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No conclusive evidence for number-induced attentional shifts in a temporal order judgment task

Hesselmann, Guido¹, Knops, André²

¹ Psychologische Hochschule Berlin (PHB), Department of General and Biological Psychology, Berlin, Germany

² UMR CNRS 8240, Department of Psychology, Université Paris Cité, Paris, France

* = correspondence should be addressed to:

André Knops, UMR CNRS 8240, Department of Psychology, Université Paris Cité, Paris, France, andre.knops@cnrs.fr

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Abstract

The Spatial Numerical Association of Response Codes (SNARC) effect refers to the observation that relatively small (e.g., 1) and large numbers (e.g., 9) elicit faster left-sided and right-sided manual responses, respectively. In a variation known as the attentional SNARC effect, merely looking at numbers caused a left- or rightward shift in covert spatial attention, depending on the number's magnitude. In our study, we probed the notion that numbers induce shifts of spatial attention in accordance with their position on a mental number line (MNL). Critically, we removed any putative spatial response code that may contaminate the responses. We used a square and a tilted square as targets, thereby situating the decisive response dimension in the ventral, non-spatial processing stream. In two experiments where numbers were used as non-informative cues preceding a temporal order judgment (TOJ) task, we did not observe a deflection of the locus of spatial attention as a function of the numerical magnitude of the cue. In a third experiment, finding a significant modulation of TOJ performance as a function of the pointing direction of arrow cues allowed us to rule out the possibility that the absence of any significant modulation in experiments 1 and 2 was due to a lack of sensitivity of our task set-up. We conclude from the current findings that the spatial codes that the perception and naming of numbers potentially elicit are not in and by themselves sufficient to elicit deflections of spatial attention.

Introduction

According to an influential notion, numerical magnitude information is mentally represented along a spatially oriented one-dimensional manifold, often referred to as the mental number line (MNL). In Western societies with left-to-right reading direction, smaller numbers are represented left from larger numbers on the MNL. The congruency between the spatial position of an internally represented number and external factors such as position of the response hand has been used to explain empirical phenomena such as the Spatial Numerical Association of Response Codes (SNARC). The SNARC effect refers to the observation that relatively small (e.g., 1) and large numbers (e.g., 9; small and large within the context of a given experiment using only one-digit numbers) elicit faster left-sided and right-sided manual responses, respectively (Dehaene, Bossini, & Giraux, 1993). In this framework, the congruency between the response side and the spatial position of the presented number on the MNL facilitates responses, whereas an incongruency between both spatial codes slows down responses.

However, different theoretical approaches have been proposed to account for the SNARC effect that do not predominantly call on the congruence between spatial semantic and motor codes. For example, Santens and Gevers (p. 269 Santens & Gevers, 2008) question a direct mapping between semantic and motor codes and instead argue for “intermediate categorization of numbers as relatively small (- polarity) or large (+ polarity) [...] that are subsequently linked with their corresponding alternatives on a response dimension (left/right, bottom/top, close/far, . . .).” Alternatively, others argue against an association of response location with a location on a long-term memory representation and instead stress the ad-hoc, task-dependent serial position in working memory as the main determinant of spatial-numerical associations (Fias, van Dijck, & Gevers, 2011; van Dijck, Abrahamse, Acar, Ketels, & Fias, 2014). To further probe the assumption of a spatial layout of the mental number representation, Fischer and colleagues (Fischer, Castel, Dodd, & Pratt, 2003) used a target detection paradigm. They centrally presented small (i.e., 1 or 2) or large (i.e., 8 or 9) numbers as non-informative cues prior to laterally presented targets. Participants were required to indicate target appearance as fast and accurately as possible via button press with the preferred hand. In line with the idea that the spatial position of the numbers deviates spatial attention to the left for smaller numbers and to the right for larger numbers, target detection was facilitated when the spatial position of the number on the MNL was congruent with the side at which the target would appear. That is, left targets were responded to faster after the presentation a smaller number, while right targets were responded to faster after the presentation of larger numbers. This attentional SNARC

effect has proven hard to replicate though – despite multiple attempts and a large number of participants (Colling et al., 2020; Fattorini, Pinto, Rotondaro, & Doricchi, 2015; Zanolie & Pecher, 2014). Hence, both the SNARC and the attentional SNARC effect do not unanimously provide evidence for the assumption of a spatially organized mental number representation.

