parity status.

Experiment 3: Small Versus Large Numbers

The purpose of Experiment 3 was to determine whether the classification of a number as larger or smaller than five would be necessary to induce an attentional asymmetry.

Participants

Twenty-nine new students (eight male and 21 female) from Ariel University participated. Their average age was 22.8 years (range = 20–28) and five reported to be left-handed.

Apparatus and Stimuli

Apparatus and stimuli were identical to Experiment 2.

Design and Procedure

The design and procedure were identical to that of Experiment 2, except that the response instruction was changed so that in one block participants responded to all targets following number cues smaller than five while in the other block they responded to targets following number cues larger than five. Block order was counterbalanced.

Results and Discussion

Practice trials were excluded from all analyses. RTs faster than 150 ms and slower than 900 ms were again excluded from the analysis because they were deemed anticipations and procrastinations, respectively (1.4% of trials). There were 2.1% omission errors, 1.2% commission errors (responses after no-go number cues), and 0.5% commission errors (responses without targets). This amount was deemed too small for statistical analysis.

The DPOC assessment revealed that 16 participants counted left-to-right while the remaining 13 participants preferred to count right-to-left. This information was entered as between-participant factor into a $2 \times 2 \times 2$ mixed-factors ANOVA on mean RT with number size (small: 1, 2; large: 8, 9), target side (left, right) and counting preference (left–right, right–left) as factors.

Average RT was 460 ms ($SE = 7$ ms) and there were no significant main effects or double interactions, all p values $>.13$. The interaction between number size and target side was again not significant, $F(1, 27) < 1$. However, it was this time modulated by counting preference, $F(1, 27) = 3.73$, $p = .06$, $\eta_p^2 = .12$. This marginal three-way interaction suggests opposite patterns of attentional cueing for the two groups of participants: Left-to-right counters showed faster target detection for left/right targets following small/large numbers, respectively. Instead, right-to-left counters showed the opposite pattern, namely faster target detection for right/left targets following small/large numbers, respectively. Means of all conditions appear in Table 1, and the Appendix contains further statistical analyses.

This pattern suggests that both magnitude processing and directional counting preference might be relevant when evaluating the potential of numbers to automatically shift attention into the left or right visual hemifield. Before we can turn to a broader discussion of our findings, we report a sufficiently powered replication of this critical third experiment that addresses also some methodological concerns.

Experiment 4: Small Versus Large Numbers

The last experiment was conducted to replicate our novel finding of an influence of DPOC on the attentional cueing effect with numbers. Specifically, it could be argued that the singular assessment of DPOC (one measurement per subject) resulted in casual responding that does not reflect a strong "participant-level moderator" (Colling et al., 2020, p. 143). We modified our procedure and assessed DPOC twice in each participant with a separation of about 1 week. This enabled us to document temporal consistency of this measure and its specific effect in each counting group. We also increased the number of participants and trials to obtain more reliable results (e.g., Brysbaert, 2019).

Participants

Seventy-five new students (10 male and 65 female) from Ariel University participated. Their average age was 22.9 years (range = 20–32) and nine reported to be left-handed.

Apparatus and Stimuli

Apparatus and stimuli were identical to Experiment 3.

Design and Procedure

The design and procedure were identical to that of Experiment 3, except that the number of trials was increased to 12 repetitions per condition, resulting in 192 trials per participant. We also assessed DPOC after each of the two experimental blocks. This was done in separate sessions approximately 1 week apart to assess temporal reliability of directional counting preferences.

Results and Discussion

RTs faster than 150 ms and slower than 900 ms were excluded from the analysis because they were deemed anticipations and procrastinations, respectively (2.5% of trials). There were 0.55% omission and 0.62% commission errors (responding to targets following "no-go" number cues). This amount was deemed too small for statistical analysis.

The counting preference assessment revealed that 33 participants consistently counted left-to-right and 28 participants consistently counted right-to-left while the remaining 14 participants changed their answer from the first to the second assessment. A $2 \times 2 \times 3$ mixed-factors ANOVA with number size (small: 1, 2; large: 8, 9), target side (left, right), and counting preference (left–right, right–left, mixed; between participants) was conducted on mean RT.

