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Embodied Magnitude Processing: On the Relation Between the SNARC Effect and Perceived Reachability

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Abstract

Magnitude information, for instance, regarding weight, distance, or velocity, is crucial for planning goal-directed interactions. Accordingly, magnitude information, including numerical magnitude, can affect actions: Responses to small numbers are faster with the left hand than the right and vice versa (hand-based SNARC effect). Previous experiments found an influence of effector placements on the SNARC effect but also an influence of the mere distance between effectors and numbers. This indicates a sensorimotor grounding of space-number processing. In the current study, we investigated this grounding by probing the SNARC effect close to and far from the hands. We used a magnitude comparison task with a fixed standard of 5 (smaller numbers 1, 2, 3, 4; larger numbers 6, 7, 8, 9) and a sagittal response arrangement to measure hand-based and sagittal SNARC effects for digits presented at different sagittal distances to the hands, i.e., in peripersonal and extrapersonal space. A significant sagittal SNARC effect was found, with the largest effect size in extrapersonal space. Meanwhile, the hand-based SNARC effect appeared only descriptively, with the largest effect size between the hands, i.e., in peripersonal space. Additionally, a purely spatial congruency effect surfaced, prioritizing responses with the hand closer to the number. Together, these results emphasize that responses in simple decision-making tasks can be influenced interactively by a multitude of task-relevant axes and relative spatial locations, including effector placement and stimulus placement, as well as number magnitude.

Keywords

SNARC effect, spatial representation, personal spaces, theory of magnitude, embodied numerical cognition, virtual reality

Non-Technical Summary

Background

Performing goal-directed actions, like grabbing a pen, is preceded by the preparation of key behavioral steps. Besides target position and grasp type, the planning dynamics also involve magnitude information like distance and weight, which influence reaching dynamics and grasping force. Even more, numerical magnitude can impact actions, e.g. by influencing the response times: Responses to small numbers are faster with the left hand than the right hand and vice versa (hand-based SNARC effect).

Why was this study done?
Previous research also indicates that the position of our hands and the distance between hands and numbers influence the SNARC effect, suggesting a connection between sensory and motor information and processing numbers and space. Our study examines this connection in detail.

What did the researchers do and find?
We investigated how number magnitude influences response times when numbers are presented at different back-front (sagittal) distances relative to the hands and body. Participants compared number magnitudes (1 to 4 and 6 to 9) to a standard of 5 by reacting with either the hand positioned near the body or the hand positioned far from the body. Numbers were presented at several distances. We observed significantly faster responses to small numbers with the hand closer to the body than the hand further away, and vice versa (sagittal SNARC effect). This effect was more pronounced when numbers were presented at the largest distance. Additionally, responses were faster with the hand near the number than the one further away.

What do these findings mean?
This study highlights the interactive influence of factors like hand and stimulus placement, as well as numerical magnitude, on decision-making tasks.

Highlights

- This experiment examines the hand-based and sagittal SNARC effect in a VR environment.
- Numbers were presented at four sagittal distances (sagittal response layout).
- We found a significant sagittal SNARC effect but no significant hand-based SNARC effect.
- The results support a sensorimotor grounding of magnitude processing.

Our everyday life is determined by goal-directed actions like grabbing a cup of coffee or turning on the light by pressing a light switch. According to theories of anticipatory behavior control, such goal-directed actions are initiated by anticipating their effects (J. Hoffmann, 1993; Prinz, 1990). This requires bidirectional mappings between motor commands and sensory changes. These mappings referred to as common codes (Hommel et al., 2001), encode action-relevant magnitude information like the distance between the hand and an object or the speed of an approaching stimulus to guide grasping or defensive movements, respectively. On the behavioral side, bidirectional mappings allow the seamless adaptation of, for instance, grasping types to object characteristics like precise grasps for a needle or whole hand grasps for a heavy stone. Further, action anticipation can bias the perceived location (Jordan et al., 2002; Kirsch, 2015) or the perceived size of a stimulus (Fagioli et al., 2007). Such bidirectional mappings can also be found between numerical magnitude and action (Lindemann et al., 2007; Shaki & Fischer, 2014). These findings show that higher cognitive functions, such as number or magnitude processing, can be modulated by action and suggest a sensorimotor grounding of those functions.

Walsh's theory of magnitude (ATOM; Bueti & Walsh, 2009; Walsh, 2003) supposes that a sensorimotor magnitude system – like the one realized in common codes – provides the foundation for a common metric. This metric appears to represent magnitudes concerning time, space, and quantity. The size-congruity effect strongly supports this: When participants judge which of two digits is numerically/physically larger, they are faster when the numerical and physical size are congruent than incongruent (e.g., Henik & Tzelgov, 1982). The size-congruity effect shows that numerical and spatial magnitudes can be activated automatically and simultaneously. Their interference implies that they share a common processing stage or representational format. Walsh (2003) furthermore proposes that the representation of these quantities evolves from interactions with the environment.

The SNARC Effect

A common representation for numbers and space and its link with action is also substantiated by the horizontal *spatial numerical association of response codes* (SNARC) effect: In tasks where participants have to judge the magnitude (e.g., smaller or greater than five) or the parity (e.g., odd or even) of a number the responses to small numbers are faster with the left response key (compared to the right response key), and vice versa (Dehaene et al., 1993). The SNARC effect has been shown for various number notations (e.g., Arabic digits or number words: Dehaene et al., 1993; Lindemann et al., 2007; Nuerk et al., 2005) and visual, auditory, and haptic stimuli (Dehaene et al., 1993; Lindemann et al., 2007; Nuerk et al., 2005). The SNARC effect is stable across modalities and number notations and, hence, is well-suited to investigate the sensorimotor grounding of numerical cognition in action.

Such a grounding would suggest that the SNARC effect is influenced by different action-relevant aspects, especially those related to the effectors (e.g., the hands). Surprisingly, no major influence of handedness on the SNARC effect (Cipora et al., 2019; Dehaene et al., 1993; Müller & Schwarz, 2007), and contradictory results for finger counting habits were found (Fabbri, 2013; Fischer, 2008; Tschentscher et al., 2012; see also Shaki & Fischer, 2021, they show that finger counting habits influence the association between space and magnitude).

However, previous studies have shown that the spatial arrangement of the effectors influences the SNARC effect. For example, response times are modulated when the response hands are crossed (Müller & Schwarz, 2007; Viarouge et al., 2014; Wood et al., 2006). Even though all three studies use different instructions and find different modulations of the SNARC effect by crossed hands, all authors indicate that the SNARC effect is influenced by spatial representational (a spatial representation serves as a reference frame to encode spatial information, i.e., a coordinate system) as well as hand-based (hands serve as a reference, i.e., the position of the left hand represents the left side of space) frames of reference. In most studies investigating the horizontal SNARC effect, the representational and hand-based frames of references are aligned, as responses on the left side are conducted with the left hand, and responses on the right side are conducted with the right hand. Hence, the horizontal (left and right side of the space) and the hand-based (left and right hand) SNARC effects are not separable in those settings.

Further studies have shown that the response layout can influence the spatial dimension along which numbers are mentally represented (Mourad & Leth-Steensen, 2017; Sixtus et al., 2019). SNARC effects were found not only on the horizontal (left-to-right) axis but also on the vertical (bottom-to-top) and sagittal (near-to-far) axes. Winter et al. (2015) pointed out that the vertical SNARC effects have been studied far less than horizontal/hand-based SNARC effects. However, several studies documented an association between small magnitudes and the bottom as well as large magnitudes and the top when responses are arranged vertically (Aleotti et al., 2020; Hartmann et al., 2014). Similarly, studies investigating sagittal SNARC effects indicate an association between small/large magnitudes and near/far space, respectively, when sagittal responses were required (Marghetis & Youngstrom, 2014; Santens & Gevers, 2008). Some studies even investigated SNARC effects on two or more axes at the same time (Aleotti et al., 2020; Aleotti et al., 2023; Hesse & Bremmer, 2017; Mourad & Leth-Steensen, 2017; see Winter et al., 2015 for a review) and indeed found co-existing SNARC effects on different axes.

Nevertheless, the SNARC effect does not always occur on the dimension along which the response buttons are arranged. For example, Wiemers et al. (2017) arranged response buttons on the vertical axis (one button was placed below and one on a tabletop). They found no vertical SNARC effect when the hand-to-button mapping changed only once, no matter whether the participants were standing or sitting. However, when they changed the hand-to-button mapping after every 16 trials, they found a vertical SNARC effect.

In typical fronto-parallel display setups, the sagittal and vertical axes can easily be confused. This happened, for example, in two studies that claimed to investigate spatial numerical associations on the vertical axis but presented stimuli in a sagittal arrangement on a table (Göbel, 2015) or mixed a vertical stimulus arrangement with a sagittal response arrangement (Li et al., 2017). In our opinion, it is essential to carefully distinguish vertical and sagittal arrangements when vertical and sagittal SNARC effects are investigated. One good possibility is to use virtual reality arrangements, such as the one used by Lohmann et al. (2018).