Another frequently used paradigm to probe attentional prior-entry biases is the temporal order judgment (TOJ) paradigm. In a typical TOJ paradigm participants are sequentially presented with two target stimuli that are presented to the left and right of a central fixation stimulus. The stimulus onset asynchrony (SOA) between both targets is manipulated such that the left target is preceding the right one by a varying duration in half of the trials and vice versa. The TOJ paradigm builds on a long-standing stance in experimental psychology that goes back to (Titchener, 1908) and is known as the prior-entry hypothesis: “the object of attention comes to consciousness more quickly than the objects which we are not attending to.” Applied to a TOJ paradigm, the target that is in the focus of attention enters the cognitive system first. This is even the case if the attended target is lagging behind in time. In a sense, the attentional benefit would compensate the temporal lag effect up to a certain degree (i.e., a certain temporal lag): the attended stimulus needs to be presented later in time in order to be perceived as simultaneous. A parameter that is often used to quantify the attentional benefit is the point of subjective simultaneity (PSS). It illustrates the estimated point in time where the probability of saying that the right stimulus appeared first equals the probability of saying that the left stimulus appeared first (i.e., 50 % each). TOJs have been deployed in a number of previous studies probing the attentional deflection following from presenting single digits (Casarotti, Michielin, Zorzi, & Umiltà, 2007; Galarraga, Pratt, & Cochrane, 2022) or arithmetic operations (Glaser & Knops, 2020). Casarotti and colleagues (2007) found that smaller numbers that were centrally presented before target onset induced a bias favouring left targets while larger numbers induced a bias favouring right targets. These results are in line with the assumption that numbers induce attentional biases as a function of their position on the MNL (i.e., their numerical magnitude). However, there remained a concern due to the fact that response side codes and the attentional effects of the number cues were confounded in Casarotti et al. (Casarotti et al., 2007). That is, participants verbally indicated which target appeared first by using non-words (fulpo/pingo) that were associated with left and right side (counterbalanced across participants). According to a prominent theory, the brain organizes the processing of visual input along two principal pathways; a ventral pathway that elaborates on object identity is contrasted with a dorsal pathway that operates on spatial attributes (Milner & Goodale, 2008; but see Schenk &

McIntosh, 2010). Task designs that explicitly associate responses with spatial codes may pre-activate the spatial processing stream (e.g., in parietal cortex) which then “contaminates response times even in tasks with arbitrary stimulus–response association rules” (Fias, Lauwereyns, & Lammertyn, 2001). That is, in tasks that require the processing of spatial stimulus properties or refer to the spatial layout of responses may facilitate the activation of the spatial dimension of numerical magnitude which may then lead to congruency effects such as the (attentional) SNARC.

To orthogonalize response dimension from the stimulus and cue dimensions, participants are asked to report which stimulus appeared second rather than which appeared first. If a left target appears first and benefits from an attentional bias (e.g., due to a small number cue), under this instruction it would not be referred to in the response. That is, the cued target is not identical with the response code which refers to the uncued target. Galarraga and colleagues (2022) used this procedure to disentangle spatial response codes from attentional prior-entry biases. They observed a reversed spatial bias because “participants were more likely to report that the right target appeared first (left-side response) following a low digit and that the left target appeared first (right-side response) following a high digit (p. 813; (Galarraga et al., 2022)).” The authors concluded that the attentional SNARC effect that is observed in TOJ tasks is not induced by attentional shifts. However, Galarraga et al. (2022) used manual button presses with laterally organized response buttons (left vs. right response button) which leads to the activation of spatial response codes and thereby may pre-activate the spatial processing of the number cues. This, in turn may have led to the current effects that can alternatively be explained by a congruency between numerical magnitude and response side. Under this alternative assumption, smaller numbers would pre-activate left sided responses while larger numbers would pre-activate right sided responses. Hence, the current evidence does not allow to decide whether or not numbers do induce spatial biases.

The current study was designed to probe the notion that numbers induce shifts of spatial attention in accordance with their position on a MNL in the absence of any putative spatial response code that may contaminate the responses. Preceding a classical TOJ task, participants were presented with non-informative number cues (experiments 1 and 2) or arrows (experiment 3). We used a square and a tilted square as targets, thereby situating the decisive response dimension in the ventral, non-spatial processing stream. To further eliminate putative response biases, participants reported which target form appeared first in one half of the experiments and

which target appeared last on the other. This procedure is commonly argued to isolate the attentional prior-entry effect (Spence & Parise, 2010).

Methods

Participants

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. No part of the study procedures or analyses was pre-registered prior to the research being conducted.