Average RT was 461 ms ($SE = 9.2$ ms) and there was only a significant main effect of side, $F(1, 72) = 4.21$, $p = .044$, $\eta_p^2 = .055$, with 6 ms advantage for the right over the left side. The critical three-way interaction between number size, target side, and counting preference was significant, $F(2, 72) = 6.99$, $p = .002$, $\eta_p^2 = .163$. Separate analyses for the three groups showed a significant Number Size × Target Side interaction in the left-to-right counters, $F(1, 32) = 8.14$, $p = .008$, $\eta_p^2 = .203$, indicating that they were 6 ms faster when small rather than large numbers preceded left targets; they also were 14 ms faster when large rather than small numbers preceded right targets. These analyses also showed a significant interaction in the right-to-left counters, $F(1, 27) = 4.95$, $p = .035$, $\eta_p^2 = .155$, indicating the opposite pattern: They were 7 ms faster when large rather than small numbers preceded left targets; and they were 10 ms faster when small rather than large numbers preceded right targets. The same interaction did not reach significance in the mixed group, $F(1, 13) = 2.20$, $p = .16$, $\eta_p^2 = .14$. Means of the groups with consistent counting conditions appear in Table 1; the Appendix contains means of the inconsistent (mixed) counting group and further statistical analyses.

Our results suggest that most people (81% in our sample) have a reliable counting direction preference, and that this preference impacts the direction of their spatial–numerical association, as evidenced by diametrically opposed att-SNARC effects following magnitude processing of number cues. We now turn to a broader discussion of our findings.

General Discussion

The present study investigated the fundamental question of how we process symbolic information and accomplished two important objectives: first, it clearly documented that the capacity of centrally presented number symbols to shift an observer's attention to the left or right side depends on (at least) two factors: the semantic processing of those numbers and the counting direction preference of the observer. We discuss each factor in turn.

Regarding first the processing of number cues, it seems necessary that the quantity-related number meaning is activated for the lateral attentional shifts to occur. This finding strengthens the claim that attention shifts induced by number presentation are not automatic but require cognitive analysis of the number cue (Fattorini et al., 2015, 2016; Pellegrino et al., 2019, 2021). Consistent with some previous work (see Introduction), we found that explicit processing of number magnitude is a necessary prerequisite for obtaining the att-SNARC. Neither the mere classification of the cue as a number, nor its classification by parity, seem sufficient to induce attentional shifts. Instead, it is the magnitude meaning of the number cue that leads to the subsequent spatial bias, as signaled in Experiment 3 and confirmed in Experiment 4. This observation fits well with the theoretical interpretation of the SNARC effect as reflecting semantic access to number concepts on a spatially oriented mental number line, thereby inducing congruency effects with spatial responses.

Our finding also speaks to theoretical views on the SNARC effect. Specifically, it negates the obligatory involvement of response codes in the origin of spatial–numerical associations: Finding the att-SNARC with a single response button (as opposed to using two lateralized buttons that may introduce extraneous spatial coding) shows that the spatial–numerical association does not exclusively depend on response choice (see also Dodd et al., 2008; Nicholls et al., 2008; Shaki & Fischer, 2018). Removing spatial response choice from the task draws attention to the importance of numerical processing requirements as determinants of spatial–numerical associations: Measuring attention deployment with go/no-go instructions, we found a dissociation between parity and magnitude tasks such that magnitude classification leads to spatial–numerical associations while parity processing does not. When response selection is included, this dissociation between tasks is not observed (see the meta-analysis by Wood et al., 2008). We believe that assigning horizontally separated buttons to the two responses introduces spatial processing to an otherwise nonspatial parity task. Instead, spatiality of processing is already inherent in magnitude classification, due to saliency of the quantity feature in number representations along a mental number line (cf. Shaki & Fischer, 2018). Such observations challenge an influential account of the SNARC effect as resulting exclusively from the response selection stage (e.g., Antoine & Gevers, 2016; Keus & Schwarz, 2005; Keus et al., 2005).

Our interpretation suggests that the original att-SNARC (Fischer et al., 2003) and its successful replications likely reflect spontaneous additional processing of the nonpredictive number cues by the participants despite instructions to ignore them. Other successful att-SNARC replications with explicit processing requirements (e.g., Casarotti et al., 2007: report the number; Zanolie & Pecher, 2014: classify the number by magnitude; Fattorini et al., 2016; Pinto et al., 2018: imagine the number) are not in conflict with this claim because automatic magnitude processing cannot be ruled out per instruction.

Similarly, and more broadly, the mixed results obtained with spatially connotative words as attention cues (cf. Estes & Barsalou, 2018; Petrova et al., 2018) can also be attributed to variability in processing depth for the cues within and across studies. In another recent study, we (Shaki & Fischer, 2023, Experiment 2) systematically manipulated the processing depth of spatially associated word cues (e.g., roof, roots) and measured the speed of target detection along the vertical visual axis with the go/no-go procedure. We found that the lexically induced attentional shift only occurred when the spatial connotation of the cue words was processed. Thus, future studies should explicitly manipulate or impose tight control over processing depth of symbolic azttentional cues.