In this study, digits were presented at different sagittal distances in a virtual environment. Participants were instructed to judge whether the presented digits were smaller or larger than five (magnitude comparison) by closing either their right or left hand. Lohmann et al. (2018) found no sagittal SNARC effect but a modulation of the horizontal/hand-based SNARC effect by distance, with the largest SNARC effect for stimuli presented close to the virtual hands on the sagittal axis. This shows that both the effectors' spatial layout and the stimuli's spatial location influence the SNARC effect. It seems that the SNARC effect can be realized within body-centric (e.g., near and far from the body) as well as effector-centered (e.g., near and far from the hands) frames of reference (Wood et al., 2006). The absence of a sagittal SNARC effect might be explained by the horizontal response arrangement, which primed a horizontal number representation (for similar results with a vertical SNARC effect, see Gevers, Lammertyn, et al., 2006). In the horizontal response setting, the representational and hand-based frames of reference are aligned. The pattern found in the horizontal/hand-based SNARC effect implies enhanced processing of stimuli presented close to the hands. While responses to stimuli close to the hand were not generally faster or slower, the SNARC effect became more extreme regarding response time differences. More precisely, (congruent) responses with the left/right hand to small/large numbers were faster, while (incongruent) responses with the left/right hand to large/small numbers were slowed down when stimuli were presented close to the hands. This might be due to a higher salience for the space close to the hands (near hand effect; Reed et al., 2006) or the modulation of spatial attention for objects presented close to the hands (e.g., Tseng et al., 2012).

There are several additional factors influencing the SNARC effect. Most importantly, the SNARC effect is more pronounced in slower responses (Cipora et al., 2019; Wood et al., 2008). Further, the task itself influences the SNARC effect. In parity or magnitude comparison tasks, numbers are processed differently; hence, the SNARC effect differs (Georges et al., 2017; van Dijck et al., 2009). For example, the SNARC effect for parity judgment tasks can be described by a linear decrease in the response time superiority of left-side responses with magnitude. In contrast, the SNARC effect in magnitude comparison tasks can be described more accurately by a categorical predictor[1], which groups the numbers into those smaller and larger than the critical number (Gevers et al., 2010; see Weis et al., 2018 for comparisons of parity judgment and magnitude comparison tasks and Wood et al., 2008 for a meta-analysis). Moreover, in a parity judgment task, both magnitude and its relation to space are automatically activated (although irrelevant). In contrast, only the relation to space has to be automatically activated in a magnitude comparison task (Weis et al., 2018).

Also, personal factors such as gender (Bull et al., 2013; but see Weis et al., 2018), age (D. Hoffmann et al., 2014; Wood et al., 2008), and mathematical skills (D. Hoffmann et al., 2014) were found to influence the strength of the SNARC effect. Furthermore, participants who read from right to left show an attenuated or even reversed SNARC effect (Shaki & Fischer, 2014; Shaki et al., 2009; Zebian, 2005).

In conclusion, the SNARC effect allows for examining the grounding of number processing in actions. Although the SNARC effect is stable across modalities and number notations and hence seems to be rather amodal, it can be influenced by modal information, such as the effector placement and the distance of the presented number to the body or the effector. Presumably, the properties of the spatial representation of the space close to the effectors – the peripersonal space – can modulate the SNARC effect.

Peri- and Extrapersonal Space

There are several different definitions of *peripersonal space*. We follow the definition of Bufacchi and Iannetti (2018), who define peripersonal space as a set of continuous fields, which describe physiological reactions evoked by a stimulus' behavioral relevance. This relevance reflects whether contact with the stimulus is desirable (leading to a reaching movement, for instance) or not (resulting in a defensive movement). Bufacchi and Iannetti (2018) postulate graded response fields for the peripersonal space instead of in-or-out zones to account for the observations that indicators measuring the peripersonal space change gradually with distance to different body parts in all three dimensions. Such behavioral findings were corroborated on a neuronal level: Neurons were found that become increasingly active with stimuli presented at nearer distances (Canzoneri et al., 2012; Sambo & Iannetti, 2013). The activation of those fields depends on the intended interactions and the axes that are the focus of attention (Bufacchi & Iannetti, 2018). The space outside the peripersonal space, which cannot be directly acted upon with the body, is called the extrapersonal space (Cléry et al., 2015).

1) The linear and the categorical models are relatively hard to distinguish empirically by means of statistical testing, especially with small *N*. Hence, using the linear model in case of magnitude comparison tasks brings an overall satisfactory fit and is quite prevalent in the literature (for one example see Bae et al., 2009).

Lohmann et al. (2018) found that the SNARC effect is largest when digits are presented close to the hands and second largest in extrapersonal space. This suggests that the SNARC effect is not modulated by sagittal distance alone but specifically by the distance between the digit and the effector. The described results imply a close coupling between spatial numerical associations and bodily representations in general and peripersonal space in particular. If this is indeed the case, it would support the assumption of ATOM that the general magnitude system is rooted in or closely linked to sensorimotor experience and is not as amodal or abstract as sometimes suggested.

The Current Study

We investigated the hand-based and sagittal SNARC effects when stimuli are presented close to and far from the hands to further examine the relationship between spatial numerical associations and continuous spatial body representations. More precisely, we investigated the hand-based and sagittal SNARC effects modulations by the sagittal distance between the participant's hands, body, and stimuli. Such modulations would support the assumption that the SNARC effect is at least partially grounded in sensorimotor experience and would provide an example of modal influences on the SNARC effect.

In a previous study by Lohmann et al. (2018), the largest SNARC effect was found for stimuli presented close to the hands, suggesting a stronger dependence of the SNARC effect (in peripersonal space) on the sagittal distance between the digit and the hands compared to the sagittal distance between the digit and the body. However, those distances were confounded because the digits were presented at different sagittal distances while the positions of the hands and the body were fixed. To avoid confounding variables, the sagittal response arrangement in the current study distinguished between the influences of those distances.

To realize an immersive setup and a realistic depth impression, we used a similar virtual reality (VR) setup as Lohmann et al. (2018). Participants performed a magnitude comparison task (indicating whether a number is smaller or larger than five) with digits 1 to 4 and 6 to 9 presented at different distances on the sagittal axis. The magnitude comparison task was used for two reasons: First, magnitude judgment tasks seem related to spatial working memory instead of verbal working memory as in parity judgment (van Dijck et al., 2009). Second, only the relation to space has to be automatically activated rather than the magnitude and its relation to space, as in a parity judgment task (Weis et al., 2018). During the experiment, hand movements were tracked using markerless optical motion capture to allow participants to respond directly by closing their hand[2].

In contrast to Lohmann et al. (2018), who arranged the hands on the horizontal axis, in the current study, a sagittal response arrangement was realized where either the left or the right hand was close to the participants, while the other hand was more distant to the body. Hence, compared to Lohmann et al. (2018), the SNARC effect in the current study is not influenced by representational frames of reference as the responses are sagitally aligned. Participants were instructed to respond to digits with small or large magnitude with either the close or the far hand. So, the sagittal axis was used for response and stimulus arrangement, and hence, this axis was primed. Accordingly, we expected to find a sagittal SNARC effect (see also Gronau et al., 2017). Meanwhile, we expected an SNARC effect along the horizontal axis, as it was shown to be robust even if the effectors were arranged on another axis (Gevers, Verguts, et al., 2006; Wiemers et al., 2017). Given the background described above, we developed the following hypotheses:

We expected to find a sagittal SNARC effect: Responses to digits with a small magnitude are faster with the hand close to the body (compared to the hand distant from the body), and responses to digits with a large magnitude are faster with the hand distant from the body (compared to the hand close to the body). We predicted this effect to be influenced by the sagittal distance between the presented digits and the hands in the way that the greater the distance, the smaller the SNARC effect.

We expected to find a hand-based SNARC effect: Responses to digits with a small magnitude are faster with the left hand (compared to the right hand), and responses to digits with a large magnitude are faster with the right hand (compared to the left hand). We also expected the sagittal distance between the presented digit and the hands to

2) Andres et al. (2004) observed faster grip closure to small numbers. This could still lead to an overall bias in favor of small numbers in the current experiment.

influence this hand-based SNARC effect in the way that the greater the sagittal distance, the smaller the hand-based SNARC effect.

Results following the hypotheses would suggest that the SNARC effect and, therefore, the mental magnitude representation can be grounded in sensorimotor experience and influenced by the distance between stimuli and effectors. This would further support ATOM's assumptions that the general magnitude system is rooted in – or closely linked to – sensorimotor experience and is not as amodal or abstract as sometimes suggested.

We evaluated these hypotheses on the mean response times level as in standard SNARC analyses. Additionally, continuous motion tracking allowed us to obtain the maximum hand closure (MHC) of the incorrect hand for each trial and the according time (MHCT). These kinematic measures enabled us to evaluate response conflicts in the different experimental conditions by registering the strength of incorrect hand closure and its time, even when these conflicts do not lead to a wrong response.