Sample size was determined apriori based on the study by Casarotti et al. (Casarotti et al., 2007). In experiment 6, the small digit (1) induced a positive temporal bias of 5.7 ms. Using WebPlotDigitizer (<https://apps.automeris.io/wpd/>), we extracted the standard error of the mean (SE) from Figure 5, and calculated the corresponding standard deviation (SD) as $2.6 * \sqrt{10} = 8.2$ ms. Using GPower 3.1.9.7 (Faul, Erdfelder, Lang, & Buchner, 2007) we then determined that for effect size $d = 0.70$, and $\alpha = 0.05$, a sample of $N = 24$ was necessary to achieve a power of 0.95 (test family: t-test; means: difference from constant, one sample case; one-tailed).

Twenty-five participants took part in experiment 1 (mean age: 23 years, range: 19-32; 16 female; right handed: 21). Participant #14 was excluded from group analysis due to a poor psychometric fit (Figure S1; see below for exclusion criteria). Thirty-two new participants took part in experiment 2 (mean age: 23 years, range: 18-46; 25 female; right handed: 27). The data from participant #1 were discarded because the participant did not follow the instructions, but named the number before the performing the ba/bo task. The data from participant #32 were not included in the analysis because the desired N had already been reached. Note that the reported results do not change substantially when including participant #32. Participants #5, #11, #15, #19, #25, and #26 were excluded from group analysis due to poor psychometric fits (Figure S2). Twenty-seven new participants took part in experiment 3 (mean age: 25 years, range: 18-50; 13 female; right handed: 25). The data from participant #19 were discarded due to technical problems during data acquisition. Participants #11 and #16 were excluded from group analysis due to poor psychometric fits (Figure S3).

Participants were recruited via student mailing lists and personal contact (exp.3). All participants had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. All participants were naïve to the purpose of the experiments, provided written informed consent and received monetary compensation (€8/h) or course credit for their participation. The total duration of the experiments was approximately 60 minutes. The experiments were conducted at the Psychologische Hochschule Berlin (PHB), and were approved by the local ethics committee (approval number PHB10032019).

Setup and stimuli

The experiment was conducted in a darkened, sound-attenuated room, with indirect light coming from the experimenter's PC screen. Participants viewed a 19" CRT monitor (SAMTRON 98PDF; 1280 x 1024 pixels; refresh rate 85 Hz) using a chinrest to stabilize head position. The viewing distance was 57 cm. All stimuli were created using Matlab 2019a (MathWorks, Natick, MA), and the Psychophysics toolbox 3.0.12 (Brainard, 1997), on a PC with Windows 10 and an AMD Radeon 6450 graphics card. Participants provided verbal responses, and used the PC keyboard to navigate through the experiments (e.g., to terminate a pause). Verbal responses were recorded using a Behringer XM8500 microphone and a Focusrite Scarlett Solo audio-interface, and stored as wav files.

Figure 1 illustrates the display sequence used in all experiments. In experiment 1, each trial began with a centrally presented fixation circle (494 ms; diameter 0.5°), followed by a digit cue (247 ms; $0.5^\circ \times 1^\circ$, width x height). Two digits were used: 1 and 9. After a jittered random delay (250 or 500 ms \pm 10%), the first target stimulus was presented, either to the left or to the right of the fixation (eccentricity 4°). The second target stimulus was presented to the other side of fixation. Two different target stimuli were used on each trial: a square, and a tilted square (both $1^\circ \times 1^\circ$). The fixation circle and target stimuli were white (101 cd/m²) on a uniformly grey background (31 cd/m²). The first target stimulus was presented for 12, 24, 35, or 71 ms, resulting in $2 \times 4 = 8$ different stimulus onset asynchronies (SOA) between the left and the right target stimulus. Following Casarotti et al. (Casarotti et al., 2007), negative SOAs refer "left target first" trials, and positive SOAs refer to "right target first" trials. Please note that all presentation durations are multiples of 11.8 ms (i.e., the duration of one screen frame at 85 Hz refresh rate). The second target stimulus was presented until a verbal response was successfully recorded, which started the next trial. In one block of trials, the participant's task was to identify

and name the target stimulus that was presented first (square = “bo”, tilted square = “ba”). In another block of trials, the task was to identify and name the stimulus that was presented last. Each block consisted of 192 trials in random order (12 trials per condition; 8 SOAs and 2 cues = 16 conditions). In each condition, both locations of the first stimulus (left/ right of fixation) and both shapes of the first stimulus (square/ tilted square) were equally likely. There were additional 30 training trials at the beginning of each block, the first 10 trials used the longest SOAs, followed by 20 trials with random SOAs. The order of the two blocks was counter-balanced across participants.