Some studies that did impose magnitude processing still failed to find the att-SNARC (cf. Experiment 6 in Zanolie & Pecher, 2014). This brings us to our second accomplishment: We showed here, for the first time, that participants' DPOC is a crucial intervening factor when measuring the att-SNARC. Our participants preferred to spontaneously count horizontally arranged objects either left-to-right or right-to-left. While left-to-right counters showed the expected pattern in the detection task following magnitude classification of number cues, the right-to-left counters showed a trend in the opposite direction in Experiment 3 and a fully reversed att-SNARC in Experiment 4 with stricter DPOC assessment (as well as a larger sample and more trials). These observations are in line with other reports of opposite spatial–numerical associations for people with opposite DPOCs (Fischer & Shaki, 2016, 2017; Shaki & Fischer, 2021).

We, therefore, assume that previous att-SNARC studies unknowingly tested both left-to-right and right-to-left counters and subsequently averaged results across them. This assumption can explain why evaluating the overall Number Magnitude × Target Side interaction in several previous studies yielded nonsignificant results and is further supported by the observation that some participants in those studies showed reverse associations (Fattorini et al., 2015). Averaging attentional cueing effects across participants with opposing DPOCs erroneously implied the absence of att-SNARC in previous work even with semantic processing of number cues. Only by considering BOTH the magnitude meaning of cues AND directional counting preferences of participants as a grouping factor is it possible to detect a significant att-SNARC and to document its dependence on counting direction. Our proposal of a counting-dependent att-SNARC also fits our observation that participants in Experiment 4 with inconsistent directional counting habits showed no overall attentional bias in either direction. Future studies should therefore assess DPOCs, document their impact on spatial–conceptual associations more broadly, and also explore their temporal dynamics.

What might be the common underlying factor that associates DPOC and att-SNARC? We note that the overt attention deployment through pointing to (and looking at) each object is accompanied by naming the corresponding numbers of the habitual counting sequence. This overt routine reveals precisely the spatial coupling between attention and numbers that likely creates the covert att-SNARC. Our DPOC assessment, which occurred after each att-SNARC assessment, uncovered this otherwise hidden association of interest. Future work should examine whether manipulating the participants' counting direction, removing the spatial component from their count, or removing the numbers from their spatial activity, will modulate a subsequent att-SNARC assessment. Consider now the more relevant covert attention deployment that is assessed by our task. Here it is important to appreciate that Hebrew readers, just as Western readers, also process numbers from left to right. Thus, both populations have similar spatial–numerical associations.

Consistent with this, a detailed study revealed typical spatial–numerical associations in Hebrew readers when the design was adapted (Shaki & Fischer, 2012; Zohar-Shai et al., 2017; present results). For these reasons, we identify all neurotypical humans with the appropriate numerical and counting experience as target population for the reported findings. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context. Nevertheless, we believe further replications and extensions with left-to-right readers to be valuable research efforts.

On a broader level, the present results also clarify the mechanism of conceptual cueing of spatial attention in the context of everyday symbol manipulation tasks, such as mental arithmetic or language comprehension. Observing the att-SNARC only in the context of deep, meaning-related number processing supports our current understanding of mental arithmetic as relying on attention shifts along a spatially oriented mental number line (Glaser & Knops, 2020; McCrink et al., 2007; Shaki et al., 2018). Arithmetic operations require full semantic processing of all symbols encountered: both the meaning of operators, such as "plus" and "minus," and the magnitude of operands is systematically associated with space because addition typically leads to larger numbers and subtraction to smaller numbers (Masson et al., 2020; Pinhas et al., 2014).

Similarly, understanding concrete concepts denoting objects with typical spatial associations, such as "hat" or "boot," will benefit from spatial attention shifts because it facilitates the localization of their referents (and often their identification; but see Estes & Barsalou, 2018). Even abstract concepts, such as those referring to temporal or religious ideas, are known to direct attention across space (for temporal concepts: von Sobbe et al., 2019; for religious concepts: Chasteen et al., 2010). Further work documenting the modulation of such symbolic cueing effects through habitual spatial activities begins to accumulate (for directional counting: Fischer & Shaki, 2016, 2017; Shaki & Fischer, 2021, and the present work; for religious practices: Casasanto, 2022). Finally, finding evidence for such attention shifts even when task instructions do not require semantic processing of the symbolic cues (e.g., Fischer et al., 2003, for number symbols) is not problematic for this view because participants may voluntarily engage in such processing and may even be unable to suppress it (cf. the Stroop effect: Stroop, 1935).