Method

Participants

An a priori power analysis revealed that for the hand-based SNARC effect – in terms of a two-way interaction between magnitude and response hand – a power of at least .90 and a partial eta-squared of $\eta_p^2 = .51$ can be reached by analyzing the data of 22 participants. For the power analysis, a Monte Carlo Simulation was conducted based on the data of Lohmann et al. (2018). The respective R script and the data can be found in Supplementary Material S1 and S2. The results of Lohmann et al. (2018) were chosen as reference data because the experiment was also conducted in VR and within a similar setting. The study was preregistered (see Supplementary Materials).

Participants were recruited through internal university communication channels primarily. Consequently, the participants were probably mostly students. Only participants with normal or corrected to normal vision were recruited for the study. Participation was voluntary, and participants received monetary compensation or course credit in exchange for their participation. All participants provided written informed consent. The ethics committee for psychological research at the University of Tuebingen[3] has approved the study protocol.

From 15.03.2022 to 30.06.2022, we collected the data from 31 participants to reach 22 participants with correct responses in at least 75% of the trials of any factor combinations. The included participants' ages ranged from 18 to 31 years (M = 23.32, SD = 3.18). Five participants reported to be male, 17 to be female, 20 reported to be right-handed, and two to be left-handed, and all participants read from left to right. All participants stated German as their mother tongue, except one who reported Spanish as their mother tongue. Three participants had already completed their master's, and all the others had a high-school diploma. Their grades in math reached from 3 to 15 (M = 10.43, SD = 3.14; one participant did not report any math grade). Details of the assessments can be found in the Procedure section below.

Material and Apparatus

Apparatus

Participants wore an HTC Vive stereoscopic head-mounted display (HMD; HTC Corporation, Taoyuan, Taiwan) to place them in a 3D environment and to track their head movements. The hand movements were tracked with a LeapMotion© (LeapMotion, Inc., San Francisco, CA, United States; SDK version 4.0.0) near-infrared sensor, which tracks the movements of the phalanges, wrist, arm, and palm. This information was used to build a hand model and to represent it in VR. The movements were tracked with a frequency of 75 Hz. The LeapMotion© sensor allows the measurement of the hand closure (the angle between the mean direction of the fingers and the direction of the hand) of the respective hand, which was used to measure response times and response kinematics in the SNARC task. The whole experiment was programmed using the C# interface provided by the Unity® engine 2018.4.11/1 and was rendered

3) Revision_1_Lohmann_2020_0323_179

in Unity on the HTC Vive and in parallel on a computer screen. This allowed the experimenter to observe the scene and assist the participants.

Virtual Reality Setup

We chose a VR setup that resembles the setup of Lohmann et al. (2018) but changed the camera position to improve the view of the digits. To avoid distractions by moving grass and to enhance the depth perception with the new camera position, the background of the VR was adapted. In the current study, the setup consisted of a pond surrounded by a beach with rocks and trees. Hills were present on the horizon. As in the study from Lohmann et al. (2018), we chose a rather natural environment to provide familiar distance cues to facilitate spatial presence[4]. On the pond's surface, ten white horizontal lines spread from 10 cm to 100 cm with a distance of 10 cm between each other (distances refer to the camera position). These lines represent discrete distance indicators, making the distinction between the reachable and unreachable space more salient. A LeapMotion© sensor placed 30 cm in front of the participants tracked the hand movements. The interaction range reached about 60 cm (from the body to the sixth line) in depth and 50 cm in width. This range limited the participant's interaction space, not the participant's arm length; hence, objects in this space were perceived as reachable in the VR. The online motion capture allowed a natural, continuous response mode. It also allowed participants a sensorimotor exploration of the task space. Hence, participants explored the VR environment with their own bodies, which has previously been shown to increase spatial perception and immersion, the subjective perception of being present in VR (Linkenauger et al., 2015; Mohler et al., 2008). This exploration task can also adjust individual differences in estimating reachability (Fischer, 2005). In our case, the exploration task is used to adjust the estimation of reachability to the space up to 65 cm from their body. Furthermore, the distinction between peri- and extrapersonal space should remain valid in such a setup (Gamberini et al., 2008). The physical setup and the real world distances corresponding to the ten white lines are shown in Figure 1; examples of the VR environment can be found in Figure 3 and Figure 4.

Design

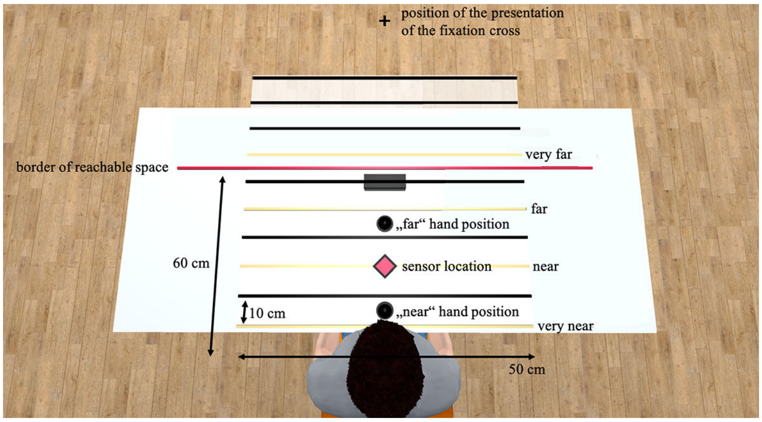
We used a 4 (spatial displacements) × 2 (digit categories) × 2 (response hands, left and right) × 2 (response distances, close and distant hand position) factorial, within-subject design (see Figure 2 for an overview of the conditions). Therefore, we presented the digits 1 to 4 (small magnitudes) and 6 to 9 (large magnitudes) on the four distances 10 cm, 30 cm, 50 cm, and 70 cm in each block. We chose those distances instead of the ones used by Lohmann et al. (2018) for ergonomic reasons. We varied the response hands and the response distances across blocks. Participants responded with the left hand to digits smaller than five and the right hand to digits larger than five, or vice versa. Each of these response mappings was combined with two different hand positions. Either the right hand was held at a distance of 40 cm and the left at 20 cm, or vice versa. This resulted in different instructions for each of the four blocks. The order of the trials in a block was randomized, and the order of the blocks was balanced. Together, these factors resulted in 32 combinations repeated 24 times each. Thus, every participant performed 768 trials in four blocks with 192 trials each.

The influence of these factors on the response time, the MHC of the wrong hand, and the respective time of the MHCT were measured. The measure of MHC is meant to roughly reflect the degree of an involuntary response preparation (incorrect responses).

4) This environment will be used in other studies as well, where we plan to vary the vertical hand position. Hence, we chose the pond as a familiar metaphor for a surface with a distinct separation between below and above. Compared to the top of a table, for instance, this boundary can be plausibly traversed.

Figure 1

Real-World Setup of the Experiment



Note. Real-world setup of the experiment (i.e., not what the participant perceives in VR, which is different). The black and yellow lines indicate the real-world equivalent of the white lines in the VR setting. If the participant holds their hand 10 cm from the body, the hand is represented in VR at the sagittal distance of the first white line. Digits were presented on the distances indicated by the four yellow lines. Hands were placed over the black circles. The red line indicates the border of the tracking range, which reflects the border of reachable space. The red diamond indicates the position of the hand-tracking LeapMotion© sensor.

