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Spatial–numerical associations from a novel paradigm support the mental number line account

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Abstract

Multiple tasks have been used to demonstrate the relation between numbers and space. The classic interpretation of these directional spatial–numerical associations (d-SNAs) is that they are the product of a mental number line (MNL), in which numerical magnitude is intrinsically associated with spatial position. The alternative account is that d-SNAs reflect task demands, such as explicit numerical judgements and/or categorical responses. In the novel "Where was The Number?" task, no explicit numerical judgements were made. Participants were simply required to reproduce the location of a numeral within a rectangular space. Using a between-subject design, we found that numbers, but not letters, biased participants' responses along the horizontal dimension, such that larger numbers were placed more rightward than smaller numbers, even when participants completed a concurrent verbal working memory task. These findings are consistent with the MNL account, such that numbers specifically are inherently left-to-right oriented in Western participants.

Keywords
Spatial–numerical associations; SNARC; mental number line; polarity correspondence; working memory; parity

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Introduction

Since the seminal work of Dehaene et al. (1993), the link between space and numbers has inspired a wealth of research. In their classic paradigm, participants made parity judgements (odd/even) of Arabic numerals using left and right response keys. Western participants responded faster to smaller numbers when using the left key and faster to larger numbers when using the right key. This general finding, known as the spatial–numerical association of response codes (SNARC) effect, has since been replicated across multiple paradigms (for a review, see Toomarian & Hubbard, 2018), such as lateralised comparison (e.g., Cheung et al., 2015; Lavidor et al., 2004), number bisection (e.g., Calabria & Rossetti, 2005), and random number generation (e.g., Di Bono & Zorzi, 2013; Loetscher et al., 2008). A common theory of these directional spatial–numerical associations (d-SNAs) is that they are the product of a mental number line (MNL), in which numbers are represented in spatial format (e.g., oriented from left to right among Westerners; for a discussion of cross-cultural effects, see Göbel et al., 2011).

Alternative accounts of d-SNAs posit task-specific demands that generate *transient*, rather than *long-term*, links between numbers and space. One such proposal argues that d-SNAs reflect polarity correspondence (Proctor & Cho, 2006), in which negative and positive poles in binary classification (e.g., left and right response keys) are mapped to binary concepts (e.g., small and large). Another proposal argues that d-SNAs can be continuous (as opposed to binary), but that this continuous relation between ordinal position and spatial direction is constructed online, in a task-specific manner, in working memory (Abrahamse et al., 2016; van Dijck et al., 2009; for a review, see Fias & van Dijck, 2016). By contrast, the MNL account suggests a long-term association between numbers and space (Dehaene et al., 1993; Zorzi et al.,

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2002), which are implicit in nature and exist in a non-binary, continuous format, contra both polarity correspondence and working memory (WM) accounts.

One clear prediction of the MNL account is that if d-SNAs arise from implicit processing, then they should be observed in the absence of explicit magnitude judgements (Shaki & Fischer, 2018). However, ruling out the role of explicit magnitude processing in the construction of d-SNAs has proven difficult. Indeed, many tasks commonly used to assess d-SNAs require explicit magnitude judgements (Shaki & Petrusic, 2005). For example, on a magnitude comparison task, participants are asked to judge whether a presented number (e.g., 9) is larger or smaller than a reference number (e.g., 5). On this task, participants have been shown to respond more quickly when responding "smaller" with the left key and "larger" with the right key. Moreover, even the parity judgement task, in which participants are asked to judge whether a number is odd or even, has been criticised for not being truly implicit. Although the parity judgement task does not require explicit magnitude processing, because parity is a numerical property, it may be sufficient to activate representations of numerical magnitude and, thus, reflect more explicit demands (Cleland & Bull, 2019; Tzelgov & Ganor-Stern, 2005).

The attentional-SNARC effect has often been put forth as evidence of d-SNAs in the absence of explicit magnitude judgements (Fischer et al., 2003). In this task, smaller numbers primed detection of a target located on the left and larger numbers primed detection of a target located on the right. However, accumulating failures to replicate the original findings cast doubt on the attentional-SNARC effect (Fattorini et al., 2015; Zanolie & Pecher, 2014). In particular, in a large-scale, preregistered study, Colling and colleagues (2020) found little to no effect of numerical magnitude on subsequent target detection, challenging claims that d-SNAs arise from long-term and automatic processes (Cipora & Nuerk, 2020). Notably, of the studies that successfully "replicated" the attentional-SNARC effect, they typically required that participants make judgements of numerical magnitude, suggesting that explicit numerical processing may be necessary for the emergence of d-SNAs, contra the predictions of the MNL account (Cipora & Nuerk, 2020; Fischer et al., 2020).

Given the aforementioned concerns, researchers have developed other tasks to more thoroughly assess whether explicit magnitude processing is necessary for the construction of d-SNAs. For example, instead of magnitude comparison, or parity, judgements, participants might complete a judgement of the perceptual, non-numerical feature of the stimulus display, such as the font colour or stimulus orientation (Fias et al., 2001; Mitchell et al., 2012; Yu et al., 2020). Such work has found that judgements of orientation (Mitchell et al., 2012; Yu et al., 2020), but not colour (Fias et al., 2001; Mitchell et al., 2012), induced d-SNAs, suggesting that in some cases, d-SNAs may occur in the absence of any explicit numerical processing.