In conclusion, we have identified two key requirements for attentional cueing with numbers, namely processing of the cue's magnitude meaning and control over the observer's DPOC. We believe that attention does shift across space as a result of sufficiently elaborate number processing, thus reaffirming the existence of shifts of attention following the presentation of number symbols (the att-SNARC effect). Together with other recent research, our documentation of the att-SNARC under specific conditions also demonstrates the feasibility of attentional probing as a general tool for the study of mechanisms involved in the deployment of cognitive resources to comprehend symbols in various contexts, ranging from mental arithmetic to language processing.

Constraints on Generality

Although this was not formally assessed, our data were predominantly obtained from native Hebrew readers who deploy their spatial attention during reading from right to left. This has previously been taken as explanation for reduced or absent spatial–numerical associations. However, a distinction between overt and covert attention deployment is important. The reading argument applies to overt behavior, such as eye or head movements. Given that only single digits were presented as cues, these did not require directional eye movements for reading. Thus, spatially directed reading activity was not part of the present task.

References

Antoine, S., & Gevers, W. (2016). Beyond left and right: Automaticity and flexibility of number-space associations. *Psychonomic Bulletin & Review*, *23*(1), 148–155. https://doi.org/10.3758/s13423-015-0856-x

Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience & Biobehavioral Reviews*, *36*(10), 2257–2273. https://doi.org/10.1016/j.neubiorev.2012.08.007

Borghi, A. M., Shaki, S., & Fischer, M. H. (2022). Abstract concepts: External influences, internal constraints, and methodological issues. *Psychological Research*, *86*(8), 2370–2388. https://doi.org/10.1007/s00426-022-01698-4

Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? A tutorial of power analysis with reference tables. *Journal of Cognition*, *2*(1), Article 16. https://doi.org/10.5334/joc.72

Casarotti, M., Michielin, M., Zorzi, M., & Umiltá, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition*, *102*(1), 101–117. https://doi.org/10.1016/j.cognition.2006.09.001

Casasanto, D. (2022, August 31). *Hierarchical construction of the mental number line*. Presentation at the 22nd Meeting of the European Society for Cognitive Psychology, Lille, France.

Chasteen, A. L., Burdzy, D. C., & Pratt, J. (2010). Thinking of God moves attention. *Neuropsychologia*, *48*(2), 627–630. https://doi.org/10.1016/j.neuropsychologia.2009.09.029

Colling, L. J., Szűcs, D., De Marco, D., Cipora, K., Ulrich, R., Nuerk, H.-C., Soltanlou, M., Bryce, D., Chen, S.-C., Schroeder, P. A., Henare, D. T., Chrystall, C. K., Corballis, P. M., Ansari, D., Goffin, C., Sokolowski, H. M., Hancock, P. J. B., Millen, A. E., Langton, S. R. H., … McShane, B. B. (2020). Registered replication report on Fischer, Castel, Dodd, and Pratt (2003). *Advances in Methods and Practices in Psychological Science*, *3*(2), 143–162. https://doi.org/10.1177/2515245920903079

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*(3), 371–396. https://doi.org/10.1037/0096-3445.122.3.371

Dodd, M. D., Van der Stigchel, S., Leghari, M. A., Fung, G., & Kingstone, A. (2008). Attentional SNARC: There's something special about numbers (let us count the ways). *Cognition*, *108*(3), 810–818. https://doi.org/10.1016/j.cognition.2008.04.006

Estes, Z., & Barsalou, L. W. (2018). A comprehensive meta-analysis of spatial interference from linguistic cues: Beyond Petrova et al. *Psychological Science*, *29*(9), 1558–1564. https://doi.org/10.1177/0956797618794131

Fattorini, E., Pinto, M., Merola, S., D'Onofrio, M., & Doricchi, F. (2016). On the instability and constraints of the interaction between number representation and spatial attention in healthy humans: A concise review of the literature and new experimental evidence. In M. Cappelletti & W. Fias (Eds.), *Progress in brain research: The mathematical brain across the lifespan* (Vol. 227, pp. 223–256). Elsevier. https://doi.org/10.1016/bs.pbr.2016.04.023

