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Spatio–Numerical Mapping in 3D: Is Horizontal Mapping the Best Candidate?

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Abstract:

The close link between number and space is illustrated by the Spatial Numerical Association of Response Codes (SNARC) effect. The current research focuses on the flexibility of the SNARC across three dimensions. [Shaki and Fischer \(2018\)](#) pointed out that spatial attributes of stimuli and response effectors can favor an *ad hoc* spatial representation. In this paper, we aimed to broaden this perspective using two Go/No-Go experiments with digits being presented at two spatial locations while a central response was required. In Experiment 1, stimuli appeared either to the left or right (horizontal) and below or above fixation (vertical). In Experiment 2, as the monitor was laying down flat on the desk, stimuli appeared either to the left or right (horizontal) and either close or far from the observer (midsagittal). The results of Experiment 1 show significant effects for the two dimensions (horizontal, vertical), while in Experiment 2, we observe only a barely significant effect for the sagittal axis. We interpret these findings as showing (1) the importance of motor response spatialization in eliciting the SNAs and (2) the dominance of the vertical axis over the horizontal when the spatial component of the motor response is removed.

Keywords: SNAs, SNARC, Mental Number Line, 3 Dimensions, Spatial Codes

Introduction:

The concept of number is central in human cognition. In most civilizations, numbers are ubiquitous and essential in daily life as they play an important role in mathematics. A better understanding of the mechanisms underpinning the processing of numbers is one of the main objectives in the field of numerical cognition. The scientific literature has put forward the hypothesis that numbers seem to be intricately linked to space. The seminal study of Dehaene et al. (1993) pointed out an astonishing link between number processing and spatialized responses. In this study, participants were to judge whether an Arabic digit centrally presented on a computer screen was either odd or even by pressing a key as fast as possible. To facilitate motor execution (both hands were mobilized), the two buttons were lateralized (left button for the left hand and reciprocally for the right hand). The results clearly showed that participants were faster to answer with the left/right hand when the number was small/large, irrespective of its parity status. The results were accounted for by the hypothesis of the mental number line (MNL, Galton, 1880; Restle, 1970), according to which numbers are thought to be spatially mapped on a horizontal, left-to-right oriented continuum. Small numbers are indeed arranged on the left side of space and large numbers on the right side of this internal representation. This widely replicated effect is referred to as the SNARC effect (Spatial Numerical Association of Response Codes). Given the robustness of this behavioral signature, it is considered the most prominent effect illustrating the spatial–numerical associations (SNAs). Dehaene et al. (1993) argued that the SNARC effect rests on the existence of the MNL, whose directionality – from left to right – was thought to be an obvious consequence of cultural education. Reading and writing habits would thus play a central role in this construction, as also suggested by other studies supporting the impact of culture on space–number associations (hereafter referred to as SNAs; Göbel et al., 2011; Hoffmann et al., 2013; Hung et al., 2008; Nuerk et al., 2015; Shaki et al., 2009, 2012). However, the exclusivity of the role played by cultural factors in the directionality of the MNL has recently been challenged. First, infant studies have shown that newborns in their first days of life and infants in their first year show a visual preference for small quantities associated with

the left side of space and large quantities with the right side of space (Bulf et al., 2016; de Hevia, 2021; de Hevia et al., 2012, 2014; Di Giorgio et al., 2019; McCrink et al., 2020). More empirical evidence against the cultural foundation of the SNAs comes from the literature on animal cognition. Several studies come together to report that numerical quantity is horizontally organized in space with the left side being associated with small magnitudes in many species, including macaques, fish, and birds (Adachi, 2014; Bisazza et al., 2010; Drucker & Brannon, 2014; Rugani & de Hevia, 2017; Rugani et al., 2020; Rugani & Regolin, 2020). These arguments favor a more rooted link between number and space and stand for an evolutionary origin of the SNAs.

Critically, the cultural origins of the SNAs have also been recently challenged by the observation that numerical quantities can be spatially organized in (at least) three dimensions. While the left-to-right organization has been widely investigated in the last decades (for a review, see Wood & Nuerk, 2008), more recent research has focused on alternative spatial mappings by investigating SNAs on the vertical, midsagittal, and even diagonal axes (Ito & Hatta, 2004 in the Japanese population, Aleotti et al., 2020; Hesse & Bremmer, 2017; Loestcher et al., 2011; Schwarz & Keus, 2004; for a review Winter et al., 2015). Overall, these studies mainly show a reliable association between number and space on multiple dimensions. The high flexibility of the SNAs entails critical theoretical implications. Cultural factors might therefore shape the directionality of the MNL, but they cannot be considered the main originating mechanism underlying the SNAs and more specifically of the SNARC effect (see review Toomarian & Hubbard, 2018).