Experiment 2 was identical with experiment 1, with the following exception. In randomly selected 33% of all trials, participants had a second task. After providing the first verbal response (“ba”, or “bo”), participants were instructed to also name the presented digit (“1”, or “9”). When this second verbal response was successfully recorded, the next trial began. Experiment 3 was identical with experiment 2, with the following exception. Instead of digits, arrow cues were presented ($2^\circ \times 1^\circ$), either pointing to the left, or to the right (Figure 1). After providing the first verbal response (“ba”, or “bo”), participants were instructed to name the direction of the arrow cue (“left”, or “right”).

<<< insert Fig. 1 about here >>>

Data analysis

Data pre-processing, descriptive and inferential statistics were performed using R 4.1.1 (R Core Team, 2021) and RStudio 2021.09.0, Build 351 (RStudio Team, 2021). Data visualizations were created with the R package ggplot2 (Wickham, 2016). Trial-by-trial data in csv-format and R scripts for data analysis are available at an online repository (<https://doi.org/10.17605/OSF.IO/T4J7W>).

The recorded verbal responses were decoded manually (experiments 1-3: “ba”, “bo”; experiment 2: “1”, “9”; experiment 3: “left”, “right”). In the rare case that the audio file contained more than one response (e.g., when a participant corrected the first response), only the first response was decoded. Training trials were discarded. Trials without audible verbal responses, and trials with incomprehensible verbal responses were marked and removed from the analysis (experiment 1: 0%; experiment 2: 0.7%; experiment 3: 1.4%; mean percentage of trials). For each participant and condition, the proportion of “left stimulus first” responses were calculated based on the verbal “ba/bo” responses. In experiment 2, the proportion of correct responses in

the number identification task was calculated for each participant. In experiment 3, the proportion of correct responses in the arrow identification task was calculated for each participant.

A logistic model was fitted to the proportion data of each participant as a function of the SOA (in frames), separately for digit 1 and digit 9 (experiment 3: arrow left and arrow right). The data were collapsed across both instructions (i.e., name the stimulus that appeared first/last). The logistic model allowed us to determine the point of subjective simultaneity (PSS) for each cue condition. Using the `psignifit4` toolbox (Schutt, Harmeling, Macke, & Wichmann, 2016) in Matlab 2019a we verified the PSS estimates (see supplementary tables S1 and S2). The PSS represents the SOA for which the observer perceives the stimuli as simultaneous. A shift in the PSS in either direction thus indicates that the cue induced a temporal bias (Casarotti et al., 2007). When piloting the first experiment, we noticed that poor psychometric fits were associated with extreme PSS values. Therefore, we decided to exclude the data from participants showing poor psychometric fits. For each participant's proportion data (collapsed across both cue conditions), we calculated McFadden's pseudo- R^2 as a goodness-of-fit measure; participants with pseudo- $R^2 < 0.18$ were excluded from group analysis (Louviere, Hensher, & Swait, 2000).

For each experiment, we computed a repeated-measures ANOVA with cue (digit 1 versus digit 9, or arrow left versus arrow right) and SOA (-6, -3, -2, -1, 1, 2, 3, 6; screen refresh frames), following Casarotti et al. (Casarotti et al., 2007). Degrees of freedom were Greenhouse-Geisser-corrected; we report uncorrected degrees of freedom, the correction value epsilon (ϵ), and the effect size partial eta-squared (η_p^2). A paired samples two-tailed t-test was then performed on the individual PSS to compare the temporal biases induced by each cue. To quantify the evidence in favour of the alternative hypothesis over the null hypothesis (or, vice versa), a Bayesian equivalent of the paired t-test was calculated using the `BayesFactor` package 0.9.12-4.4 in R. Bayes factors describe the relative probability of data under competing positions (e.g., a null model H_0 and one alternative model H_1). The Bayes factor (BF) refers to the ratio of marginal likelihoods of different models under consideration, and quantify the change from prior to posterior model odds. The prior odds describe the beliefs about the models before observing the data. The BF thus describes how the evidence from the data should change beliefs. The subscripts on BFs refer to the models being compared, with the first and second subscript referring to the model in the numerator and denominator, respectively. For example, a BF_{10} of 5 indicates that the data are five times more likely under H_1 than under H_0 . We used

the `ttestBF` and `extractBF` functions from the `BayesFactor` package. `TtestBF` uses a Cauchy prior (scale parameter: $\sqrt{2}/2 = .707$). Models, priors, and methods of computation are provided in Rouder et al. (Rouder, Morey, Speckman, & Province, 2012). Classification schemes can be used to group Bayes factors into different categories. According to Lee and Wagenmakers (2013), BFs between 1 and 3 indicate anecdotal evidence, BFs larger than 3 moderate evidence, and BFs larger than 10 strong evidence.