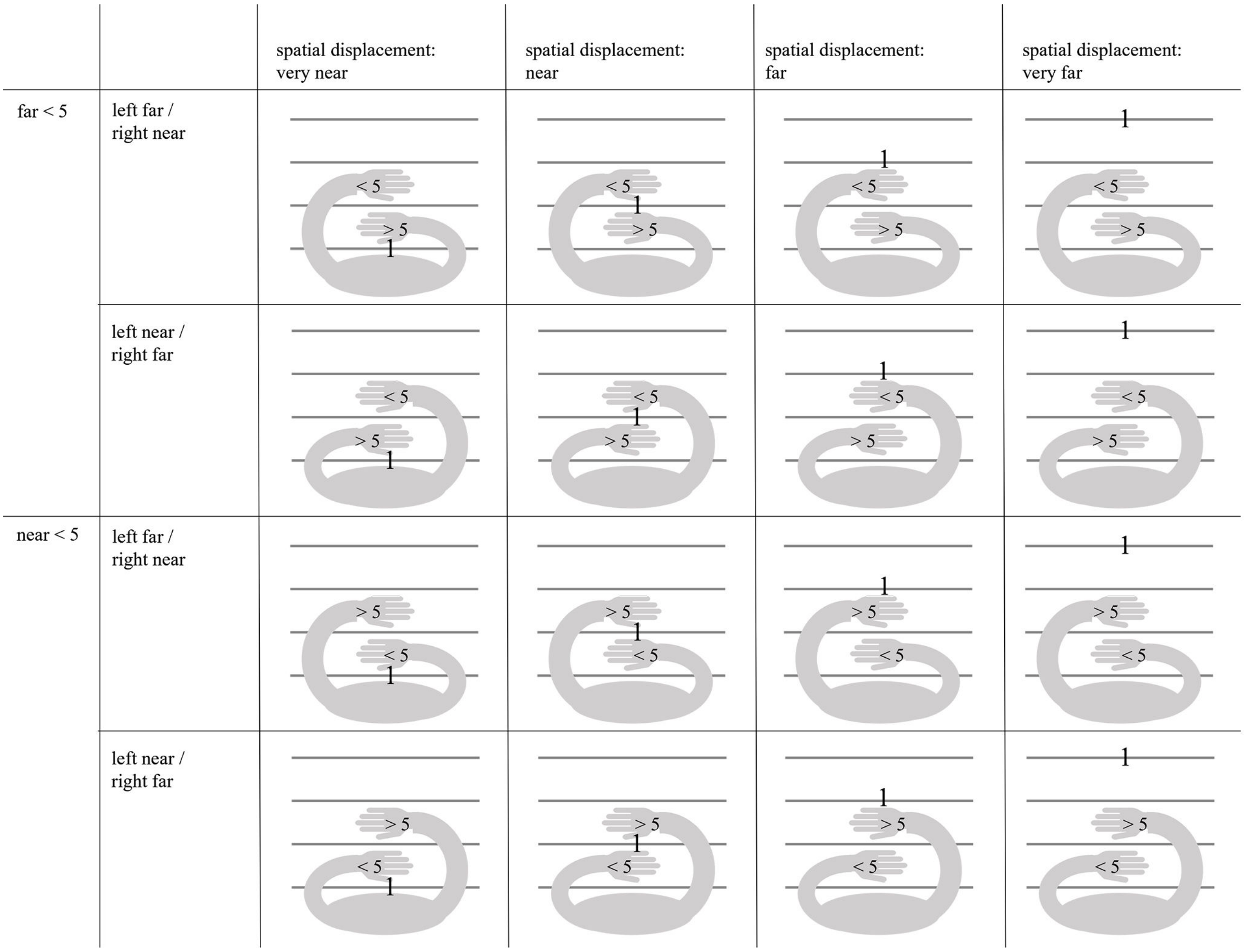
Procedure

The experiment took about 90 minutes. A video of the procedure can be found in Supplementary Materials S8. First, we obtained demographic information because there are some indications that these factors might influence the SNARC effect. We asked for age (self-report: open text field), gender (self-report: male/female/diverse), handedness (self-report: left/right), reading direction (self-report: from left to right/from right to left/both), education level (self-report: Hauptschulabschluss [secondary school leaving certificate]/Realschulabschluss [comprehensive school leaving certificate]/Abitur [high-school diploma]/apprenticeship/completed bachelor/completed master/Ph.D./other), last grade in mathematics (self-report: 0 – very bad to 15 – very good, like in the German high school exam grading pattern), finger counting habits (described below), and mother tongue (self-report: open text field). Finger counting habits were assessed using the instruction: "Please clap into your hands, then count with your fingers from 1 to 10 and indicate the order in which you counted with your fingers." followed by a picture of two hands similar to Wasner et al. (2014).

Verbal instruction regarding the VR equipment followed. Then, the HMD was put on, and the scene was calibrated. Therefore, the participants put their hands in the starting position, and the experimenter adjusted the position of the virtual hand such that the participants were in a comfortable seating and hand position. Afterward, the participants were asked to extend their right arm and touch a cardboard box with the tip of their middle finger. Participants were instructed that this position is the most distant reachable point. The position of the cardboard box corresponded to the outer limit of the radial tracking range and the sixth horizontal white line in the VR, which reflected the border of reachable space (see Figure 1). This provided a haptic indicator for the bounds of the task space.

Figure 2

Overview of Experimental Conditions



Note. The figure shows the different spatial displacements, reaction instructions, and hand positions. The correct response can be with the left or the right hand and with the near or the far hand. Further, the number, here 1 comes from the set 1, 2, 3, 4, 6, 7, 8, and 9.

After that, the sensorimotor exploration task and the magnitude comparison task were conducted. Both are described in detail below. Ultimately, participants were asked to complete a presence questionnaire (IPQ; Schubert et al., 2001) and a questionnaire to assess finger-counting habits (Fischer, 2008). The IPQ questionnaire[5] is used to test for a sufficient level of immersion and spatial perception in VR, which is necessary to ensure a similar influence of the space and the body on number processing as in reality. We assessed finger counting habits with two different assessments to be able to analyze influences of situated cognition because Wasner et al. (2014) showed that the proportion of left- and right-starters differs considerably, depending on how you ask participants. In their (between-participant) study, 72% started with their *right* hand when they counted spontaneously. However, 62% reported starting with their *left* hand when they were given a finger-counting questionnaire and had their pen in their hand. Because of such considerable differences, we used both assessments.

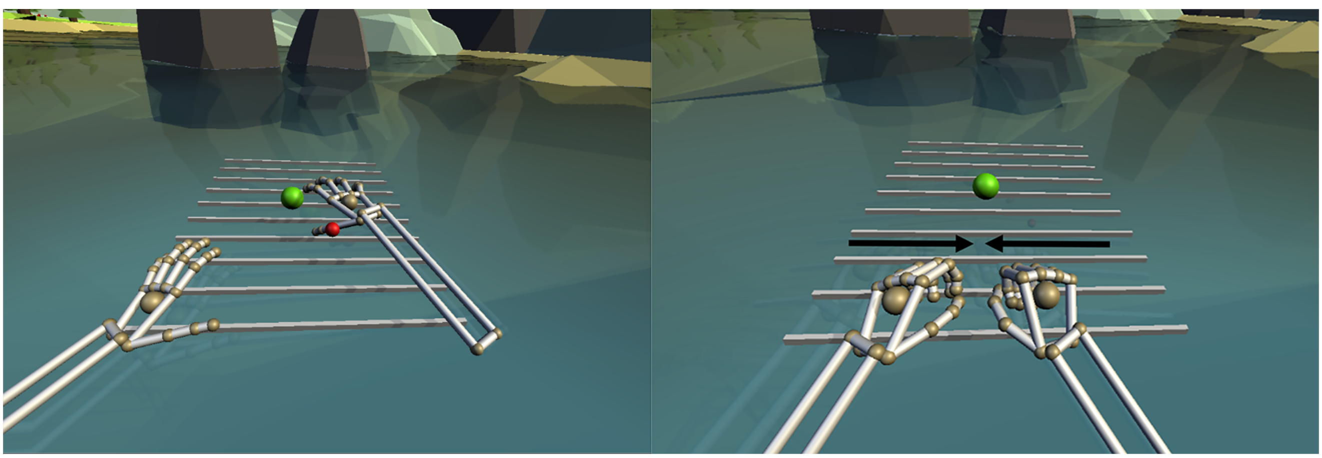
5) A description of the scale construction can be found at: http://www.igroup.org/pq/ipq/construction.php

Sensorimotor Exploration Task

The sensorimotor exploration task aimed at familiarizing the participant with the sensorimotor mapping and experiencing the reachability and distances in the VR setup (the performance in this task was not evaluated). The participants had to touch yellow spheres with the left hand and green spheres with the right hand (diameter: 6.67 cm; see Figure 3, left panel) and bring their fists together whenever a sphere was unreachable (see Figure 3, right panel). The respective instruction was presented in a text field (80 cm away from the participant). It included a video showing the participants how to bring their fists together. Afterward, one sphere at a time was presented on one of the four distances 10, 30, 50, or 70 cm, the spheres covered a visual angle of 16.52°, 10.46°, 7.05°, and 5.23°, respectively (see Supplementary Material S3 for the calculation; the participant's head position in the virtual environment, distances, and visual angles refer to the camera position). The horizontal position was sampled over the whole width of the task space (from left to right), so the participants had to conduct ipsilateral as well as contralateral reaching movements. The spheres turned white for correct responses, while for incorrect responses, they turned red. Afterward, they disappeared.

Figure 3

Sensorimotor Exploration Task



Note. Spheres were presented at different distances in the task space. Reachable spheres (left): Yellow spheres had to be touched with the left hand and green spheres with the right hand. Non-reachable spheres (right): Participants had to bring their fists together if the sphere was outside the reachable space. The red sphere indicates the center of the visual field of the participant.

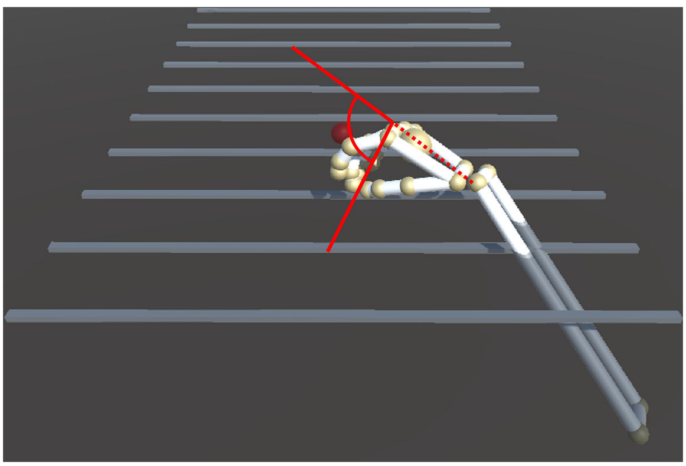
Each participant had to perform at least ten correct responses per distance (five with the left hand and five with the right hand) to start the magnitude comparison task. Hence, during training, participants completed at least 40 trials. The presentation order of these trials was randomized. A new trial was added for each error trial, presenting the sphere at the same distance as the erroneous trial and at a newly sampled horizontal position.