The recent series of evidence from developmental studies in newborns and infants, as well as evidence from behavioral studies in animals, have undoubtedly weakened the cultural origins hypothesis of the SNARC effect. The main objective here was thus to further investigate the theoretical foundations of the SNA by testing the flexibility of number–space associations in the context of a multispace environment (horizontal, vertical, and midsagittal axes).

Recent studies have provided evidence for the superiority of the vertical over the horizontal axis for space–number associations in adults. In a cleverly designed study

by [Shaki and Fischer \(2018\)](#), both response buttons and the stimuli were spatially centralized to play down the role of spatial attributes. Depending on the trial at hand, the stimulus was either an Arabic digit or an arrow, centrally presented. Participants were asked to perform a Go-NoGo task on the two types of stimuli by pressing the space bar for a given orientation and given digits. Instructions were manipulated across blocks, leading participants to respond only to small digits and leftward arrows during a block for instance or to small digits and rightward arrows. This manipulation generated congruent and incongruent mappings on the horizontal and vertical axes. Additionally, to avoid explicit numerical processing, participants completed either a magnitude or a parity judgment task on Arabic digits (small/large or odd/ even). The authors provided straightforward evidence that in the absence of explicit processing spatial and magnitude clues, space–number associations only emerge on the vertical axis (small numbers associated with the downward direction and large numbers with the upward direction). Similar results have been reported in a Go/NoGo design with a central response study conducted by [Sixtus et al. \(2019\)](#), in which participants looked for a number, previously auditorily presented, in a grid. They found evidence for a vertical SNA (small numbers associated with down or lower space and large numbers with up or upper space) but no significant effect for an SNA on the horizontal axis. Overall, these studies suggest that vertical SNAs are stronger, and more reliable compared to horizontal ones, in adults.

Recently, the hypothesis has been put forward that horizontal SNAs are more fragile relative to vertical ones and that they are emerging ad hoc in specific contexts which favor explicit numerical processing (e.g., magnitude comparison task) and spatial induction (e.g., spatial response codes, [Pinto, Pellegrino, Lasaponara, Cestari, et al., 2019](#), [Pinto, Pellegrino, Lasaponara, et al., 2021](#); [Pinto, Pellegrino, Marson, et al., 2021](#); [Santens & Gevers, 2008](#); [Vellan & Leth-Steensen, 2019](#)).

To deepen our understanding of the relation between number and space, we added the midsagittal dimension (i.e., depth: near vs. far) in our experimental protocol. Investigating SNAs along this axis is of critical interest given the scarcely available literature about it. For instance, [Chen et al. \(2015\)](#) conducted a SNARC-like experiment to understand SNAs in a peripersonal space in which the response buttons

were organized as near and far, and they found a reliable effect in performance favoring responses of the sort small/near versus large/far. Nevertheless, this axis is thought to share many mechanisms with the vertical axis, and in fact, the vertical and midsagittal axes are often interchanged with one another in the literature (Ito & Hatta, 2004). Different theoretical implications have been discussed about the origins of the vertical and sagittal SNAs, with the most common account residing on the embodied, grounded, and situated cognition (e.g., with an emphasis on natural account based on gravity for the vertical axis and the peripersonal space for the sagittal axis (Fischer, 2012, 2018; Götz et al., 2020; Lakoff & Nuñez, 2000; Myachykov & Fischer, 2019; Prete & Tommasi, 2020; Vicovaro & Dalmaso, 2020). To better understand the mechanisms underpinning SNAs across these three dimensions, in the present study, we aim to investigate the strength of SNAs in three-dimensional space (vertical, horizontal, and midsagittal axes).

To avoid explicit spatial induction in response effectors, participants were required to perform a Go /NoGo task with only one, centralized response button to mimic the procedure recently used by Shaki and Fischer (2018). Our objective is to test the reliability of SNAs in a Go/NoGo task, while numbers are spatialized, depending on the to- be-emphasized axis, either on the left versus right of fixation, or below versus above fixation, and or near versus far concerning the observer (see Figure 1). To the best of our knowledge, no study has ever tested the SNAs in the context of spatially distributed numbers using a unique centralized response procedure on the three axes. This experimental protocol allowed us to further understand the results observed by Shaki and Fischer (2018) and by Sixtus et al. (2019) while adding the midsagittal dimension.