Results – experiment 1

Figure 2A shows the mean percentage of left-first responses as a function of SOA in experiment 1, separately for digits 1 and 9. As expected, both psychometric curves show a decreasing shape, but they overlap to a large degree, irrespective of SOA. Accordingly, the rm-ANOVA revealed that only the main effect of SOA was significant ($F(7,161) = 141.95$, $p < .001$, $\eta_p^2 = .86$, $\text{eps} = .31$). Neither the main effect of digit magnitude ($F(1,23) < 1$, $p = .421$, $\eta_p^2 = .03$, $\text{eps} = 1$), nor the interaction were significant ($F(7,161) < 1$, $p = .690$, $\eta_p^2 = .03$, $\text{eps} = .75$).

In order to measure the amount of temporal bias induced by each number, we calculated the PSS for each individual psychometric curve, i.e., the point at which the observer perceived the stimuli as simultaneous. Figure 3A shows the mean temporal biases induced by digits 1 and 9. Digit 1 resulted in a negative bias of -2.9 ms (i.e., in the wrong direction), and digit 9 induced a negative bias of -1.9 ms (i.e., in the predicted direction). The statistical comparison between the temporal biases turned out to be not significant ($t(23) = -0.40$, $p = .694$; paired two-tailed t-test), with a Bayes Factor favouring the null over the alternative hypothesis ($\text{BF}_{01} = 4.35$).

<<< insert Figure 2 about here >>>

Discussion

Experiment 1 aimed at probing the notion that numbers induce shifts of spatial attention in accordance with their position on a MNL in the absence of any putative spatial response code that may contaminate the responses. The results do not support this notion. The results revealed a small overall shift of spatial attention to the right side of space. Importantly, there was no interaction with the numerical magnitude of the number cue. Rather, the Bayesian analysis revealed evidence that favoured the null hypothesis over the alternative hypotheses when comparing the number cues. In sum, when removing all spatial associations from the paradigm,

the presentation of a number did not induce shifts of spatial attention. However, since the number cues in the current paradigm were task-irrelevant, one might argue that the absence of spatial cueing was due to the fact that the number cues were not actively processed by the participants. Previous studies (e.g. Zanolie & Pecher, 2014) suggest that the attentional SNARC arises when participants actively processed the number cues (but see Galarraga et al., 2022). Indeed, the number cues were non-informative and despite the fact that adult participants cannot not read written symbols (e.g. Pattamadilok et al., 2017), we cannot know to what extent the semantic content of the numbers has been processed. We therefore replicated experiment 1 and added a secondary task that would require participants to identify and memorize the number cues. In 33% of the trials, participants were asked to name the number cue after having completed the TOJ task.

Results – experiment 2

In experiment 2, the mean performance in the number naming task was 85% (range 66-94%). Figure 2B shows the mean percentage of left-first responses as a function of SOA, separately for digits 1 and 9. Both psychometric curves show a decreasing shape, and again overlap to a large degree, irrespective of SOA. Accordingly, the rm-ANOVA revealed that only the main effect of SOA was significant ($F(7,161) = 186.69, p < .001, \eta_p^2 = .89, \text{eps} = .50$). Neither the main effect of digit magnitude ($F(1,23) = 3.78, p = .064, \eta_p^2 = .14, \text{eps} = 1$), nor the interaction were significant ($F(7,161) < 1, p = .727, \eta_p^2 = .02, \text{eps} = .64$).

Figure 3A shows the mean temporal biases induced by digits 1 and 9. Digit 1 resulted in a positive bias of 6.9 ms (i.e., in the predicted direction), and digit 9 induced a positive bias of 4.5 ms (i.e., in the wrong direction). The statistical comparison between the temporal biases turned out to be not significant ($t(23) = 1.52, p = .142$; paired two-tailed t-test), with a Bayes Factor slightly favouring the null over the alternative hypothesis ($\text{BF}_{01} = 1.70$), albeit providing only anecdotal evidence. When the data from both experiments 1 and 2 were analysed together ($N=48$), the temporal biases turned out to be 2.0 ms and 1.3 ms for cue numbers 1 and 9, respectively, and they were statistically not different from each other ($t(47) = 0.51, p = .612$; $\text{BF}_{01} = 5.64$).