Magnitude Comparison Task

In the main task, participants judged whether single digits (1 to 4 and 6 to 9) were smaller or larger than five by reacting with either clenching their left or right fist. At the beginning of the task, an instruction was given (e.g., "left hand near/right hand far, smaller five near/larger five far"). Afterward, the participants performed training trials until they had performed nine of the last ten trials correctly. During the training trials, the participants had to react by clenching the left fist to digits smaller than five (here, only 0 is used) and by clenching the right fist to digits larger than five (here, only 10 was used). Note that those training digits were not part of the actual stimulus set during the subsequent main experiment. The LeapMotion© sensor measured the hand closure using the grasping angle, which reaches from 0° for an open hand (fingers are stretched out) to 180° for a closed hand (the hand forms a fist). A response was recorded when the angle was larger than 100° (the angle between the fingers' mean direction and the hand's direction; see Figure 4). A prior test has shown that this angle was suitable to capture only intentional movements and that the corresponding movement was easy and natural for the participants. During the main experiment, each testing block started with instructions showing participants the response mapping and hand placement. Each trial started with a fixation cross (size 16.67 cm/7.82° in the middle of the screen at a distance of 121.67 cm and 9.33 cm above the surface of the pond) and two semi-transparent red spheres (with size 3.33 cm and at the distances 45 cm/3.57° and 15 cm/5.84° in the middle of the screen and 3.33 cm above the pond's surface), which indicated the correct hand positions. The center of the fixation cross (8.33 cm/3.91° height and width, in the middle of the screen directly on the fixation cross) turned green once the center of the visual field (indicated by a red sphere, cf. Figure 4 left panel) overlapped with the fixation cross. The spheres turned green once the hands were in the correct position and were opened (the grasping angle was smaller than 45°).

Figure 4

The Critical Hand Closure

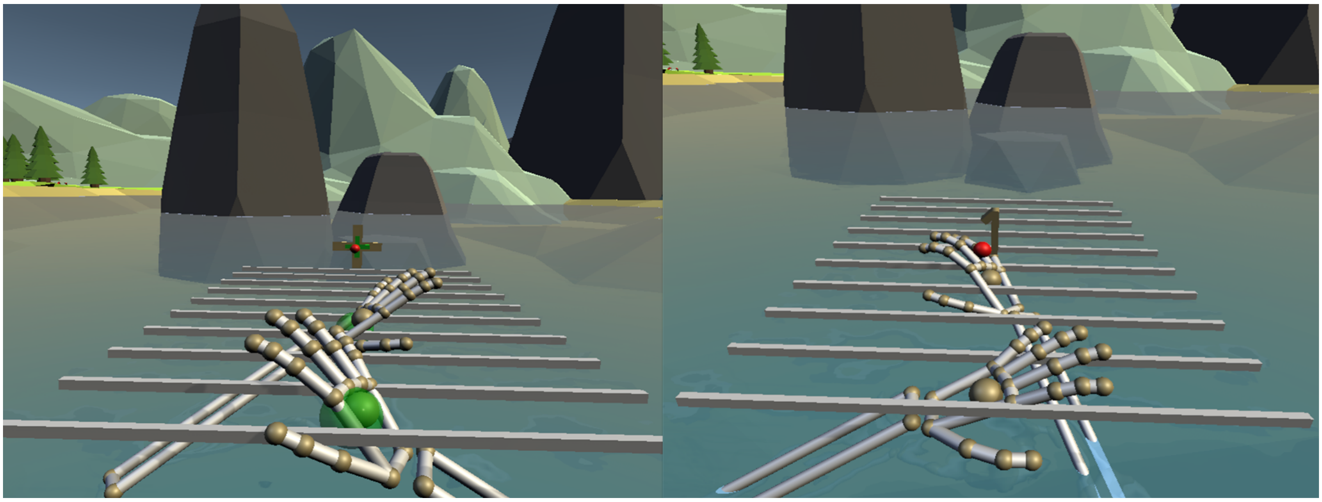


Note. The picture shows how far the participants had to close their hand to cause a response. The red sphere indicates the center of the visual field.

Figure 5 (left panel) shows the VR setup with the focused fixation cross and the hands in the starting position. When both criteria were met for 500 ms, the fixation cross and the spheres disappeared. After a stimulus onset delay (SOD) of 250 ms, a brown 3D mesh of an Arabic digit (either out of the range of 1 to 4 or of 6 to 9) was presented (see Figure 5). It was 9.17 cm in height and covered a visual angle of 19.36°, 13.40°, 9.38°, and 7.06° at the respective presentation distances of 10 cm, 30 cm, 50 cm, and 70 cm. Trials were canceled in the 250 ms SOD either when the participants clenched their fists or when the hands left the starting position. Trials were also canceled after a 2000 ms digit presentation without any response. All canceled trials were repeated at the end of the corresponding block. For time-outs (no response in 2000 ms), early movements (clenching a fist in the SOD), or wrong responses, the participants received respective feedback (time-outs: "please respond faster...", early response: "please stay in the starting position...", false response: "false response..."). The feedback was presented for 1000 ms at eye height, no matter where the participants looked. The participants could always take a break by not putting their hands in the starting position or not focusing on the fixation cross. However, they were asked to wear the HMD during the whole procedure.

Figure 5

Magnitude Comparison Task



Note. Starting position (left): The fixation cross is focused (the center of it has turned green), and the hands are in the correct position and opened (the spheres have turned green). Those two criteria had to be met to start a trial. Stimulus presentation (right): One of the single digits was presented at one of the distances. Participants had to classify this digit as smaller or larger than five by clenching either their left or right fist. The red sphere indicates the center of the visual field.

Analysis

Data Exclusion

Participants with less than 75% correct trials in any factor combinations were excluded from the response time analysis. Afterward, data from error trials and trials with a response time below 100 ms (this criterium was not preregistered; however, it excludes accidental reaction times as discussed in Whelan, 2008 and hence is important for the validity of the results) were excluded from our analysis. For the analysis of the MHC and MHCT, we additionally excluded MHCTs faster than 20 ms for technical reasons (this choice was ad-hoc, no strong standards exist in the literature for the exclusion of MHCTs) and participants who showed no changes in the closure of the incorrect hand.

Data Analysis

We used ANOVAs and linear mixed models (LMMs) to analyze response times, MHC, and MHCT. The reported *p*-values of the ANOVAs were adjusted with the Greenhouse-Geisser correction in case of sphericity violations. All *p*-values from *t*-tests were subjected to a Bonferroni-Holm adjustment. The significance level was .05. Pilot data, collected data, and analysis scripts are available in Supplementary Materials S4 – S7.

As the background section on the SNARC effect describes, a categorical predictor can better describe the SNARC effect in a magnitude judgment task. Hence, we merged all data from the digits 1 to 4 to the category small magnitudes (coded as -1) and the data from the digits 6 to 9 to the category large magnitudes (coded as 1). These categories were used for the analysis. We conducted a repeated measure ANOVA on the mean response times of correct responses to each number with spatial displacement, digit category, response hands, and response distances as factors. Additionally, we planned to conduct a corresponding LMM with a maximal random effects structure (Barr et al., 2013). However, as the LMM with a maximal random effect structure and one with only random main effects did not converge, this analysis is not described in the Results section. Supplementary Materials S9 reports the results from LMMs, including only random slopes for each participant. In the ANOVA and the LMM, a hand-based SNARC effect would be indicated by an interaction between the response hand and digit category (faster responses with the left hand for small digits and faster responses with the right hand for larger digits). A sagittal SNARC effect would be indicated by an interaction between response distance and digit category (faster responses with the close hand for small digits, faster responses with the far hand for larger digits). The analyses of MHC and MHCT were conducted the same way as the analyses of the response times.

We also conducted a linear regression with number magnitude and digit category as predictors for mean reaction times to investigate whether an additional variance is explained when the numerical magnitude is included. However, this analysis has a low power due to few observations.

The data from the IPQ questionnaire were compared with reference data provided by the igroup project consortium[6]. This comparison was made using independent sample *t*-tests on the three IPQ scales *spatial presence*, *involvement*, and *realism*.

Results

In addition to the preregistered analyses of the response times, MHC, and MHCT, further exploratory results are reported. For the response time analysis, we excluded 1009 trials (6% of the trials) in which the participants responded with the wrong hand, had a response time below 100 ms, or did not respond. The analysis of the IPQ data indicates that a sufficient level of immersion was reached during the experiment[7].