Fattorini, E., Pinto, M., Rotondaro, F., & Doricchi, F. (2015). Perceiving numbers does not cause automatic shifts of spatial attention. *Cortex*, *73*, 298–316. https://doi.org/10.1016/j.cortex.2015.09.007

Faulkenberry, T. J., Cruise, A., Lavro, D., & Shaki, S. (2016). Response trajectories capture the continuous dynamics of the size congruity effect. *Acta Psychologica*, *163*, 114–123. https://doi.org/10.1016/j.actpsy.2015.11.010

Fischer, M. H. (2003). Spatial representations in number processing—Evidence from a pointing task. *Visual Cognition*, *10*(4), 493–508. https://doi.org/10.1080/13506280244000186

Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex*, *44*(4), 386–392. https://doi.org/10.1016/j.cortex.2007.08.004

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience*, *6*(6), 555–556. https://doi.org/10.1038/nn1066

Fischer, M. H., Dodd, M. D., Castel, A. D., & Pratt, J. (2020). The unbearable lightness of attentional cuing by symbolic magnitude: Commentary on the registered replication report by Colling et al. *Advances in Methods and Practices in Psychological Science*, *3*(2), 163–165. https://doi.org/10.1177/2515245920902743

Fischer, M. H., & Knops, A. (2014). Attentional cueing in numerical cognition—A commentary on Zanolie & Pecher (2014). *Frontiers in Cognition—Psychology*, *5*, Article 1381. https://doi.org/10.3389/fpsyg.2014.01381.

Fischer, M. H., & Shaki, S. (2014). Spatial associations in numerical cognition: From single digits to arithmetic. *Quarterly Journal of Experimental Psychology*, *67*(8), 1461–1483. https://doi.org/10.1080/17470218.2014.927515

Fischer, M. H., & Shaki, S. (2016). Measuring spatial-numerical associations: Evidence for a purely conceptual link. *Psychological Research*, *80*(1), 109–112. https://doi.org/10.1007/s00426-015-0646-0

Fischer, M. H., & Shaki, S. (2017). Implicit spatial-numerical associations: Negative numbers and the role of counting direction. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(4), 639–643. https://doi.org/10.1037/xhp0000369

Fischer, M. H., & Shaki, S. (2018). Number concepts: Abstract and embodied. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1752), Article 20170125. https://doi.org/10.1098/rstb.2017.0125

Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R. (2019). *Cognitive neuroscience: The biology of the mind*. W. W. Norton Publishers.

Glaser, M., & Knops, A. (2020). When adding is right: Temporal order judgements reveal spatial attention shifts during two-digit mental arithmetic. *Quarterly Journal of Experimental Psychology*, *73*(7), 1115–1132. https://doi.org/10.1177/1747021820902917

He, D., He, X., Zhao, T., Wang, J., Li, L., & Louwerse, M. (2020). Does number perception cause automatic shifts of spatial attention? A study of the att-SNARC effect in numbers and Chinese months. *Frontiers in Psychology*, *11*, Article 680. https://doi.org/10.3389/fpsyg.2020.00680

Hommel, B., Pratt, J., Colzato, L., & Godijn, R. (2001). Symbolic control of visual attention. *Psychological Science*, *12*(5), 360–365. https://doi.org/10.1111/1467-9280.00367

Keus, I. M., Jenks, K. M., & Schwarz, W. (2005). Psychophysiological evidence that the SNARC effect has its functional locus in a response selection stage. *Cognitive Brain Research*, *24*(1), 48–56. https://doi.org/10.1016/j.cogbrainres.2004.12.005

Keus, I. M., & Schwarz, W. (2005). Searching for the locus of the SNARC effect: Evidence for a response-related origin. *Memory & Cognition*, *33*(4), 681–695. https://doi.org/10.3758/BF03195335

Masson, N., Andres, M., Alsamour, M., Bollen, Z., & Pesenti, M. (2020). Spatial biases in mental arithmetic are independent of reading/writing habits: Evidence from French and Arabic speakers. *Cognition*, *200*, Article 104262. https://doi.org/10.1016/j.cognition.2020.104262

McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the number line: Operational momentum in non-symbolic arithmetic. *Perception & Psychophysics*, *69*(8), 1324–1333. https://doi.org/10.3758/BF03192949

Nicholls, M. E. R., Loftus, A., & Gevers, W. (2008). Look, no hands: A perceptual task shows that number magnitude induces shifts of attention. *Psychonomic Bulletin & Review*, *15*(2), 413–418. https://doi.org/10.3758/PBR.15.2.413