Discussion – experiment 2

The results of experiment replicated those from experiment 1. We did not observe a significant modulation of the locus of spatial attention as a function of the numerical magnitude of the number cue. Since participants were asked to identify and memorize the number cue, we can exclude that the absence of a number-induced attentional bias is due to the lack of cognitive resources deployed on the processing of the number cues. Instead, these results underline the notion that in the absence of any spatial codes at the task level, numbers do not induce shifts of spatial attention.

Although TOJ tasks have been used to demonstrate spatial biases in the past, we scrutinized the potential of revealing spatial biases in the current cueing set-up in a third experiment. In experiment 3, we replaced the number cues by non-informative arrows. All other details were identical to experiment 2, including the secondary task asking participants to identify and memorize the direction that the arrows pointed to.

Results – experiment 3

In experiment 3, the mean performance in the arrow naming task was 95% (range 83-100%). Figure 2C shows the mean percentage of left-first responses as a function of SOA, separately for left and right arrows. Both psychometric curves show a decreasing shape. At short SOAs between the stimuli, however, the data points from the left arrow curve lie above the data points from the right arrow curve. The rm-ANOVA revealed a significant main effect of SOA ($F(7,161) = 147.52, p < .001, \eta_p^2 = .87, \epsilon_s = .40$), but also a significant main effect of arrow direction ($F(1,23) = 14.98, p < .001, \eta_p^2 = .39, \epsilon_s = 1$), and a significant interaction ($F(7,161) = 4.24, p = .003, \eta_p^2 = .16, \epsilon_s = .61$).

Figure 3C shows the mean temporal biases induced by left and right arrows. Left arrows resulted in a positive bias of 6.7 ms, and right arrows induced a negative bias of -11.6 ms. Thus, both biases were in the expected direction. The statistical comparison between the temporal biases turned out to be significant ($t(23) = 3.78, p < .001$; paired two-tailed t-test), with a Bayes Factor strongly favouring the alternative over the null hypothesis ($BF_{10} = 36.03$).

<<< insert Figure 3 about here >>>

Discussion – experiment 3

Experiment 3 was designed to test the potential of our TOJ set-up to reveal attentional biases. When using arrows instead of numbers as non-informative cues, we observed a reliable deflection of spatial attention in the direction that the arrows pointed to. Hence, we can exclude that the absence of spatial biases in experiments 1 and 2 were due to our task set-up.

General Discussion

The current study was designed to probe the notion that numbers induce shifts of spatial attention in accordance with their position on a MNL in the absence of any putative spatial response code that may contaminate the responses. In two experiments where numbers were used as non-informative cues preceding a TOJ task, we did not observe a deflection of the locus of spatial attention as a function of the numerical magnitude of the cue. By making the number cues task-relevant in a secondary task in experiment 2 (while still being non-informative for the primary TOJ task), we sought to guarantee that the cues were actively processed by the participants. Even under these conditions, the number cues did not influence the locus of spatial attention. Finding a significant modulation of TOJ performance as a function of the pointing direction of arrow cues in experiment 3 allowed us to rule out the possibility that the absence of any significant modulation in experiments 1 and 2 was due to a lack of sensitivity of our task set-up.

Inspired by the metaphor of the mental number line, a spatial representation of numerical magnitude, the idea that numbers can induce shift of spatial attention as a function of their position on this one-dimensional manifold has received empirical support from behavioural experiments (Casarotti et al., 2007; Fischer et al., 2003; Ristic, Wright, & Kingstone, 2006), neural measures (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009; Pinto et al., 2018) and neuropsychological observations (Zorzi et al., 2012; Zorzi, Priftis, & Umiltà, 2002). At the behavioural level, however, the attentional effects have not always been successfully replicated (Colling et al., 2020; Zanolie & Pecher, 2014). Casarotti and colleagues (2007) presented number cues prior to a TOJ task to probe this notion and observed a preference for left targets following small number cues, and a preference for right targets following large number cues. However, this study suffered from two major shortcomings that lead to confounds with non-numerical mechanisms. First, they consistently instructed participants to report the target that appeared first. Second, although they replaced the words ‘left’ and ‘right’ by pseudowords (fulpo/pingo), participants responded by referring to the spatial position of the target that

appeared first. This may have primed a spatial processing pathway and thereby paved the way for putative deflections of spatial attention (Fias et al., 2001).