Another prediction of the MNL account is that d-SNAs are mapped to space in a continuous, as opposed to categorical, manner (Wood et al., 2008). To assess the distinction between continuous and categorical mappings, Gevers and colleagues (2006) developed a computational model of the SNARC effect, as generated by explicit (i.e., magnitude comparison) and implicit (i.e., parity judgement) tasks. They found that whereas the magnitude comparison task yielded a categorical SNA, the parity judgement task yielded a continuous d-SNA. However, proponents of the polarity correspondence account have suggested that even implicit tasks, such as parity judgement, can nonetheless yield polarity correspondence between the task-irrelevant dimension of number and the lateralised response scheme (left/right) (Proctor & Cho, 2006; Proctor & Xiong, 2015). Specifically, tasks that use this kind of response scheme may induce a binary mapping of small/left and large/right, during participants' planning and generating of motor actions (e.g., right key press; Fattorini et al., 2016), resulting in categorical d-SNAs, rather than the continuous d-SNAs predicted by the MNL account (but see Gevers et al., 2006).

Most recently, Shaki and Fischer (2018) developed a novel go/no-go task, modelled after the Implicit Association Test (IAT; Greenwald et al., 1998), to remove explicit numerical judgements and lateralised responses (see also Pinto et al., 2019). For example, participants were instructed to associate numerical parity (even or odd) with arrow colour (red or green), where colour was mapped to arrow direction (e.g., arrows facing upward were always displayed in red). Shaki and Fischer reported a congruity effect such that large and small numbers were associated with upward and downward arrows, respectively, which they suggested reflected a conceptual association between numbers and vertical space, consistent with the MNL account, but only for the vertical direction. Yet this task remains susceptible to an account based on polarity correspondence (Casasanto, 2009; Gevers et al., 2010; Holmes et al., 2019; Meier & Robinson, 2004; Proctor & Xiong, 2015). Effects on the IAT generally, and in Shaki and Fischer (2018) specifically, could reflect a type of polarity correspondence in which dominant stimulus features are associated (e.g., upward arrow and large number). Thus, in the go/no-go task, rules that pair congruent stimulus features in terms of their polarity (upward/large and downward/small) should yield quicker responses than rules that pair incongruent stimulus features (upward/small and downward/large).

Other studies have focused on assessing d-SNAs using non-binary, continuous responses. For example, there is evidence for continuous d-SNAs from eye-tracking studies in which the current numerical value during a task predicts participants' gaze location, in a continuous manner (Holmes et al., 2016; Loetscher et al., 2010). For example, in Loetscher et al. (2010), participants' eye movements were predictive of their random number generation, such that leftward and downward eye movements were predictive of smaller number values, and rightward and upward eye movements were predictive of larger values. However, it remains unclear whether these d-SNAs arise automatically, given that they required explicit numerical processing. There is also the number bisection task in which participants bisect a line comprised of numerals (Calabria & Rossetti, 2005). Participants' estimates of the midpoint were biased by numbers that made up the line, such that lines comprising small numbers were judged to have more leftward midpoints. However, because this task requires the bisection of a horizontal line, it is possible that this horizontal line made directional information particularly salient. Thus, although both eye-movement and bisection tasks provide evidence for d-SNAs that are continuous in nature, contrary to the aforementioned studies with binary responses, it is unclear whether the stimuli used were sufficiently implicit. The MNL account, unlike the WM account, predicts d-SNAs that follow relatively automatically from implicit processing, rather than explicit demands.

Relatedly, providing evidence for the MNL account also requires addressing the extent to which d-SNAs depend on cognitive resources. According to the MNL account, d-SNAs should be observed even when cognitive resources such as working memory are reduced. However, if d-SNAs are constructed online during a task, then the reduction of working memory resources should eliminate d-SNAs. Moreover, if d-SNAs are constructed online, as argued by the WM account, then other ordinal sequences, such as letters of the alphabet, would be similarly associated with space (Abrahamse et al., 2016, 2017; van Dijck & Fias, 2011), given task demands comparable to those that result in an association between numbers and space.

Present study

Without both implicit numerical processing and a non-categorical response scheme, it is unclear whether the association between numbers and space involves an MNL or, rather, a transient, task-specific effect. Here we designed a task to address these critical issues. First, we developed a novel d-SNA task that eliminated explicit numerical processing and categorical responses. Second, we tested whether similar effects occurred for letters on this task. Third, we taxed working memory resources while participants completed the task.

Using a between-subject design, to minimise potential priming effects between conditions, we conducted three separate experiments that evaluated the divergent predictions of the MNL and WM accounts. In Experiment 1, we presented participants with the novel "Where was The Number?" (WTN) task. In this task, participants simply viewed a number on a screen, memorised its location, and after a short delay, placed the number back in its original location. Thus, this task does not require explicit numerical judgements, nor are participants' responses categorical as in tasks involving dichotomised responding. In Experiment 2, we conducted a comparable task with letters as stimuli. If directional spatial associations are specific to numbers, as predicted by the MNL account, and not a reflection of all ordinal processing, as predicted by the WM account, then no effect for letters is expected. However, if spatial associations are task dependent and the result of working memory, then letters should similarly show an association with space. In other words, the WM account views spatial associations for numbers simply as a subset of spatial associations for ordinal sequences, with spatial associations for all ordinal sequences, including numbers, arising from the same processes. In Experiment 3, we assessed whether d-SNAs on the WTN task were dependent on working memory resources. According to the WM account, associations between ordinal sequences and space are a result of a binding process in verbal working memory (Abrahamse et al., 2017). Thus, in Experiment 3, we included a verbal working memory interference task that participants completed concurrently with the WTN task. If d-SNAs result from linking ordinal position with space in verbal working memory, then d-SNAs should not be observed under working memory load (van Dijck et al., 2009).