To this aim, we formulated a prediction regarding the interaction between SNAs and the specific axes. We expected to find weaker SNAs along the horizontal axis compared to both the vertical and midsagittal ones. This prediction arises from the idea that horizontal SNAs might be mainly driven by the spatial mapping of the response codes. Crucially, the present study could potentially extend the conclusions of recent studies, in which explicit spatial response codes are used, suggesting similar SNAs along the three axes, both in adults (Aleotti et al., 2020) and children (Cooney et al.,

2021).

In Experiment 1, stimuli were displayed along a horizontal and a vertical continuum to test the hypothesis of more robust vertical SNAs. Then, by laying down a flat computer screen on a table (see Figure 2, Methods of Experiment 2), we tested the strength of the SNAs on midsagittal, as well as horizontal axes. Based on an embodied and grounded perspective of the space–number link, we expected the SNA to be stronger on the midsagittal axis compared to the horizontal one.

For one experimental group, the horizontal and vertical axes were successively emphasized (Experiment 1), while the horizontal and midsagittal axes were targeted for the second group (Experiment 2). Given the theoretical context and the results of previous studies, we expected a more robust effect on the midsagittal or vertical axis than on the horizontal axis.

EXPERIMENT 1

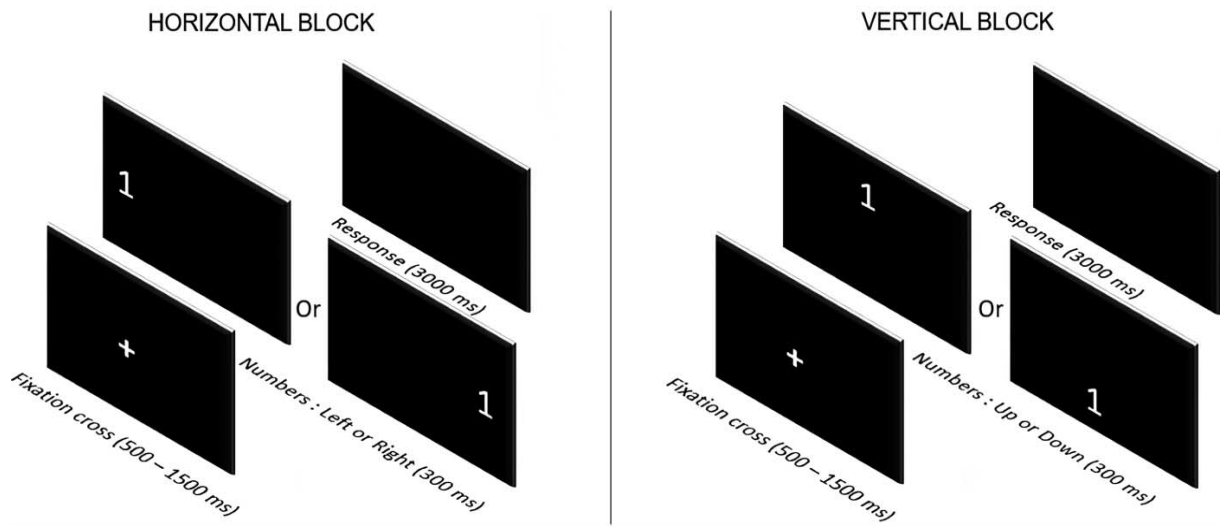


Figure 1. Design and procedure of Experiment 1.

The experiment is composed of two blocks: In the horizontal block, numbers can appear either on the right or on the left; in the vertical block, stimuli can appear either up or down.