To address the first issue, a previous study used a TOJ in combination with number cues and found that spatial response correspondences overshadow putative attentional biases induced by numbers (Galarraga et al., 2022). By asking participants to decide which target in a TOJ task appeared second, Galarraga and colleagues (2022) orthogonalized the assumed attentional deflection due to the number cues with biases that might arise from response-based spatial correspondences. For example, with the instruction to report the first target, both the left-sided bias due to a small number cue is confounded with the correspondence between left target side and left response side. By instructing to report the second target, this confound is alleviated. Galarraga and colleagues found an overall preference for left-first/right-second targets that was more pronounced for the large cue number (9) compared to the small cue number (1). Hence, the response bias followed the side of response rather than the spatial position of the number on the mental number representation, taking the form of a response-related SNARC effect. In the current experiments, we counter-balanced the correspondence effects between manual response side and number cues within-participant by instructing participants to report the first target in one half of the trials, while reporting the second target in the other half of the trials. Hence, if the response-related spatial correspondence is what drives the observed biases, these effects would be cancelled out by our procedure. Our results are consistent with this interpretation since they show that (a) numbers do not elicit deflections of spatial attention when (b) no spatial correspondences are present in the experimental procedure.

The current experiments also help addressing the second issue that we identified in the study by Casarotti and colleagues (2007). We tried to eliminate a maximum of spatial codes from our task. Most crucially, instead of reporting the side which the first or the second target appeared on, participants reported the shape of the target under question (square/ tilted square). We thereby eliminated the focus on the spatial dimension of the target and primed ventral processing pathways. Under these conditions, numbers no longer induced any spatial deflections of spatial attention. Note however, that this manipulation does not prevent putative attentional biases from emerging. Provided the cue possesses sufficiently strong spatial codes, as is the case for the arrow cues, attentional biases should still be detectable by the TOJ task. This is exactly what we observe in experiment 3 where arrow cues elicit an attentional bias over and above the counter-balanced response mapping.

While we cannot rule out that our task design is not sufficiently sensitive for detecting spatial biases for example by using online measures of brain activity such as EEG (Pinto et al., 2018), the cognitive cascade initiated by our task requirements (identifying, maintaining in working memory, and naming) are not sufficient to elicit spatial biases that can be detected in a TOJ task.

We conclude from the current findings that the spatial codes that the perception and naming of numbers potentially elicit are not in and by themselves sufficient to elicit deflections of spatial attention. These findings add to existing evidence that question the reflexive and automatic nature of attentional shifts elicited by centrally presented number cues (Galfano, Rusconi, & Umiltà, 2006; Ristic et al., 2006). To deflect attention in space, centrally presented numbers need to be embedded in a context that triggers spatial associations. This includes, but is not limited to, the activation of top-down mental sets as demonstrated by reversed spatial effects with imagined right-to-left number lines or clock faces (Ristic et al., 2006) or the explicit association of number cues with spatial positions via cue validity (Galfano et al., 2006). At a very minimum, the task context needs to activate spatial references at the stimulus or response level which may then coincide with the processing of numerical magnitude. This may have its origin in an overlap of processing sites in the parietal cortex (Fias et al., 2001).

Spatial-numerical associations are often discussed in the context of dual-route models with a “parallel activation of preexisting links between magnitude and spatial representation and short-term links created on the basis of task instructions (Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006).” The present results add to the body of evidence that either questions the existence of “pre-existing links” that are automatically activated or the degree to which those unconditional processing routes impact overt behaviour.

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Figure Captions

Figure 1. Display sequence (not drawn to scale). Each trial began with a centrally presented fixation circle (494 ms), followed by a digit cue (1 or 9) in experiments 1 and 2, or by an arrow cue (left or right) in experiment 3 (247 ms). After a jittered random delay (250 or 500 ms \pm 10%), the first target stimulus was presented, either to the left or to the right of the fixation (12, 24, 35, or 71 ms). The second target stimulus was presented to the other side of fixation, until the verbal response was provided. In one block of trials, the participant's task was to identify and name the target stimulus that was presented first (square = "bo", tilted square = "ba"). In another block of trials, the task was to identify and name the stimulus that was presented last. Please note that all presentation durations are multiples of 11.8 ms (i.e., the duration of one screen frame at 85 Hz refresh rate).

Figure 2. Mean percentage of left-first responses in experiments 1-3 (each N=24), as a function of SOA (in ms). (A) Data from Experiment 1, separately for number magnitude (1 = green, 9 = red). (B) Data from Experiment 2, separately for number magnitude (1 = green, 9 = red). (C) Data from Experiment 3, separately for arrow direction (left = green, right = red). Negative and positive values of SOA refer to left- and right-side stimulus precedence, respectively. Error bars indicate 95% confidence intervals calculated for within-subject data using the `summarySEwithin` function from the `Rmisc` package (version 1.5.1).