In the present work, our predictions primarily concerned the horizontal dimension, given the focus on left-to-right associations in the MNL and WM accounts of d-SNAs. However, we, nevertheless, also assessed d-SNAs in the vertical dimension, given recent controversy on this issue (Aleotti et al., 2020; Shaki & Fischer, 2018; Sixtus et al., 2019; Winter et al., 2015).

Experiment 1: WTN task

The WTN task was designed to assess whether participants exhibited d-SNAs in the absence of explicit numerical processing and categorical responses. Like other implicit tasks (e.g., perceptual judgements of non-numerical information), the WTN task did not require participants to assess any numerical property of the presented stimulus. But unlike typical implicit tasks, the WTN task also allowed for assessing d-SNAs in non-binary fashion. In particular, we measured bias in participants' memory for a location within a rectangular space. If d-SNAs are not dependent on explicit numerical judgements or categorical responses, then we should observe d-SNAs on this task.

Method

Participants. A total of 38 undergraduates (M_{age} = 19.29 years; 26 female, 12 male; 33 right-handed, 5 left-handed) participated in this experiment for course credit. Using G*Power 3 (Faul et al., 2007), we conducted a power analysis with an estimated effect size (d = .60) based on meta-analytic

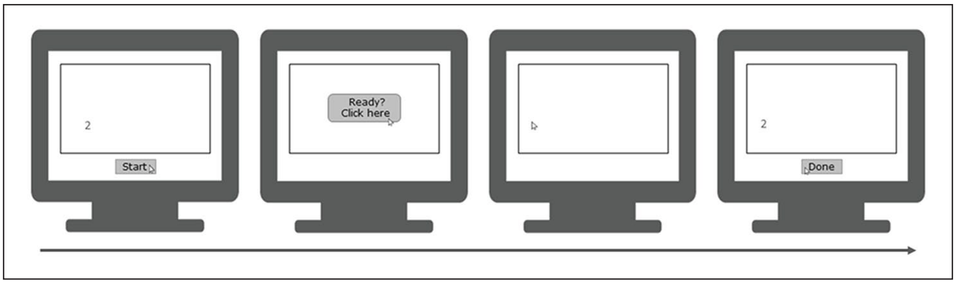

Figure 1. A single trial of the WTN task (Exp. 1). At the start of the trial, an Arabic numeral appeared onscreen (randomised location). At this time, participants were instructed to click the Start button when they had sufficiently memorised the numeral's location. When the Start button was clicked, the numeral disappeared and a centrally presented button ("Ready? Click here") appeared. Next, participants clicked this button, intended to minimise variability in initial cursor location. Then, this button disappeared, and participants clicked the remembered location to place the numeral at that location. Finally, participants confirmed their placement of the numeral (which appeared after they clicked the remembered location) by clicking a virtual button ("Done") and proceeded to the next trial.

reporting of implicit d-SNA tasks (Wood et al., 2008). This power analysis indicated that this sample size provided adequate power ($1-\beta > .90$) to detect d-SNAs as assessed with a two-tailed, one-sample *t*-test. All participants had normal or corrected-to-normal vision. Procedures were approved by the Institutional Review Board (IRB) at Emory University.

Procedure. Participants viewed a number (Arabic numerals 1–9) presented in black Myriad Pro font at a random location within a rectangle (white fill with black outline; 918 × 495 pixels). The number's location was random with respect to both the horizontal and vertical axes. Each number was presented 20 times for a total of 180 trials (randomised order). Numbers were presented within an invisible, square bounding box (40 × 40 pixels). Position of the stimulus was calculated as the top-left corner of this bounding box. This task was created in Visual Basic (Microsoft Corp.) and presented on a 48-cm computer monitor. Participants sat approximately 65 cm from the monitor.

A schematic illustration of each trial is depicted in Figure 1. On each trial, participants were instructed to remember the location of the number. The number remained onscreen until participants clicked a virtual button located at the bottom of the screen, which caused the number to disappear. Participants were then asked to reproduce the original location of the number as accurately as possible using the computer mouse ("Do your best to recreate the location of the number you saw before. Double-click to place the number at the cursor location; you may then drag the number to adjust as needed."). Participants confirmed their final placement by clicking another virtual button onscreen and then immediately proceeded to the next trial.

Results

For each participant, trials were trimmed for poor accuracy, defined as trials where accuracy was greater than 2.5 *SD*s from individual mean accuracy (2.11% of total trials). Accuracy was calculated as the unsigned Euclidean distance between the number's original location and the participant's final placement of the number (i.e., the direct path between the original and final locations), taking into account both the horizontal and vertical dimensions. Moreover, participants were removed if their individual mean accuracy (after trial-level trimming) was greater than 2.5 *SD*s from the group mean accuracy. Two participants were excluded based on this criterion.