EXPERIMENT 2

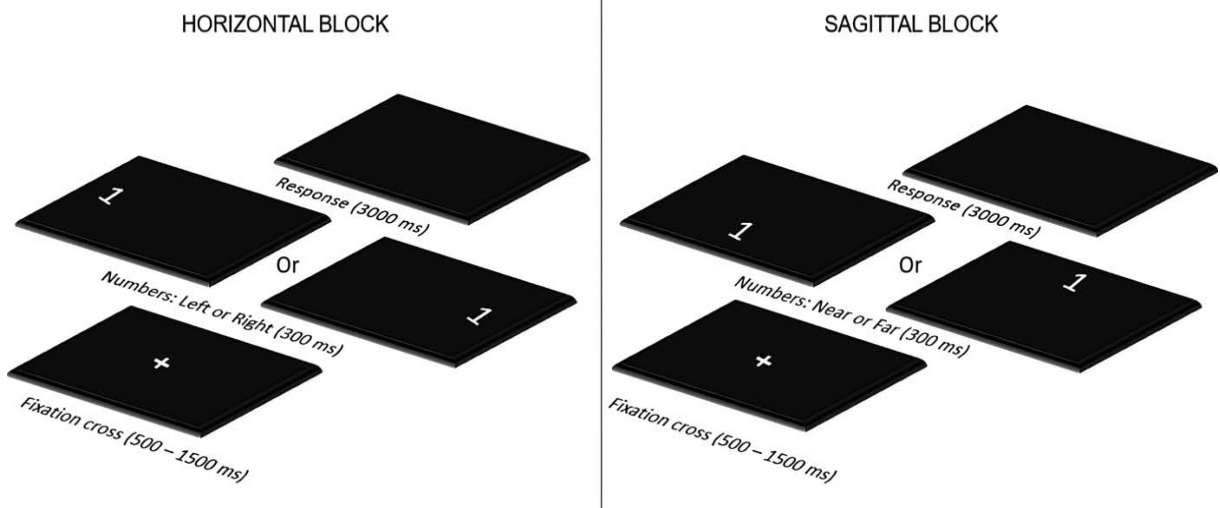


Figure 2. Design and procedure of Experiment 2.

The screen is laying down, perpendicular to the participant. The experiment is composed of two blocks: In the horizontal block, numbers can appear either on the right or on the left, and in the midsagittal block, stimuli can appear either near or far.

Methods:

Experiment 1:

In the following experiment, participants were required to judge numbers as being smaller or larger than 5. Depending on the block instructions, they had to press the spacebar as fast as possible when numbers were either smaller or larger than 5. Stimuli, Arabic digits between 1 and 9 (except 5), were briefly flashed to the left or right of the fixation point in the horizontal blocks, while below or above the fixation point in the vertical blocks. The experiment consisted of four blocks, alternating instructions and axes (see the Methods section for further details). As a whole, we expected faster RTs when the number stimulus is congruent with its localization (small on the left or below fixation and large on the right or above fixation). Additionally, we predicted a weaker congruency effect on the horizontal compared to the other axes, revealing that the SNAs are stronger on the vertical and/or midsagittal axes.

Participants:

Thirty-four participants took part in the experiment in exchange for course credits. The mean age was 20.9 years (18–46, 5.47 SD). All participants were female, and 30 were right-handed. All subjects were declared to have normal or corrected-to-normal visual acuity. All the participants, who were recruited from the University Paul Valéry Montpellier (France), gave their written informed consent. This study was carried out under the principles of the Declaration of Helsinki and by the Department of Psychology Ethics Committee guidelines (University Paul Valéry Montpellier).

Apparatus and Stimuli:

The experiment was carried out at a specific platform dedicated to the study of human behavior (PEACH = Plateforme d'Etude et d'Analyse des Comportements Humains). This platform is located at the University Paul Valéry Montpellier 3 (France). Participants were individually tested in a room while seated and faced a computer (22-inch screen; $1,920 \times 1,080$ pixels; 60 Hz refresh rate; DELL) at a distance of 60 cm from the screen. Stimuli consist of Arabic numbers (1, 2, 3, 4, 6, 7, 8, 9) presented in silver against a dim grey background, in Arial font (size: 60). The response effector was a central button – the spacebar – for both Experiments 1 and 2. The experiment is programmed and run on E-Prime2.0 (Schneider et al., 2002).

Design and Procedure:

For each trial, a black fixation cross ($0.5^\circ \times 0.5^\circ$) was presented against a dim gray background, for a random duration between 500 and 1,500 ms. An Arabic digit stimulus then lasted for 300 ms on the screen. Participants provided a button press, if required, within the time limit window of 3,000 ms. The experiment was divided into two parts since instructions were switched from “press only when seeing a number inferior to 5” to “press only when seeing a number superior to 5,” or the other way around, depending on the participants (counterbalanced mapping to avoid order effects). The emphasis on the horizontal or vertical axes alternated across blocks. The order of axis blocks was also counterbalanced across participants. Given the instructions for manipulation and axes, every participant performed a total of two blocks with the horizontal axis (left-right positions) and two blocks with the vertical axis (below-above locations). For each trial, an Arabic digit appeared at 4° away from fixation, and participants were required to perform a Go/NoGo task based on the digit magnitude (i.e., smaller or larger than 5, depending on the instructions) by pressing the spacebar. In the vertical blocks, participants were required to

perform the very same task as in the horizontal block, except that numbers were presented above (4°) or below (4°) the fixation cross.