Response Times

The results of the repeated measures ANOVA on the response times are shown in Table 1. The ANOVA revealed significant interaction effects of response distance and digit category (sagittal SNARC effect; $F(1, 21) = 4.48$ $p = .046$, $\eta_p^2 = .18$) and response distance and spatial displacement (spatial congruency effect; $F(3, 63) = 64.18$, $p < .001$, $\eta_p^2 = .75$).

The interaction between response distance and digit category indicates the expected sagittal SNARC effect, as responses to small numbers were faster with the near hand (M_{near} = 624.81 ms) compared to the far hand (M_{far} = 656.37 ms; $t(21) = -4.28$, $p < .001$, Cohen's $d = 0.91$), while responses to large numbers did not differ (M_{near} = 645.20 ms, M_{far} = 648.61 ms; $t(21) = -0.37$, $p = .718$, Cohen's $d = 0.08$). The influence of the spatial displacement of the numbers did not yield a significant interaction with the sagittal SNARC effect. The effect size of the sagittal SNARC effect was largest when numbers were presented in extrapersonal space (Figure 6; very near: $t(21) = 1.45$, $p = .322$, Cohen's $d = 0.31$; near: $t(21) = 1.68$, $p = .322$, Cohen's $d = 0.36$; far: $t(21) = 1.59$, $p = .322$, Cohen's $d = 0.34$; very far: $t(21) = 2.37$, $p = .111$, Cohen's $d = 0.50$).

The interaction between response distance and spatial displacement showed a significant response time advantage when numbers were presented in the very near space, and the response was conducted with the near hand (M_{near} = 626.57 ms, M_{far} = 713.33 ms; $t(21) = -10.55$, $p < .001$, $\eta_p^2 = 2.25$). For all other spatial displacements, no difference was found (near: M_{near} = 633.31 ms, M_{far} = 647.23 ms; $t(21) = 1.34$, $p = .390$, $\eta_p^2 = 0.42$; far: M_{near} = 643.06 ms, M_{far} = 625.92 ms; $t(21) = 2.53$, $p = .059$ $\eta_p^2 = 0.54$; very far: M_{near} = 636.88 ms, M_{far} = 626.45 ms; $t(21) = 1.58$, $p = .389$, $\eta_p^2 = 0.34$).

Further, main effects of response distance (M_{near} = 634.87 ms, M_{far} = 652.34 ms; $F(1, 21) = 12.27$, $p = .002$, $\eta_p^2 = 0.37$), number magnitude (M_{small} = 640.39 ms, M_{large} = 646.63 ms; $F(1, 21) = 4.96$, $p = .037$, $\eta_p^2 = 0.19$), and spatial displacement ($M_{verynear}$ = 668.46 ms, M_{near} = 639.99 ms, M_{far} = 634.15 ms, $M_{veryfar}$ = 631.54 ms; $F(3, 63) = 24.67$, $p < .001$, $\eta_p^2 = 0.54$) were found. Further *t*-tests showed that the response times to numbers presented in the very near space were significantly larger compared to the response times to stimuli presented further away from the body (very near vs. near: $t(21) = 5.85$, $p < .001$, Cohen's $d = 1.25$; very near vs. far: $t(21) = 6.89$, $p < .001$, Cohen's $d = 1.47$; very near vs. very far: $t(21) = 7.00$, $p < .001$, Cohen's $d = 1.49$; all other tests: $p > .117$).

6) The data was obtained from participants playing video games equipped with HMD and is available at: http://www.igroup.org/pq/ipq/data.php. We used the data from 24 participants collected in a similar setup to ours. A description of the scale construction can be found at: http://www.igroup.org/pq/ipq/construction.php

7) The detailed results are reported in Supplementary Material S9.

Table 1

Repeated Measurement ANOVA

Predictor	df_{Num}	df_{Den}	F	p	η_p^2
(Intercept)	**1**	**21**	**2906.77**	**< .001*****	**0.99**
digit category	**1**	**21**	**4.96**	**.037***	**0.19**
response hand	1	21	0.31	.584	0.01
response distance	**1**	**21**	**12.27**	**.002****	**0.37**
digit category x response hand (hand-based SNARC)	1	21	2.41	.135	0.10
digit category x response distance (sagittal SNARC)	**1**	**21**	**4.48**	**.046***	**0.18**
response hand x response distance	1	21	1.53	.230	0.07
digit category x response hand x response distance (sagittal x hand-based SNARC)	1	21	1.40	.251	0.06
spatial displacement	**3**	**63**	**24.67**	**< .001*****	**0.54**
digit category x spatial displacement	3	63	1.17	.330	0.05
spatial displacement x response hand	3	63	0.11	.951	0.01
spatial displacement x response distance (spatial congruency effect)	**3**	**63**	**64.18**	**< .001*****	**0.75**
digit category x spatial displacement x response hand (hand-based SNARC x spatial displacement)	3	63	1.99	.124	0.09
digit category x spatial displacement x response distance (sagittal SNARC x spatial displacement)	3	63	0.20	.896	0.01
spatial displacement x response hand x response distance	3	63	0.08	.970	< 0.01
digit category x spatial displacement x response hand x response distance (hand-based SNARC x sagittal SNARC x spatial displacement)	3	63	0.14	.934	0.01

*p < .05. **p < .01. ***p < .001.

Linear Regression With Number Magnitude and Digit Category

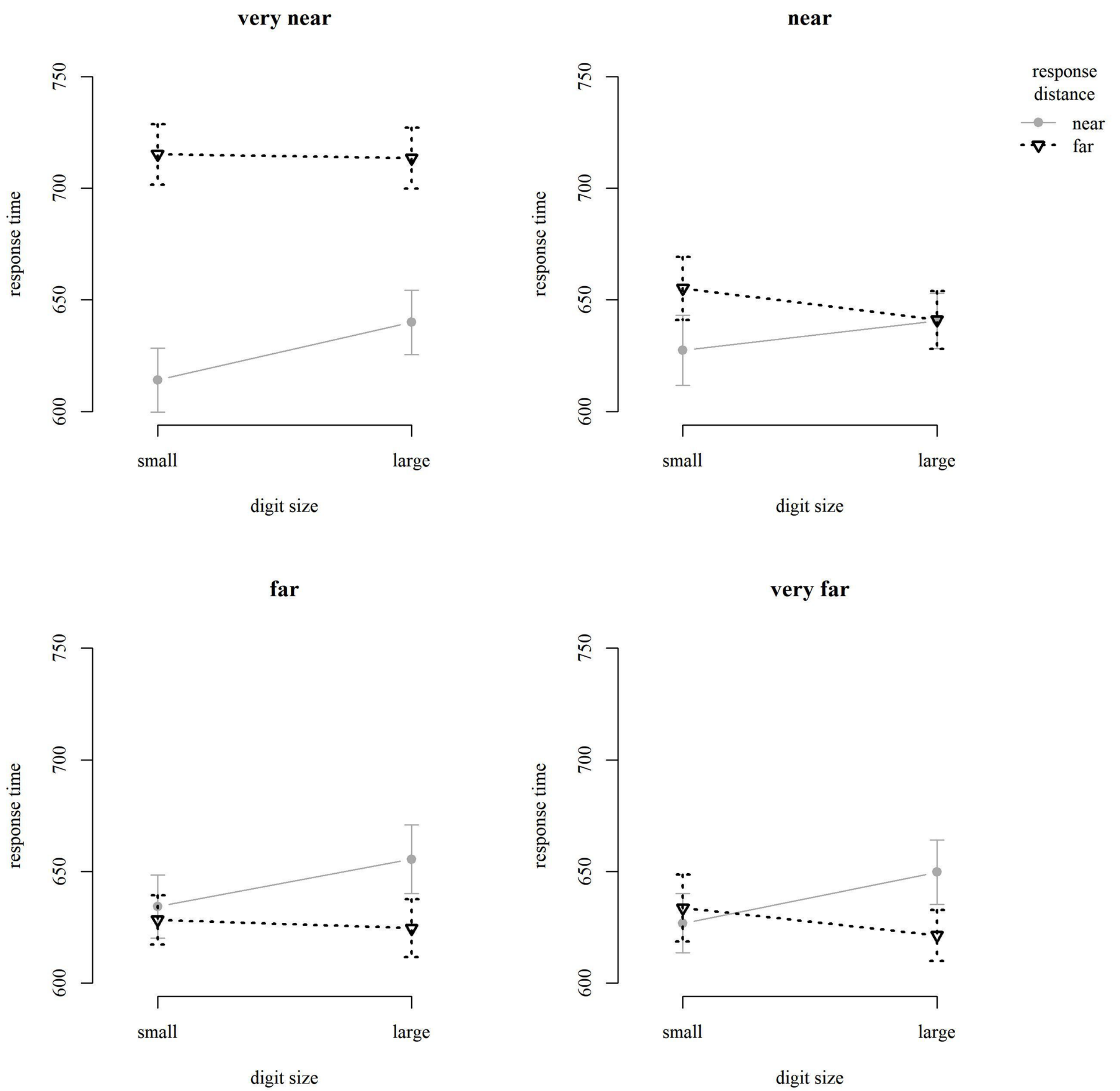
Including number magnitude (1, 2, 3, 4, 6, 7, 8, or 9) in addition to the magnitude (small or large) in a linear model predicting response time revealed similar results as the ANOVA on the response times with two main differences: significant interactions between the digit category and target magnitude (F(1, 21) = 236.60, p < .001, η_p^2 = 0.09) and response hand and response distance (F(1, 21) = 35.02, p < .001, η_p^2 = 0.35). Further, marginally significant interactions between digit category, target magnitude, response hand, and response distance (interaction between horizontal and sagittal SNARC-like effects; F(1, 21) = 3.90, p = .053, η_p^2 = 0.06) and between digit category, target magnitude, response hand, and response distance (sagittal SNARC-like effects; F(1, 64) = 2.94, p = .091, η_p^2 = 0.04) were found. No significant interaction between the response hand and digit category on response time was found (horizontal SNARC-like effect; F(1, 21) = 0.00, p = .961, η_p^2 < 0.01). An overview of all results can be found in Table 2.