The remaining participants ($N = 36$) had a mean accuracy of 16.86 pixels ($SD = 7.25$), such that participants' placement of all numerals deviated from their original location by a mean Euclidean distance of 16.86 pixels (irrespective of direction). D-SNAs were measured as participants' bias along the horizontal axis. For each trial, bias was calculated as the difference between the x-coordinate of the participant's final placement and the x-coordinate of the number's original location, such that a negative value represented leftward placement relative to the original location and a positive value represented rightward placement relative to the original location. For each participant, we calculated mean bias in the horizontal dimension for each number. With numerical magnitude as the predictor of mean bias, we then calculated the slope of the line of best fit for each participant. Thus, in these analyses, a *positive* slope represents the canonical left-to-right SNA (as opposed to a negative slope, typical in the classic SNARC effect; Dehaene et al., 1993).

Participants' slopes were significantly greater than zero, $t(35) = 2.74$, $p = .009$, $d = 0.46$, $BF_{10} = 4.39$, such that participants placed larger numbers more rightward than smaller numbers (see Figure 2). Following the recommendation of Winter (2013), we also assessed participants' spatial bias on this task using a linear mixed-effects model with number as the predictor and with random slopes and intercepts for participants. This model revealed a significant effect of numerical magnitude on spatial bias in the horizontal dimension, $\chi^2(1) = 5.02$, $p = .025$, $\eta_p^2 = .01$, supporting the finding of the previous analysis. To ensure that this spatial bias could not be attributed to known associations between numerical parity and horizontal space (Linguistic Markedness of Response

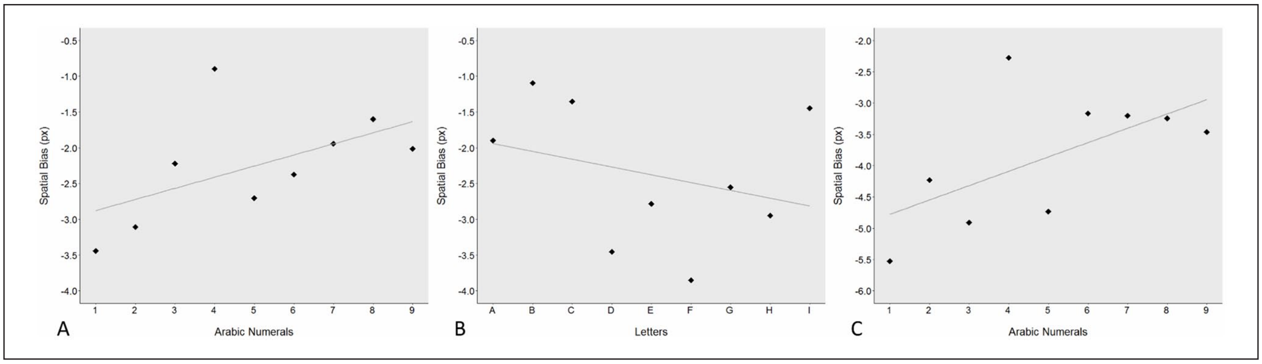

Figure 2. Spatial bias along the horizontal dimension in Experiments 1–3. Data points reflect the mean horizontal bias, in pixels, for each corresponding numeral/letter. Because bias is calculated as the signed difference between original and final locations, a positive slope reflects a left-to-right SNA. Participants displayed an overall leftward bias across all experiments, possibly due to the measurement bias resulting from defining stimulus location as the top-left of the bounding box (see section "Method") and/or a visuospatial attentional bias known as pseudoneglect (Jewell & McCourt, 2000; Longo & Lourenco, 2010). Importantly, however, in Experiments 1 and 3 (A and C), this bias varied as a function of numerical value, such that the bias became less leftward as the numerical value increased. We did not observe a significant relation between the space and letters (Exp. 2, B).

Note: Notably, this leftward bias was less pronounced for numeral "4" compared to the other numerals. One possible reason for this difference is that "4" does not extend as far into the top-left of the square bounding box used to measure the location of each numeral (see section "Method"). Importantly, the effects reported in the main text are qualitatively similar if the numeral "4" is removed from the analyses.

Codes [MARC] effect; Nuerk et al., 2004), we evaluated a model in which we included both numerical magnitude and parity (odd/even) as predictors of spatial bias. This model found a significant effect of numerical magnitude on spatial bias, $t(288)=2.42$, $p=.016$, $\eta_p^2=.02$, and no effect of parity, $t(288)=1.41$, $p=.159$, $\eta_p^2=.007$, suggesting that the d-SNA observed here cannot be accounted for by an effect of numerical parity.

We additionally examined spatial bias in the vertical dimension. For each trial, bias was calculated as the difference between the *y*-coordinate of the participant's final placement and the *y*-coordinate of the number's original location, such that a negative value represented a downward placement relative to the original location and a positive value represented an upward placement relative to the original location. For each participant, we calculated mean bias in the vertical dimension for each number. With numerical magnitude as the predictor of mean bias, we then calculated the slope of the line of best fit for each participant. Participants' slopes were not significantly different from 0, $t(35)=1.72$, $p=.093$, $d=0.29$, $BF_{10}=.705$. We further assessed participants' spatial bias in the vertical dimension on this task using a linear mixed-effects model with number as a predictor and with random slopes and intercepts for participants. This model revealed no effect of numerical value on spatial bias in the vertical dimension, $\chi^2(1)=2.64$, $p=.104$, $\eta_p^2=.001$, supporting the finding of the previous analysis.

Discussion

In the absence of explicit numerical processing and categorical responses, participants' responses indicated a left-to-right d-SNA, consistent with the MNL account in which the link between numbers and space are implicit and continuous in nature. Nevertheless, it is unclear whether this effect is unique to numbers, which we test in Experiment 2, and whether the left-to-right d-SNA on this task is dependent on general cognitive resources such as working memory, which we test in Experiment 3.