Pellegrino, M., Pinto, M., Marson, F., Lasaponara, S., & Doricchi, F. (2021). Perceiving numerosity does not cause automatic shifts of spatial attention. *Experimental Brain Research*, *239*(10), 3023–3034. https://doi.org/10.1007/s00221-021-06185-7

Pellegrino, M., Pinto, M., Marson, F., Lasaponara, S., Rossi-Arnaud, C., Cestari, V., & Doricchi, F. (2019). The attentional-SNARC effect 16 years later: No automatic space–number association (taking into account finger counting style, imagery vividness, and learning style in 174 participants). *Experimental Brain Research*, *237*(10), 2633–2643. https://doi.org/10.1007/s00221-019-05617-9

Petrova, A., Navarrete, E., Suitner, C., Sulpizio, S., Reynolds, M., Job, R., & Peressotti, F. (2018). Spatial congruency effects exist, just not for words: Looking into Estes, Verges, and Barsalou (2008). *Psychological Science*, *29*(7), 1195–1199. https://doi.org/10.1177/0956797617728127

Pinhas, M., Shaki, S., & Fischer, M. H. (2014). Heed the signs: Operation signs have spatial associations. *Quarterly Journal of Experimental Psychology*, *67*(8), 1527–1540. https://doi.org/10.1080/17470218.2014.892516

Pinto, M., Fattorini, E., Lasaponara, S., D'Onofrio, M., Fortunato, G., & Doricchi, F. (2018). Visualising numerals: A ERPs study with the attentional SNARC task. *Cortex*, *101*, 1–15. https://doi.org/10.1016/j.cortex.2017.12.015

Posner, M. I. (1978). *Chronometric explorations of mind*. Oxford University Press.

Shaki, S., & Fischer, M. H. (2012). Multiple spatial mappings in numerical cognition. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 804–809. https://doi.org/10.1037/a0027562

Shaki, S., & Fischer, M. H. (2018). Deconstructing spatial-numerical associations. *Cognition*, *175*, 109–113. https://doi.org/10.1016/j.cognition.2018.02.022

Shaki, S., & Fischer, M. H. (2021). Systematic spatial distortion of quantitative estimates. *Psychological Research*, *85*(6), 2177–2185. https://doi.org/10.1007/s00426-020-01390-5

Shaki, S., & Fischer, M. H. (2023). How does language affect spatial attention? Deconstructing the prime-target relationship. *Memory & Cognition*, *51*(5), 1115–1124. https://doi.org/10.3758/s13421-022-01390-3

Shaki, S., Pinhas, M., & Fischer, M. H. (2018). Heuristics and biases in mental arithmetic: Revisiting and reversing operational momentum. *Thinking & Reasoning*, *24*(2), 138–156. https://doi.org/10.1080/13546783.2017.1348987

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/h0054651

Toomarian, E. Y., & Hubbard, E. M. (2018). On the genesis of spatial-numerical associations: Evolutionary and cultural factors co-construct the mental number line. *Neuroscience & Biobehavioral Reviews*, *90*, 184–199. https://doi.org/10.1016/j.neubiorev.2018.04.010

van Dijck, J. P., Abrahamse, E., Acar, F., Ketels, B., & Fias, W. (2014). A working memory account of the interaction between numbers and spatial attention. *Quarterly Journal of Experimental Psychology*, *67*(8), 1500–1513. https://doi.org/10.1080/17470218.2014.903984

von Sobbe, L., Scheifele, E., Maienborn, C., & Ulrich, R. (2019). The space-time congruency effect: A meta-analysis. *Cognitive Science*, *43*(1), Article e12709. https://doi.org/10.1111/cogs.12709

Weger, U. W., & Pratt, J. (2008). Time flies like an arrow: Space-time compatibility effects suggest the use of a mental timeline. *Psychonomic Bulletin & Review*, *15*(2), 426–430. https://doi.org/10.3758/PBR.15.2.426

Winter, B., Matlock, T., Shaki, S., & Fischer, M. H. (2015). Mental number space in three dimensions. *Neuroscience & Biobehavioral Reviews*, *57*, 209–219. https://doi.org/10.1016/j.neubiorev.2015.09.005

Wood, G., Nuerk, H. C., Willmes, K., & Fischer, M. H. (2008). On the cognitive link between space and number: A meta-analysis of the SNARC effect. *Psychology Science Quarterly*, *50*(4), 489–525.