Each block included 128 trials (8 repetitions per condition). The participants performed a total of 256 trials, for an approximate duration of 30 min.

Experiment 2:

In this experiment, we aimed to further assess the SNAs along the horizontal and the midsagittal axes. To do so, the monitor was laying down flat on the desk, and stimuli were presented to the left or right of fixation to enhance the horizontal axis or near or far from the observer to emphasize the midsagittal axis. As numbers in this experiment appeared near or far from the observer (see Figure 1), we were able to test SNAs along the sagittal axis.

Participants:

Thirty-two new participants took part in Experiment 2 in exchange for course credit (age $M = 20.25$, $SD = 2.91$, range 18–31 years). Twenty-eight participants were female, and four were left-handed. All subjects were declared to have a normal or corrected-to-normal visual acuity. All the participants were recruited from the University Paul Valéry Montpellier (France) and gave their written informed consent. This study was carried out under the principles of the Declaration of Helsinki and by the Department of Psychology Ethics Committee guidelines (University Paul Valéry Montpellier).

Materials and Methods:

The methods of Experiment 2 were strictly identical to Experiment 1, except that the monitor was placed perpendicular to the participant, laying down flat on the desk. With this protocol, the vertical axis of Experiment 1 became the midsagittal axis in Experiment 2 (see Figure 1).

Data Trimming and Analyses:

As none of the participants exhibited an accuracy rate inferior to 93%, no participant was excluded from data analyses based on the accuracy (i.e., 99% mean for both experiments). However, one participant was excluded from data analyses in Experiment 1 based on RTs given an abnormally high SD (i.e., superior to 2.5 the group mean (SD = 97 ms); individual SD = 250 ms).

The RT analyses were performed on the correct Go trials only. RT for a given trial was considered as an outlier when falling outside the range defined by the mean RT \pm 2.5 SD for each participant separately. Less than 3% of the trials were excluded from the data analyses (2.3% for Experiment 1 and 2.2% for Experiment 2).

In the pre-registration of this study, we planned to conduct three main analyses for Experiments 1 and 2: the numerical distance analysis, the congruity score per axis, and the difference between congruity scores (between the horizontal and vertical axes for Experiment 1 and between the horizontal and midsagittal axes for Experiment 2).

For the numerical distance effect (NDE), we computed RTs for the numerical stimuli 1, 2, 8, and 9 labeled as large distance and the numerical stimuli 3, 4, 6, and 7 labeled as small distance as they were compared to reference number 5. Paired sample t-tests were used to test for significant differences. Regarding the congruity score, mean RTs were computed for incongruent and congruent trials as a function of response mapping. By subtracting mean RTs (incongruent minus congruent), each participant obtained a congruity score per axis (horizontal and vertical axes in Experiment 1 and horizontal and midsagittal axes in Experiment 2). We performed one-sample t-tests on the congruity score separately for each axis to test whether the score was significantly different from 0. Finally, we tested the strength of the 3D SNA by

comparing the congruity scores as a function of the axis using paired- samples t-tests: horizontal versus vertical axis in Experiment 1 and horizontal versus midsagittal axis in Experiment 2. All the analyses were done unilaterally. Cohen's d (Cohen, 1977) was used as a measure of effect size for the t-tests.

Experiment 1 Results:

With respect to the NDE, paired-sample t-tests revealed a significant difference between large and small distances for both the horizontal and vertical axes [$t(32) = 3.178$; $p = .002$, $d = 0.553$, and $t(32) = 1.820$; $p = .039$, $d = 0.317$, respectively]. As expected, RTs for the large distance were significantly shorter than for the small distance (horizontal axis: small distance, $M = 499.1$ ms, $SD = 109.72$; large distance, $M = 465.4$ ms, $SD = 99.82$; vertical axis: small distance, $M = 504.6$ ms, $SD = 106.32$; large distance, $M = 479.9$ ms, $SD = 98.26$).

One-sample t-tests on the congruity scores revealed significant effects for both the horizontal and vertical axes [$t(32) = 1.869$, $p = .035$, $d = 0.325$, and $t(32) = 2.625$, $p = .007$, $d = 0.457$, respectively] (Figure 3). Overall, participants responded faster when small numbers were presented at the left and down locations and when large numbers were presented at the right and up locations. When comparing the two congruity scores using a paired- sample t-test, we did not find any significant difference between the horizontal and vertical axes [$t(32) = 0.575$, $p = .284$, $d = 0.1$].¹

Experiment 2 Results:

As predicted, the analysis revealed a significant NDE on mean RTs for both the horizontal and midsagittal axes [$t(31) = 8.658$, $p < .001$, $d = 1.531$, and $t(31) = 6.444$, $p < .001$, $d = 1.139$, respectively]. Mean RTs for the large distance were significantly shorter than for the small distance (horizontal axis: small distance, $M = 483.4$ ms, $SD = 101.95$, large distance, $M = 464.3$ ms, $SD = 94.04$; sagittal axis: small distance, $M = 491.5$ ms, $SD = 106.02$, large distance, $M = 463.8$ ms, $SD = 88.28$).