The findings from the present experiment further suggest that the d-SNAs on this task are specific to the horizontal dimension. Although other studies have similarly found specificity in this regard (e.g., Holmes et al., 2016; Holmes & Lourenco, 2012; Wiemers et al., 2017), the data on this effect are clearly mixed. Shaki and Fischer (2018) found evidence for the spatial representation of numbers in the vertical dimension (and not the horizontal dimension). Other research, using different paradigms, has found evidence for both horizontal and vertical dimensions (e.g., Aleotti et al., 2020; Hartman et al., 2012; Hesse & Bremmer, 2017; Loetscher et al., 2010; Schwarz & Keus, 2004). We thus examine this effect further in the subsequent experiments (see also section "General discussion").

Experiment 2: "Where was The Letter?" task

To determine whether the directional spatial associations observed in Experiment 1 were unique to numbers or whether they manifest for any ordinal sequence, we conducted an additional experiment with letters. The task here was identical to the previous version, except that letters replaced numbers. Accordingly, we refer to the task in the current experiment as the "Where was The Letter?" (WTL) task. If directional spatial associations are unique to numbers, as an MNL account would predict, then we should not observe a systematic relation between space and letters in the WTL task.

Method

Participants. A total of 37 undergraduates ($M_{age}=19.47$ years; 22 female, 15 male; 30 right-handed, 7 left-handed) participated for course credit. Sample size followed that of Experiment 1. All participants had normal or corrected-to normal vision. Procedures were approved by the IRB at Emory University.

Procedure. The procedure for Experiment 2 was identical to that of Experiment 1, except that instead of the Arabic numerals (1–9) as stimuli, participants were presented with the first nine letters of the alphabet (A–I).

Results

For each participant, trials were trimmed for poor accuracy (>2.5 *SD*s) from individual means (1.91% of total trials), where accuracy was calculated as the distance between the letter's original location and the participant's final placement, taking into account both horizontal and vertical dimensions. One participant was excluded from the statistical analyses for poor overall accuracy (>2.5 *SD*s).

The remaining participants ($N=36$) had a mean accuracy of 14.25 pixels ($SD=7.62$), such that participants' placement of all letters deviated from their original location by a mean Euclidean distance of 14.25 pixels (irrespective of the direction of deviation). For each participant, we calculated mean bias in the horizontal dimension for each letter. With ordinal value as the predictor of mean bias, we then calculated the slope of the line of best fit for each participant. In contrast with the findings of Experiment 1, participants' slopes did not differ significantly from 0, $t(35)=1.57$, $p=.125$, $d=0.26$, $BF_{10}=0.55$ (see Figure 2). These results suggest that letters are not mapped spatially in left-to-right orientation in this paradigm. We also assessed participants' spatial bias in the horizontal dimension using a linear mixed-effects model with the ordinal value of the letters as a predictor and with random slopes and intercepts for participants. This model revealed no effect of letter on spatial bias in the horizontal dimension, $\chi^2(1)=2.44$, $p=.118$, $\eta_p^2=.07$, supporting the finding of the previous analysis.

We additionally examined spatial bias in the vertical dimension. Participants' slopes were not significantly different from 0, $t(35)=1.04$, $p=.306$, $d=0.17$, $BF_{10}=0.30$, suggesting no spatial bias for letters in the vertical dimension either. We further assessed participants' spatial bias for letters in the vertical dimension using a linear mixed-effects model with the ordinal value of the letters as a predictor and with random slopes and intercepts for participants. This model revealed no effect of letters on spatial bias in the vertical dimension, $\chi^2(1)=.949$, $p=.330$, $\eta_p^2=.005$, supporting the finding of the previous analysis.

Discussion

Unlike Experiment 1, we did not observe a significant spatial association for letters on the WTL task, in either the horizontal or vertical dimension (see also, Cheung & Lourenco, 2016). That is, across Experiments 1 and 2, we observed significant left-to-right representation of numbers, but not letters, on a task that does not require explicit processing of ordinal information or categorical responses. These results provide support for the specificity of d-SNAs, consistent with an MNL account.

Experiment 3: working memory interference

Although the lack of a left-to-right spatial association for letters in Experiment 2 argues that spatial associations are number-specific, it does not directly address whether d-SNAs are long-term, rather than constructed online in working memory. To address this question directly, Experiment 3 tested whether d-SNAs, like those observed in Experiment 1, are dependent on working memory resources.

Following the procedure of van Dijck and colleagues (2009), we implemented a concurrent verbal working memory interference task which participants completed during the WTN task. Although some recent work on the WM account emphasises visuospatial working memory in particular (Abrahamse et al., 2016; but see Abrahamse et al., 2017), it was previously shown that verbal, *not* visuospatial, working memory, interference reduced d-SNAs on tasks in which magnitude was processed implicitly. As a result, because the WTN task assesses magnitude implicitly, we employed verbal, as opposed to visuospatial, working memory interference in the present experiment.

Moreover, because the WTN task requires memory for a spatial location, the use of verbal, rather than visuospatial, working memory ensured that any effect of interference on d-SNAs could be attributed to the role of working memory in the construction of d-SNAs specifically, as opposed to an influence of task performance more generally. Thus, if d-SNAs are dependent on working memory, then we should no longer observe a significant d-SNA on the WTN task with a concurrent verbal working memory task. However, if d-SNAs are not dependent on working memory resources, per the MNL account, then the findings of Experiment 3 should replicate those of Experiment 1.