Zanolie, K., & Pecher, D. (2014). Number-induced shifts in spatial attention: A replication study. *Frontiers in Psychology*, *5*, Article 987. https://doi.org/10.3389/fpsyg.2014.00987

Zohar-Shai, B., Tzelgov, J., Karni, A., & Rubinsten, O. (2017). It does exist! A left-to-right spatial–numerical association of response codes (SNARC) effect among native Hebrew speakers. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(4), 719–728. https://doi.org/10.1037/xhp0000336

(*Appendix follows*)

Appendix

Additional Statistics (Linear Mixed Models) for Each of the Four Experiments

Table A1
Summary of Results From Linear Mixed Effects Modeling of Experiment 1 (Classification)

	RT			
Predictors	Estimates	*SE*	Statistic	*p*
(Intercept)	485.955***	10.649	45.633	<.001
Random effects				
σ^2	9,873.060			
$\tau_{00\ \text{subject}}$	2,745.739			
Intraclass Correlation Coefficient	0.218			
N_{subject}	28			
Observations	646			
Marginal R^2/conditional R^2	.000/.218			

Note. No significant main effects, no interactions. RT = reaction time.
*** $p < .01$.

Table A2
Summary of Results From Linear Mixed Effects Modeling of Experiment 2 (Parity)

	RT			
Predictors	Estimates	*SE*	Statistic	*p*
(Intercept)	480.713***	10.643	45.169	<.001
Random effects				
σ^2	9,970.818			
$\tau_{00\ \text{subject}}$	3,139.481			
Intraclass Correlation Coefficient	0.239			
N_{subject}	30			
Observations	1,159			
Marginal R^2/conditional R^2	.000/.239			

Note. No significant main effects, no interactions. RT = reaction time.
*** $p < .01$.

Table A3
Summary of Results From Linear Mixed Effects Modeling of Experiment 3 (Magnitude)

	RT			
Predictors	Estimates	*SE*	Statistic	*p*
(Intercept)	459.842***	6.327	72.679	<.001
Size sum size	−7.859*	4.352	−1.806	.071
Side sum side	−4.017	4.352	−0.923	.356
Counting sum counting	−8.051	12.654	−0.636	.525
Size Sum Size × Side Sum Side	3.943	8.703	0.453	.651
Size Sum Size × Counting Sum Counting	4.847	8.703	0.557	.578
Side Sum Side × Counting Sum Counting	−4.747	8.703	−0.545	.586
Size Sum Size × Side Sum Side × Counting Sum Counting	−32.848*	17.407	−1.887	.059
Random effects				
σ^2	10,550.046			
$\tau_{00\ \text{subject}}$	1,012.582			
Intraclass Correlation Coefficient	0.088			
N_{subject}	29			
Observations	2,253			
Marginal R^2/conditional R^2	.005/.092			

Note. There was a marginally significant triple interaction between number size, target side, and counting direction ($p = .059$). RT = reaction time.
* $p < .1$. *** $p < .01$.

(*Appendix continues*)

Table A4

Summary of Results From Linear Mixed Effects Modeling of Experiment 4 (Magnitude)

	RT			
Predictors	Estimates	*SE*	Statistic	*p*
(Intercept)	463.946***	9.982	46.479	<.001
Size sum size	−1.333	2.720	−0.490	.624
Side sum side	1.999	2.720	0.735	.462
Count sum count	11.746	19.964	0.588	.556
Size Sum Size × Side Sum Side	0.959	5.439	0.176	.860
Size Sum Size × Count Sum Count	5.447	5.439	1.001	.317
Side Sum Side × Count Sum Count	−1.954	5.440	−0.359	.720
Size Sum Size × Side Sum Side × Count Sum Count	−36.726***	10.878	−3.376	.001
Random effects				
σ^2	10,739.465			
$\tau_{00\ \text{subject}}$	5,924.846			
Intraclass Correlation Coefficient	0.356			
N_{subject}	61			
Observations	5,854			
Marginal R^2/conditional R^2	.004/.358			

Note. There was a significant three-way interaction between number size, target side, and counting direction. The following analyses document this triple interaction, releveling by target side and counting direction. RT = reaction time.
*** $p < .01$.

Table A5

Detailed Analysis for Experiment 4. Condition: Side = Right, Counting = Left-To-Right

	RT			
Predictors	Estimates	*SE*	Statistic	*p*
(Intercept)	456.585***	13.651	33.448	<.001
Size sum size	−13.717***	5.210	−2.633	.008
Side [2]	2.975	3.678	0.809	.419
Count [2]	12.723	20.150	0.631	.528
Size Sum Size × Side [2]	19.322***	7.354	2.627	.009
Size Sum Size × Count [2]	23.810***	7.710	3.088	.002
Side [2] × Count [2]	−1.954	5.440	−0.359	.720
(Size Sum Size × Side [2]) × Count [2]	−36.726***	10.878	−3.376	.001
Random effects				
σ^2	10,739.465			
$\tau_{00\ \text{subject}}$	5,924.846			
Intraclass Correlation Coefficient	0.356			
N_{subject}	61			
Observations	5,854			
Marginal R^2/conditional R^2	.004/.358			

Note. RT = reaction time.
*** $p < .01$.