Regarding the congruity score, t-tests revealed no significant effect for the horizontal axis [$t(31) = 0.063$, $p = .525$, $d = 0.011$] and nonsignificant effect (although close to the threshold) for the midsagittal axis [$t(31) = 1.662$, $p = .053$, $d = 0.294$]. The difference between the two axes did not reach significance, as revealed by a paired-sample t-test [$t(31) = 0.929$, $p = .180$, $d = 0.164$] (Figure 3).²

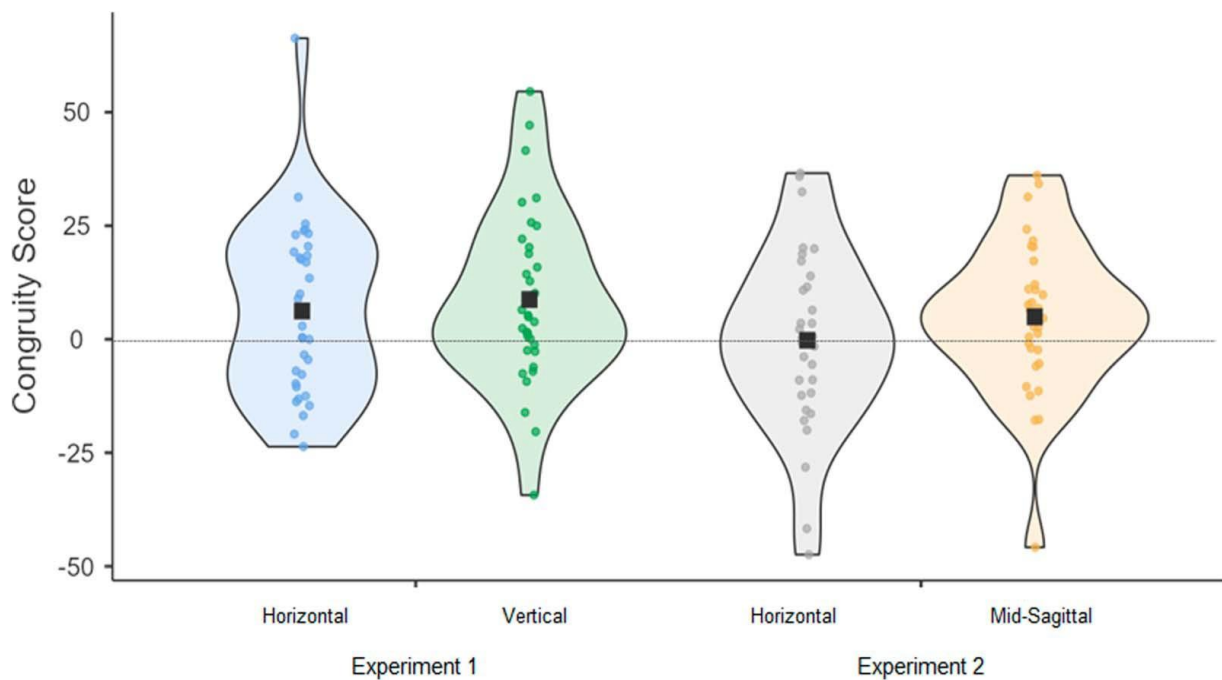


Figure 3. Congruity score (ms) per axis (black squares = mean, colored dots = individual data).

¹ Preliminary analyses tested for the order effect of the axis (horizontal vs. vertical) and instruction (“answer when the numbers are smaller vs. answer when the numbers are larger”). Independent-samples t-tests showed no significant difference for the order of axis on the horizontal congruity score, $t(31) = -0.764$; $p = .451$, the vertical congruity score, $t(31) = 0.380$; $p = .707$, nor the order of instruction, $t(31) = 1.026$; $p = .313$ and $t(31) = 1.931$; $p = .063$.

² Similar to Experiment 1, we tested for the order effect for the axis (horizontal and sagittal) and instruction.