Method

Participants. A total of 37 undergraduates ($M_{age}=19.59$ years; 29 female, 8 male; 31 right-handed, 6 left-handed) participated for course credit. Sample size followed that of Experiments 1 and 2. All participants had normal or corrected-to-normal vision. Procedures were approved by the IRB at Emory University.

Procedure. To ensure that the verbal working memory interference task was matched in difficulty across participants, verbal working memory span was determined for each individual participant (van Dijck et al., 2009). To determine verbal working memory span, participants were asked to memorise and recall arbitrary consonant strings (i.e., unordered letters with respect to the alphabet) presented sequentially (i.e., forward digit span, modified from Szmalec & Vandierendonck, 2007; van Dijck et al., 2009). Consonant strings increased in length from three to eight consonants over the course of the task (18 trials; 3 trials per letter string). On each trial, each consonant was presented for 1,250 ms (250-ms ISI). After the entire string was presented, a blank screen appeared for 1,500 ms. Participants were then prompted to type the consonant string into a text box. Responses were considered correct only if all consonants were recalled in the correct order. Participants' individual verbal working memory spans were defined as the last consonant string length for which the consonant strings were recalled correctly on two of three trials. After completion of this task, participants then proceeded to the modified WTN task.

The procedure for the modified WTN task was identical to that of Experiment 1 except that it included a concurrent verbal working memory interference task. First, participants were presented with a consonant string to retain in memory. As in the span task, each consonant was presented for 1,250 ms (250-ms ISI). The length of the consonant strings remained constant throughout the experiment (individual span − 1). Then, participants immediately completed nine trials of the WTN task in accordance with the methods of Experiment 1 (1 trial per number, 1–9, randomly ordered). Following completion of these nine trials, participants were immediately prompted to enter the consonant string into a text box. Thus, and critically, participants were required to hold the consonant string in memory during the WTN trials, to successfully complete the verbal working memory interference task. This procedure was repeated 20 times, for a total of 180 WTN trials and 20 verbal working memory interference trials.

Results

One participant was excluded from statistical analyses for failing to complete all trials. The remaining participants (N = 36) had a mean verbal working memory span of 5.72 (SD = 1.70). For the verbal working memory interference trials completed during the WTN task, responses were considered correct only if all consonants were recalled in the correct order. Participants' mean accuracy on these verbal working memory interference trials was 79% (SD = 23%), confirming that participants held the consonant strings in verbal working memory.

On the WTN task, trials were trimmed for poor accuracy (>2.5 *SD*s) from individual means (2.41% of total trials). As in the previous experiments, accuracy was calculated as the distance between the letter's original location and the participant's final placement, taking into account both horizontal and vertical dimensions. Participants had a mean accuracy of 20.84 pixels (SD = 9.61), such that participants' placement of all numerals deviated from their original location by a mean Euclidean distance of 20.84 pixels (irrespective of the direction of deviation). A comparison to mean accuracy from Experiment 1 suggests that accuracy in Experiment 3 was worse, as expected, given the working memory interference, though this effect did not meet statistical significance, $t(70) = 1.98, p = .052, d = 0.47, BF_{10} = 1.10$. Participants' accuracy on the verbal working memory interference trials was not significantly correlated with their overall accuracy on the WTN task, $r(34) = .155, p = .367$, or with spatial bias in the horizontal dimension (slopes) on the WTN task, $r(34) = .071, p = .680$, suggesting no trade-off between performance on the verbal working memory interference trials and WTN trials. Consistent with the findings of Experiment 1, participants' slopes were significantly different from 0, $t(35) = 2.59, p = .014, d = 0.43, BF_{10} = 3.19$ (see Figure 2), suggesting that even when verbal working memory was taxed, participants displayed evidence of the canonical left-to-right SNA, placing larger numbers rightward of smaller numbers.

We also assessed participants' horizontal spatial bias on this task using a linear mixed-effects model with numerical value as a predictor and with random slopes and intercepts for participants. This model revealed a significant effect of numerical value on spatial bias in the horizontal dimension, $\chi^2(1) = 6.30, p = .012, \eta_p^2 = .03$, supporting the finding of the previous analysis. To ensure that this spatial bias could not be attributed to known associations between numerical parity and horizontal space (MARC effect; Nuerk et al., 2004), we evaluated a model in which we included both numerical magnitude and parity (odd/even) as predictors of spatial bias. This model found significant effects of both numerical magnitude, $t(288) = 3.02, p = .003, \eta_p^2 = .03$, and parity, $t(288) = 2.89, p = .004, \eta_p^2 = .03$, on spatial bias, suggesting independent effects of both number and parity.

We additionally examined spatial bias in the vertical dimension. As in Experiment 1, participants' slopes were not significantly different from 0, $t(35) = 1.75, p = .090, d = .29, BF_{10} = .683$, suggesting no effect of numerical value on spatial bias in the vertical dimension, whether or not verbal working memory resources were available. We further assessed participants' spatial bias in the vertical dimension on this task using a linear mixed-effects model with numerical value as a predictor and with random slopes and intercepts for participants. This model revealed no significant effect of numerical value on spatial bias in the vertical dimension, $\chi^2(1) = 3.01, p = .083, \eta_p^2 = .02$, supporting the finding of the previous analysis.