The analysis of the MHC did not show any significant predictions (p > .058). The analysis of MHCT only revealed a significant interaction effect between response distance and spatial displacement (spatial congruency effect; F(3, 63) = 12.54, p < .001, η_p^2 = 0.37). The respective main effects of spatial displacement (F(3, 63) = 5.43, p = .002, η_p^2 = 0.21), and response distance (F(1, 19) = 4.86, p = .039, η_p^2 = 0.19) also got significant (all other tests p > .107)[8]. Hence, these analyses did not provide further information.

8) More detailed analyses can be found in Supplementary Materials S9.

Figure 6

The Sagittal SNARC Effect at the Different Spatial Displacements



Note. Bullets and triangles represent the mean of the participant's mean response times depending on the digit category and response distance. Error bars indicate the standard error of the mean. The main sagittal SNARC effect is significant but does not reach significance at any specific distance. Descriptively, the effect size grows with the stimulus distance to the body.

Explorative Results

Although not significant, the response times descriptively showed a hand-based SNARC pattern: Responses to small numbers were faster with the left compared to the right hand, and the response pattern to large numbers was reversed. So, while we do not wish to interpret non-significant results as significant, we want to notice that the non-significance of the results could also arise due to the low effect size and relatively low sample size. A further investigation of the hand-based SNARC for the different spatial displacements showed a marginally significant hand-based SNARC effect when the numbers were presented between the hands ($t(21) = 2.43$, $p = .097$, Cohen's $d = 0.52$; left bottom graphic in Figure 7).

Table 2

Results of Linear Regression With Target Magnitude and Digit Category to Predict Mean Response Times

Predictor	df_{Num}	df_{Den}	F	p	η_p^2
digit category	**1**	**21**	**6.32**	**.014***	**0.09**
target magnitude	1	21	2.64	.109	0.04
response hand	1	21	0.69	.410	0.01
response distance	**1**	**21**	**49.55**	**< .001*****	**0.44**
digit category x target magnitude	**1**	**21**	**235.60**	**< .001*****	**0.79**
digit category x response hand (hand-based SNARC)	1	21	0.00	.961	< 0.01
target magnitude x response hand (hand-based SNARC)	1	21	2.67	.107	0.04
digit category x target magnitude x response hand (hand-based SNARC)	1	21	0.01	.924	< 0.01
digit category x response distance (sagittal SNARC)	**1**	**64**	**5.43**	**.023***	**0.08**
target magnitude x response distance (sagittal SNARC)	1	64	0.06	.813	< 0.01
digit category x target magnitude x response distance (sagittal SNARC)	**1**	**64**	**2.94**	**.091†**	**0.04**
response hand x response distance	**1**	**64**	**35.02**	**< .001*****	**0.35**
digit category x response hand x response distance (sagittal x hand-based SNARC)	1	64	2.09	.153	0.03
target magnitude x response hand x response distance (sagittal x hand-based SNARC)	1	64	0.93	.339	0.01
digit category x target magnitude x response hand x response distance (sagittal x hand-based SNARC)	**1**	**64**	**3.90**	**.053†**	**0.06**
spatial displacement	**3**	**64**	**46.55**	**< .001*****	**0.68**
digit category x spatial displacement	3	64	0.61	.609	0.03
target magnitude x spatial displacement	3	64	0.25	.863	0.01
digit category x target magnitude x spatial displacement	3	64	1.34	.268	0.06
spatial displacement x response hand	3	64	0.09	.967	< 0.01
spatial displacement x response distance (spatial congruency effect)	**3**	**64**	**84.24**	**< .001*****	**0.80**
spatial displacement x response hand x response distance	3	64	0.15	.927	< 0.01
digit category x spatial displacement x response hand (hand-based SNARC x spatial displacement)	3	64	1.25	.299	0.06
target magnitude x spatial displacement x response hand (hand-based SNARC x spatial displacement)	3	64	1.64	.188	0.07
digit category x target magnitude x spatial displacement x response hand (hand-based SNARC x spatial displacement)	3	64	0.83	.481	0.04

Predictor	df_{Num}	df_{Den}	*F*	*p*	η_p^2
digit category x spatial displacement x response distance (sagittal SNARC x spatial congruency effect)	3	64	1.28	.290	0.06
target magnitude x spatial displacement x response distance (sagittal SNARC x spatial congruency effect)	3	64	1.97	.128	0.08
digit category x target magnitude x spatial displacement x response distance (sagittal SNARC x spatial congruency effect)	3	64	0.49	.690	0.02
digit category x spatial displacement x response hand x response distance (hand-based SNARC x sagittal SNARC x spatial displacement)	3	64	0.22	.879	0.01
target magnitude x spatial displacement x response hand x response distance (hand-based SNARC x sagittal SNARC x spatial displacement)	3	64	0.19	.904	< 0.01
digit category x target magnitude x spatial displacement x response hand x response distance (hand-based SNARC x sagittal SNARC x spatial displacement)	3	64	0.21	.887	< 0.01

[†] $p < .10$. * $p < .05$. ** $p < .01$. *** $p < .001$.

When the numbers were presented very near and far from the body, the hand-based SNARC effect did not reach significance (very near: $t(21) = 1.20$, $p = .535$, Cohen's $d = 0.26$; far: $t(21) = 1.34$, $p = .535$, Cohen's $d = 0.30$; see Figure 7 left panels). When the numbers were presented very far from the body (extrapersonal space), the effect size was very low and far from any significance ($t(21) = 0.28$, $p = .780$, Cohen's $d = 0.06$).

Additionally, we calculated the mean response times for each participant per combination of digit category spatial displacement, response distance, and response hand. We calculated dRTs to further analyze the hand-based (dRT: response time of the right minus response time of the left hand) and sagittal (dRT: response time of the far minus response time of the near hand) SNARC effect. Based on both the sagittal and hand-based dRTs, we conducted a linear regression for each person for each spatial displacement, predicting the dRTs for each digit category. The differences in the resulting beta-coefficients of the sagittal and hand-based dRTs between different spatial displacements were tested using two separate ANOVAs. The beta-coefficients of the horizontal hand-based and sagittal dRTs were compared. Note that both analyses are based on the same data but with different dRT tailored to different questions. The mean beta coefficients are shown in Table 3. We further analyzed the quadratic contrasts for the ANOVAs.

Both the ANOVA of the hand-based ($F(3, 63) = 2.07$, $p = .113$, $\eta_p^2 = .09$) as well as the ANOVA of the sagittal ($F(3, 63) = 0.30$, $p = .825$, $\eta_p^2 = .01$) dRT found no difference between the beta-coefficients for different spatial displacements (see Table 3). The analysis of the quadratic contrasts of the hand-based dRT revealed a marginally significant result ($t(63) = 1.71$, $p = .092$), indicating that the hand-based SNARC was largest near the effectors and then decreased with increasing distance from the effectors (corroborating Lohmann et al., 2018, who found similar results). The analysis of the quadratic contrasts of the sagittal dRT was non-significant ($t(63) = -0.77$, $p = .446$). The beta-coefficients of the hand-based and sagittal dRTs did not differ ($t(87) = 0.88$, $p = .379$).