Independent-samples t-tests revealed no significant differences for the order of axis on the horizontal congruity score, $t(30) = 0.839$; $p = .408$), the sagittal congruity score, $t(30) = 0.526$; $p = .603$, nor for the order of instruction, $t(30) = -0.319$; $p = .752$ and $t(30) = 0.057$; $p = .955$.

Discussion:

The present study aimed to further investigate the mental representation of numerical magnitude along three spatial dimensions: horizontal, vertical, and sagittal. As several studies have pointed out the role of hand-effector in the spatial representation of numbers (Riello & Rusconi, 2011; Viarouge et al., 2014), we opted for a Go/NoGo task in which stimulus location was manipulated along the horizontal and vertical space in Experiment 1 and horizontal and midsagittal space in Experiment 2. The overarching objective was to remove the spatial component of the motor response to test the strength of space–number associations in three dimensions. In Experiment 1, digits were presented either to the left or right of the fixation point for the horizontal block, while they were presented either above or below fixation for the vertical block. In Experiment 2, the screen was laid down flat on the desk, perpendicular to participants, to present digit stimuli either to the left or right of fixation for the horizontal block and near or far for the sagittal block. Depending on the instruction, participants were asked to judge an Arabic digit as smaller or larger than 5 so that in a given block, they only responded to either small or large numbers. The use of a Go/NoGo procedure enabled us to test the robustness of number–space associations in the absence of lateralized response mapping.

Our results provide evidence for a reliable NDE in the two experiments confirming that participants processed numerical magnitude. Regarding SNAs in Experiment 1, participants exhibited effects on both the horizontal and vertical axes. In Experiment 2, the findings revealed a nonsignificant effect on the horizontal axis and a close to the threshold but no significant effect on the midsagittal axis. Overall, these results suggest that participants can flexibly arrange numerical quantities along the three dimensions. However, while these mappings appear to co-exist, the horizontal SNA seems more fragile, as revealed by the lack of effect in Experiment 2. This observation is discussed hereafter.

The present results are partially consistent with recent studies reporting flexible SNARC effects in both adults and children (Aleotti et al., 2020; Cooney et al., 2021).

In these experiments, motor responses were spatially grounded by using an external apparatus specifically designed for the task. Overemphasizing the spatial component of motor responses could have played a crucial role in the manifestation of SNAs in 3D.

Additionally, in accordance with recent studies (Shaki & Fischer, 2018; Sixtus et al., 2019), we expected the SNA along the horizontal axis to be more fragile. Our results indeed provide evidence for vertical SNAs, but inconsistent effects regarding the horizontal axis. Note however that although the horizontal SNA appears more fragile in our study (Experiment 1) with a small effect size ($d = 0.325$) compared to the vertical SNA ($d = 0.457$), we have no clear evidence for the superiority of vertical or sagittal organization over the horizontal one.

The lack of horizontal SNA in Experiment 2 is surprising and could be accounted for by the removal of spatially grounded motor response. Pinto, Pellegrino, Marson, Lasaponara, and Doricchi (2019) indeed pointed out the need for horizontal SNAs to occur to have a spatial and number-magnitude joint code. Alternatively, one could wonder whether the absence of horizontal SNA in Experiment 2 could result from the screen orientation, as the screen was laid down flat on the desk. To the best of our knowledge, no study has ever explored the impact of screen orientation (parallel vs. perpendicular) on the horizontal SNA. Regarding the midsagittal axis in Experiment 2, even if the p-value was not significant ($p = .053$), the effect size can be interpreted as a small effect ($d = 0.294$). Although our results are not significant, we find a pattern which matches with the idea of SNAs arising in 3D (i.e., where small numbers are associated with the near space and large numbers with the far space).

The present study extends previous reports suggesting that numbers can be flexibly arranged along the three dimensions and shows that SNAs can occur in the absence of spatially grounded motor response. The question of the mechanisms underlying these behavioral effects is still under debate. The number–space associations are supposed to emerge from distinct origins. The horizontal SNARC has been interpreted, in the first place, as an expression of the mental number line, oriented from left to right in Western cultures (Dehaene et al., 1993). Yet, evidence for a left-to-right organization

in human infants and animals has challenged this theoretical interpretation by suggesting a role of hemispheric specialization and core attentional biases (de Hevia et al., 2014, 2017; Di Giorgio et al., 2019; Rugani et al., 2020). The theoretical account for the horizontal SNA has been reconsidered with some recent proposals underscoring the role of basic brain asymmetries in the processing of low-level, spatial frequency information [i.e., the spatial frequencies contained in small, nonsymbolic vs. large sets engage the right- vs. the left-brain hemisphere, respectively, resulting in left- vs. right-lateralized responses. However, this view needs to address how spatialization of symbolic numbers takes place (Felisatti, Aagten-Murphy, et al., 2020; Felisatti, Laubrock, et al., 2020)].