Discussion

Experiment 3 replicates and extends the findings of Experiment 1. In particular, we again found that numbers biased participants' judgements of horizontal (not vertical) location, such that larger numbers were placed more rightward (but not higher) than smaller numbers, even when accounting for an effect of parity. Crucially, in this experiment, this d-SNA occurred under verbal working memory load, suggesting that d-SNAs on the WTN task are not dependent on working memory resources.

However, one possible explanation for the d-SNA observed here is that verbal working memory was not sufficiently taxed, and thus, did not influence performance. This is unlikely given that mean accuracy in Experiment 3 (20.84 pixels) was worse than Experiment 1 (16.86 pixels), though this difference was not statistically significant. Moreover, in other work (van Dijck et al., 2009), the same verbal working memory interference task resulted in significant interference during other d-SNA tasks, further suggesting that the task does induce a significant verbal working memory load. Future work, however, could use a backward, rather than forward, digit span task, as backward digit span is more difficult (Baddeley, 1986) and, thus, more likely to ensure a sufficient reduction in working memory resources.

Another possibility is that visuospatial, not verbal, working memory is critical for task-specific construction of d-SNAs (e.g., Abrahamse et al., 2016; Herrera et al., 2008). Indeed, it would appear that SNAs on some tasks, such as magnitude comparison, are disrupted by visuospatial, not verbal, working memory. Importantly, however, other tasks, such as parity judgement, are disrupted by verbal, not visuospatial, working memory (e.g., van Dijck et al., 2009). A challenge for the WM account of d-SNAs is how to reconcile these disparate effects, especially given that, according to this account, the critical feature of d-SNA construction is "serial order memory," which characterises *both* verbal and visuospatial working memory (Abrahamse et al., 2016, 2017) Accordingly, both verbal and visuospatial working memory interference should be detrimental to the construction of SNAs, insofar as they both require memory for serial order.

Between-experiment analyses

In a final set of analyses, we directly compared the results of Experiments 1–3 by conducting a one-way analysis of variance (ANOVA) on participant's slopes for the horizontal dimension, with experiment as the between-subject factor. This analysis yielded a significant main effect of experiment,[1] $F(2, 105)=5.99, p=.003, \eta_p^2=.10, BF_{10}=10.50$. Post hoc comparisons (Bonferroni corrected) revealed significant differences between participants' slopes in Experiment 1 (number) and Experiment 2 (letter), $t(70)=2.57$, $p=.002$, $d=.694$, $BF_{10}=18.56$, and between Experiment 2 (letter) and Experiment 3 (number with verbal working memory interference), $t(70)=3.29$, $p=.004$, $d=.704$, $BF_{10}=10.35$ (see Figure 3), but not between Experiment 1 (number) and Experiment 3 (number with verbal working memory interference), $t(70)=0.71, p=.48, d=.136, BF_{10}=0.30$ (see Figure 3). Consistent with the MNL account, these findings provide support for the specificity of directional spatial associations, such that numbers, but not letters, are associated with horizontal space, and also suggest that d-SNAs occur even when verbal working memory is taxed.

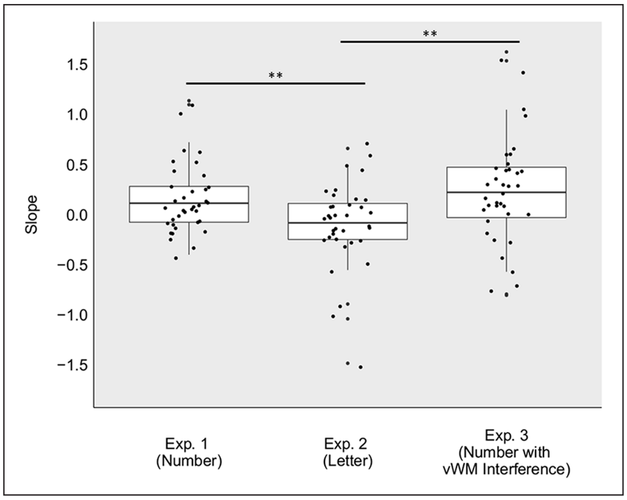

Figure 3. Box and whisker plots for Experiments 1–3. Centre lines represent median slope for spatial bias in the horizontal dimension. Lower and upper hinges represent the first and third quartiles. Lower and upper whiskers represent the respective quartile ±1.5 × interquartile range (IQR). Data points represent individual participants' slopes.
$^{**}p<.01$.

Although the analyses in Experiments 1 and 3 already demonstrated that the SNAs were restricted to the horizontal dimension, for completeness, we also examined spatial bias in the vertical dimension across all experiments. A one-way ANOVA on participants' slopes, with experiment as the between-subject factor, found no effect of experiment, $F(2, 105)=0.34$, $p=.713$, $BF_{10}=0.114$, suggesting participants' bias in the vertical dimension did not differ significantly across experiment. Thus, in contrast to the effect of numbers on participants' placements in the horizontal dimension, we found no evidence of an effect of numbers (or letters) on placement in the vertical dimension in this paradigm.

General discussion

The primary goal of the present study was to provide a strong test of the MNL account of d-SNAs. With the novel WTN task, we asked whether (1) d-SNAs occur in the absence of explicit numerical judgements and categorical responses; (2) the links to space are specific to numbers; and (3) d-SNAs are dependent on working memory resources. In contrast to previous d-SNA tasks, neither explicit numerical processing nor categorical responses were necessary to complete the WTN task. Moreover, with a concurrent verbal working memory load, d-SNAs were still observed for horizontal space, as was a MARC effect. By contrast, we observed no such links between a non-numerical ordinal sequence (i.e., letters) and space. Thus, the horizontal d-SNAs observed in the present study (Experiments 1 and 3), and the lack of an observed spatial association for letters (Experiment 2) provide support for an MNL account, which posits an intrinsic, continuous relation between numbers and space.