Figure 3. Mean temporal biases induced by digits and arrows in Experiments 1-3 (each N=24). (A) Data from Experiment 1, separately for number magnitude (1 = green, 9 = red). (B) Data from Experiment 2, separately for number magnitude (1 = green, 9 = red). (C) Data from Experiment 3, separately for arrow direction (left = green, right = red). The temporal bias is identical with the point of subjective simultaneity (PSS), and was determined by fitting a logistic model to the individual probabilities of left-first responses. Grey connected dots indicate PSS values from individual participants in both conditions. Error bars indicate 95% confidence intervals calculated for within-subject data using the `summarySEwithin` function from the `Rmisc` package (version 1.5.1).

Figure 1

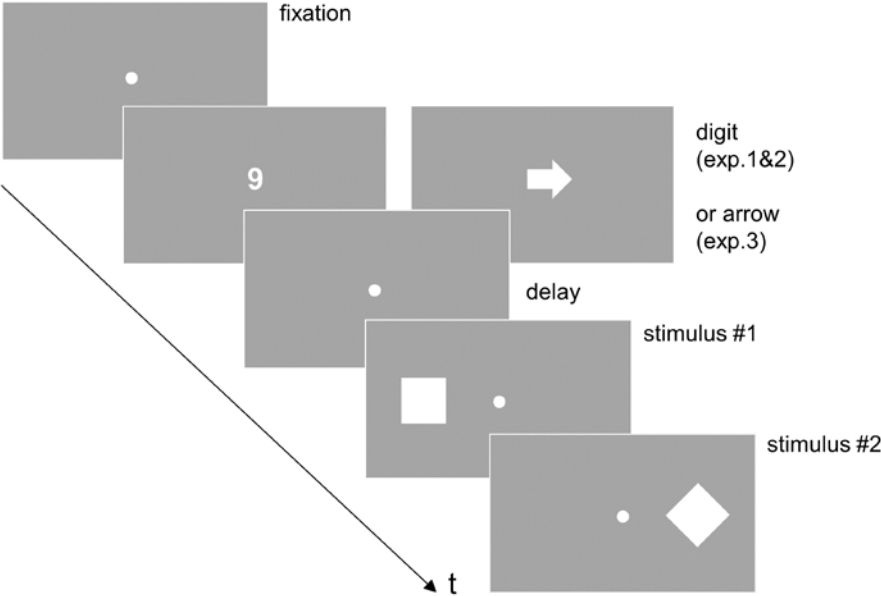


Figure 2

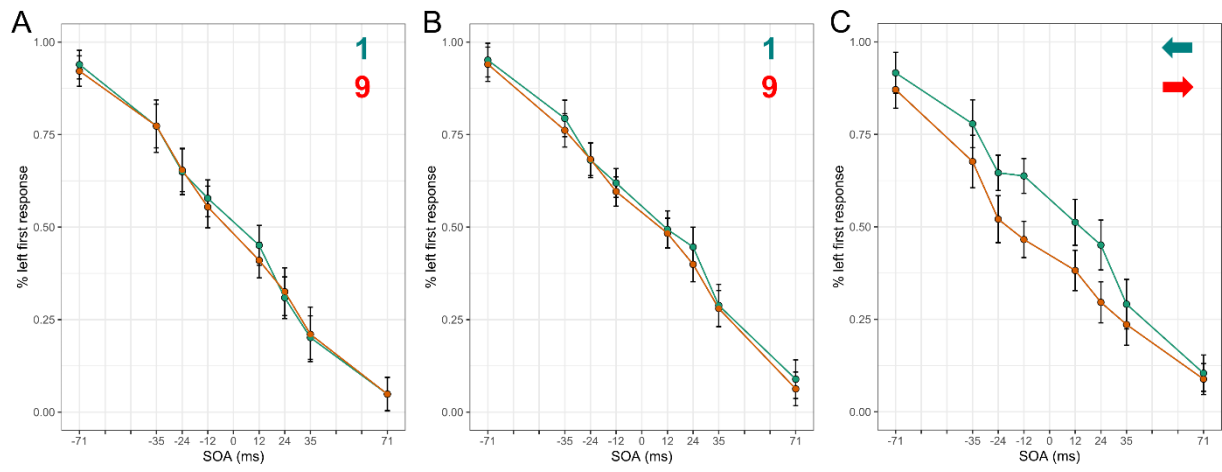


Figure 3