(*Appendix continues*)

Table A6
Detailed Analysis for Experiment 4. Condition: Side = Right, Counting = Right-to-Left

Predictors	RT			
	Estimates	*SE*	Statistic	*p*
(Intercept)	469.308***	14.822	31.664	<.001
Size sum size	10.093*	5.683	1.776	.076
Side [2]	1.022	4.008	0.255	.799
Count [1]	−12.723	20.150	−0.631	.528
Size Sum Size × Side [2]	−17.404**	8.015	−2.171	.030
Size Sum Size × Count [1]	−23.810***	7.710	−3.088	.002
Side [2] × Count [1]	1.954	5.440	0.359	.720
(Size Sum Size × Side [2]) × Count [1]	36.726***	10.878	3.376	.001
Random effects				
σ^2	10,739.465			
$\tau_{00\ \text{subject}}$	5,924.841			
Intraclass Correlation Coefficient	0.356			
N_{subject}	61			
Observations	5,854			
Marginal R^2/conditional R^2	.004/.358			

Note. RT = reaction time.
* $p < .1$. ** $p < .05$. *** $p < .01$.

Table A7
Detailed Analysis for Experiment 4. Condition: Side = Left, Counting = Left-To-Right

Predictors	RT			
	Estimates	*SE*	Statistic	*p*
(Intercept)	459.561***	13.648	33.671	<.001
Size sum size	5.605	5.191	1.080	.280
Side [1]	−2.975	3.678	−0.809	.419
Count [2]	10.769	20.146	0.535	.593
Size Sum Size × Side [1]	−19.322***	7.354	−2.627	.009
Size Sum Size × Count [2]	−12.916*	7.674	−1.683	.092
Side [1] × Count [2]	1.954	5.440	0.359	.720
(Size Sum Size × Side [1]) × Count [2]	36.726***	10.878	3.376	.001
Random effects				
σ^2	10,739.465			
$\tau_{00\ \text{subject}}$	5,924.841			
Intraclass Correlation Coefficient	0.356			
N_{subject}	61			
Observations	5,854			
Marginal R^2/conditional R^2	.004/.358			

Note. RT = reaction time.
* $p < .1$. ** $p < .05$. *** $p < .01$.

(*Appendix continues*)

Table A8
Detailed Analysis for Experiment 4. Condition: Side = Left, Counting = Right-To-Left

Predictors	RT			
	Estimates	*SE*	Statistic	*p*
(Intercept)	470.330***	14.819	31.739	<.001
Size sum size	−7.311	5.652	−1.294	.196
Side [1]	−1.022	4.008	−0.255	.799
Count [1]	−10.769	20.146	−0.535	.593
Size Sum Size × Side [1]	17.404**	8.015	2.171	.030
Size Sum Size × Count [1]	12.916*	7.674	1.683	.092
Side [1] × Count [1]	−1.954	5.440	−0.359	.720
(Size Sum Size × Side [1]) × Count [1]	−36.726***	10.878	−3.376	.001
Random effects				
σ^2	10,739.465			
$\tau_{00\ \text{subject}}$	5,924.846			
Intraclass Correlation Coefficient	0.356			
N_{subject}	61			
Observations	5,854			
Marginal R^2/conditional R^2	.004/.358			

Note. RT = reaction time.
* $p < .1$. ** $p < .05$. *** $p < .01$.

Table A9
Overview of Results From the Mixed Counting Group (N = 14) in Experiment 4

Experiment/task	Inconsistent counters				Att-SNARC effect
	Left targets		Right targets		
	Small numbers	Large numbers	Small numbers	Large numbers	
4/Magnitude	451 (16)	476 (18)	444 (11)	454 (15)	+7

Note. Values are mean RTs (standard errors in brackets) in milliseconds. Att-SNARC effects were computed by assuming the canonical congruency relationship between numbers and space (details in the main text). Att-SNARC = attentional spatial–numerical association of response codes; RT = reaction time.

Received January 6, 2023
Revision received August 8, 2023
Accepted August 15, 2023 ■