We also did not observe a significant vertical d-SNA in either Experiment 1 or 3, suggesting a privileged relation between numbers and horizontal space (see also Aulet & Lourenco, 2018, for a similar effect in children). In addition, this finding challenges a recent hypothesis that, in the absence of contextual priming (i.e., explicit magnitude or spatial-directional processing), vertical, but not horizontal, d-SNAs are observed (Shaki & Fischer, 2018; Sixtus et al., 2019). Indeed, our task was designed to evaluate d-SNAs in the absence of explicit numerical processing and categorical responses. Accordingly, our results suggest that, when d-SNAs are assessed implicitly and in a continuous fashion, the horizontal axis emerges as the primary axis for d-SNAs.

The present findings contrast with theories of d-SNAs, such as the hierarchical view (Fischer, 2012; Shaki & Fischer, 2018), which posit the vertical axis as the primary axis for d-SNAs. These accounts argue that vertical d-SNAs are primary because they reflect the statistical regularities in the physical world. That is, larger objects typically extend further upward in one's field of view (but see Holmes & Lourenco, 2012). By contrast, they suggest that horizontal (i.e., left-to-right) d-SNAs are culturally mediated by experiences such a reading direction (Guida et al., 2020; Shaki et al., 2009) and, thus, are necessarily secondary to vertical d-SNAs.

However, recent behavioural and neural research on number representations highlights several potential mechanisms that predict left-to-right horizontal d-SNAs and are not dependent solely on cultural factors. For example, Schwiedrzik and colleagues (2016) observed behavioural cross-adaptation between number and horizontal motion, such that adaptation to leftward motion led to numerosity underestimation and adaptation to rightward motion led to numerosity overestimation (see also Knops et al., 2009). This finding is consistent with the notion of neuronal recycling (Anderson, 2010; Dehaene & Cohen, 2007), whereby pre-existing cortical functions (e.g., visuospatial processing) are repurposed for functions that are more evolutionarily recent (e.g., numerical processing). Other neural accounts of SNAs, such as laterality accounts (Rugani et al., 2015; Vallortigara, 2018), likewise point to mechanisms underlying number representations that link between number and horizontal space (i.e., left/right), specifically.

Nevertheless, we acknowledge that the rectangular response space in the WTN task may have constrained responses in the vertical dimension, resulting in a lack of a significant vertical d-SNA. Based on these conflicting results, future work will be needed to understand why the relative primacy of horizontal and vertical d-SNAs differs across tasks. A possible approach would be to use tasks such as the WTN task to more thoroughly assess whether effects along other axes (i.e., vertical and sagittal) also reflect implicit and continuous relations between numbers and space.

In addition to a significant d-SNA for the horizontal dimension, we also observed a significant MARC effect in Experiment 3, wherein odd numbers were placed more leftward than even numbers (Nuerk et al., 2004). Moreover, this effect occurred in the absence of explicit magnitude processing, suggesting that parity may be accessed automatically, like magnitude, and that it is not dependent on a binary response scheme. In other words, although the MARC effect is commonly thought to be linguistic in nature (but see Huber et al., 2015), spatial associations for parity may, nonetheless, emerge as a by-product of its status as a numerical property.

The present work found that, when assessed implicitly and continuously, there is no significant association between the ordinal property of letters and horizontal space. However, some previous studies *do* report associations between non-numerical ordinal sequences and space. What might account for the discrepancies across studies? It is likely that effects of ordinal sequences demonstrated in previous work were dependent on explicit ordinal processing, categorical responses, and/or other task demands (Gevers et al., 2003; van Dijck & Fias, 2011). Importantly, however, it is well-documented that people can organise information in a variety of spatial arrangements and this spatialisation of information has often been considered important for reasoning (Huttenlocher, 1968; Johnson-Laird, 1983). Accordingly, we acknowledge that non-numerical sequences can be spatially organised, but that the mechanisms supporting such organisation are likely distinct from those of d-SNAs. In the case of non-numerical sequences, working memory and other explicit strategies are likely candidate mechanisms (see Ginsburg & Gevers, 2015).

Conclusion

The results from the present study provide strong evidence for SNAs that are consistent with the MNL account. Specifically, we found evidence of horizontal d-SNAs in the absence of explicit numerical processing or dichotomous responses, and under working memory load. Moreover, we did not find evidence of spatial representations of a non-numerical ordinal sequence (i.e., letters). Taken together, these findings suggest that numerical representations are inherently spatial, a relation which may have arisen from the engagement of cortical areas originally evolved for visuospatial processing.

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Note

1. To ensure that the failure to observe directional spatial associations for letters could not be attributed to differences in variance, we compared the variances across all three experiments. There was a significant difference across experiment, as determined by Bartlett's test for homogeneity of variances, $p = .032$. However, and critically, pairwise comparisons, as determined by Levene's test for homogeneity of variances, revealed that whereas variances in Experiments 1 and 3 were significantly different from each other, $p = .009$, variances in Experiments 1 and 2, and Experiments 2 and 3, were not ($ps > .277$). Accordingly, these results suggest that the failure to observe directional spatial associations for letters (Exp. 2) cannot be attributed to variance differences across experiments.

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