On the other hand, the most prominent theories accounting for vertical and sagittal SNAs are derived from grounded cognition proposals (Barsalou, 1999, 2008). Under this view, number concepts are assumed to emerge from sensory–motor experience, in which they may be modal and intrinsically linked to space (Fischer, 2018; Fischer & Shaki, 2018). The vertical SNA could be based on gravity and more broadly on the natural laws according to which “More is Up – Less is down” (Lakoff & Johnson, 2008). While experimental studies regarding the sagittal axis are scarce, SNAs related to depth (near vs. far) could emerge in the peripersonal space (Chen et al., 2015). We posit that processing the spatial distance between an object/stimulus and us – more space, larger magnitude, and vice-versa – could be a reliable hypothesis for accounting for the SNAs observed across vertical and sagittal axes. Further investigation is needed to explore this issue and to deepen our understanding of the SNA in 3D.

Finally, we believe the SNARC effect is probably resulting from a blend of diverse factors such as cultural habits, innate and neurally based links between space and number, and short-term memory or polarity correspondence (Abrahamse et al., 2016; Hubbard et al., 2005; Previtali et al., 2010; Proctor & Cho, 2006; Shaki, Fischer & Petrusic, 2009; Van Dijck et al., 2011). Distinct but complementary mechanisms might be involved in the spatial mental representation of numbers. Although SNAs may be flexible and idiosyncratic, they might be mainly and differentially driven by the spatial dimension (horizontal, vertical, or sagittal). In this context, it is possible that horizontal

SNAs are more dependable on resources in working memory and more easily modified by cultural habits; in contrast, both the vertical and sagittal SNAs might be more rooted and grounded in the body–environment interaction.

Limitations and Future Directions:

Further investigation is definitely needed to complement the present results. Regarding SNAs on the sagittal axis, one should address the issue of retinal size. As in our protocol, number stimuli were displayed at different locations; retinal size was thus impacted and could significantly modulate numerical magnitude processing (e.g., size effect: Henik & Tzelgov, 1982). However, numbers appearing far should be perceived as smaller than numbers appearing closer. We should therefore observe a reverse association (small numbers associated with a far position and large numbers associated with a close position). While the SNA theory predicts an association of small numbers in near space and large numbers in far space. The results from the present study tentatively point in this direction. Further studies should also stress the surprising lack of SNARC effect on the horizontal axis in Experiment 2. The SNA on the horizontal axis is considered as one of the most robust effects in numerical cognition. Could the manipulations of Experiment 2, such as the centralization of the response button and the tilted screen, have completely abolished the effect? Given that we observed a significant NDE effect, we are confident that participants successfully accessed numerical magnitude information when performing our task. Further studies should further investigate this issue more in depth. The horizontal SNARC effect is usually tested when numbers presented parallel to the participant and not when presented perpendicularly. The tilted screen could, after all, have played a relevant and unexpected role on participants' performance. One could argue that using a central response with spatially lateralized stimuli, instead of using spatially lateralized responses with central stimuli in a typical SNARC paradigm, might have resulted in a

different SNA. An important role could be played by motor response-related spatialization relative to the spatialization of the stimuli.

As pointed out by an anonymous reviewer, the magnitude is a task-relevant aspect in our experiments after all. To further broaden the theoretical understanding of the role played by numerical magnitude, future follow-up studies using a different task setting where numerical magnitude is irrelevant to the task should be conducted (i.e., parity judgment task).

Conclusion:

To sum up, nowadays, empirical evidence indicates that SNAs can be elicited not only along the horizontal axis but also along the vertical and sagittal ones. In addition, it has been suggested that vertical and sagittal SNAs may be more robust as they are mainly rooted in natural laws and may therefore emerge from the interaction between the environment and the body as predicted by the view of grounded cognition. In contrast, horizontal SNAs may be rooted in hemispheric lateralization and also be significantly shaped by cultural habits. According to this reasoning, horizontal SNAs would be more fragile, subject to the limited resources of working memory, and weakened in the absence of explicit spatial processing (Pinto, Pellegrino, Marson, Lasaponara, & Doricchi, 2019; Van Dijck et al., 2011). Additional empirical evidence is needed to investigate the mechanisms underlying the SNAs for each spatial dimension.

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