Table 3

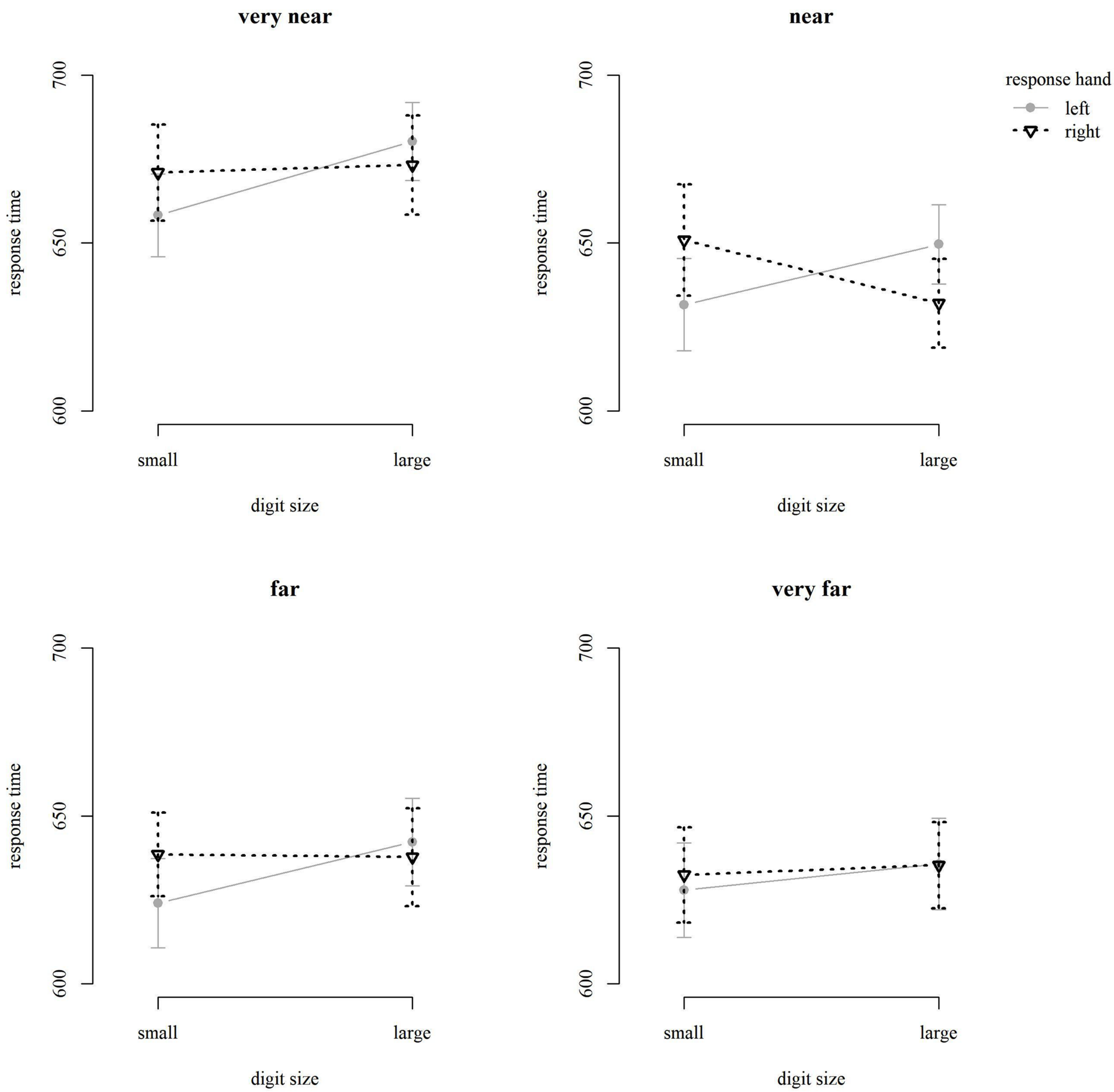
Mean Beta Coefficients

Spatial displacement	hand-based SNARC effect	Sagittal SNARC effect
very near	-19.92	-29.49
near	-37.32	-27.38
far	-19.12	-21.91
very far	-5.65	-35.46

Note. The mean was calculated over the beta coefficients, calculated per participant.

Figure 7

The Hand-Based SNARC Effect at the Different Spatial Displacements



Note. Bullets and triangles represent the mean of the participant's response times depending on the digit category, the response hand, and the spatial displacement. Error bars indicate the standard error of the mean. The main hand-based SNARC effect did not reach significance. However, it reached marginal significance when the numbers were presented at a near distance but not at any other distance.

Discussion

The current study examined the link between magnitude and action. More precisely, the study investigated the influence of peri- and extrapersonal space on the association between numbers and space concerning the hand-based and sagittal

SNARC effect. Therefore, participants performed a magnitude judgment task in a virtual reality environment while their hands were aligned on the sagittal axis, and the numbers were presented at different sagittal distances.

As expected, the sagittal response arrangement led to the emergence of the sagittal SNARC effect: With the near hand, response times to small numbers were smaller than response times to large numbers. Regarding the far hand, no such difference was found. The lack of a complete response time reversal can be explained by a problem size effect, i.e., that responses to small numbers were faster in all trials. However, no significant variation in effect sizes of the sagittal SNARC effect with distance was found. Descriptively, contrary to our hypotheses based on the literature, the sagittal SNARC effect size was largest in extrapersonal space.

In contrast to our hypotheses and the results from Lohmann et al. (2018), the hand-based SNARC effect was non-significant in the current study. Exploratory investigations showed a marginally significant hand-based SNARC effect when the numbers were presented between the hands. Hand-based SNARC effect sizes were non-significant (and descriptively smaller) in all other cases. An exploratory trend analysis on the hand-based dRT showed a marginally significant quadratic trend, corroborating this observation. If any indication of a SNARC effect was observed, it tended to be largest between the hands and then dropped off to both sides. Note, however, that this effect was marginally significant; therefore, we report it as it is in line with previous literature (Lohmann et al., 2018) but do not base strong conclusions on this marginally significant result.

Nevertheless, the question remains why the hand-based SNARC was significant in Lohmann et al. (2018) and Aleotti et al. (2023) but not (or at the most marginally) significant in our study. The main difference between the experiment conducted by Lohmann et al. (2018) and the current one is the response layout. The different response layouts could strengthen different SNARC effects. This seems to further align with Aleotti et al. (2023). They found both the sagittal and hand-based SNARC. However, their response layout also primed both the horizontal and the sagittal axes: They arranged the responses diagonally with differences on all three axes. Hence, the response layout primed all three axes (Aleotti et al., 2020 used a similar response layout that primed more than one axis). In contrast, our response layout primed only the sagittal axis; the hands might not have been salient enough to produce the hand-based SNARC effects in the present setup. When the horizontal axis is also primed, as in Aleotti et al. (2023), the hand-based SNARC effect might be more salient and more significant.

In addition to the hypothesized results, we found a purely spatial congruency effect between response hand and target displacement. Responses were faster when the response hand was closer to the stimulus than in trials in which it was further away. This effect in our study is in line with, for example, the near-hand effect (Reed et al., 2006) and the Simon effect (Simon & Rudell, 1967), which yield faster responses to stimuli close to the hands and response properties and generalized previous findings from real-life experiments in mostly horizontal space to sagittal virtual 3D space. Moreover, in our study, the observed spatial congruency effect was strongest when the numbers were presented very close to the body. In the far condition, the far hand reaction time was faster than the near hand only with marginal significance. The difference did not reach significance in the very far condition outside of peripersonal space. Similarly, the difference favors the hand closer to the body in the near condition, but this did not reach significance. Thus, the spatial congruency effect is mainly based on significant differences in the conditions when numbers were presented very close to the body. Effects for all other distances were not or, at best, marginally significant.

The significant interaction of the response hand and response distance found in the linear regression implies that it is more natural to hold the right hand in front of the left instead of vice versa. This could indicate an association between the right hand with the far space and the left with the near space.

Further, a marginally significant four-way interaction effect of response hand, response distance, digit category, and number magnitude on the response time in the linear regression was found. While we do not wish to interpret non-significant results as significant, we want to notice that the non-significance of the results could also arise due to the low effect size and relatively low sample size. Further studies with a larger sample size are necessary to validate or dismiss this result.

Implications

In contrast to Lohmann et al. (2018), we found a sagittal and no (or at best marginally) significant hand-based SNARC effect, with the only main change between these experiments being the response layout. These results support the assumption of a general magnitude system that is rooted in, or closely linked to, sensorimotor experience, as proposed by ATOM (Bueti & Walsh, 2009; Walsh, 2003), as well as a bidirectional mapping between motor commands and sensory changes, as described in common codes (Hommel et al., 2001). They even align with more general theories of task processing and the resource-oriented pre-activation of task sets for particular events (Butz, 2022; Frings et al., 2020; Heald et al., 2021; Heald et al., 2023). Such task sets may include numbers expected to be processed, which would be in line with the working memory account of the SNARC effect (van Dijck & Fias, 2011; van Dijck et al., 2009). Moreover, trial preparations may pre-activate possible stimulus locations in space, inducing a sagittal stimulus axis, the possible sagittal response locations, and horizontal left versus right response decisions.

Response-influencing interactions unfold on modal sensory- and motor-respective axes as well as on somewhat amodal, magnitude-respective axial arrangements. Thereby, a multitude of axial interactions applies, including purely spatial compatibility effects, which side-step the amodal magnitude component, and magnitude-dependent interactions, which reveal flexible bidirectional modal-to-amodal associations.

Conclusion

In this preregistered report, we intended to examine the proposed grounding of magnitude processing in the sensorimotor system. We initially expected to find a hand-based and a sagittal SNARC effect. Moreover, we expected both SNARC effects to decrease with a larger distance between digit and hands because we expected that reachability would influence the strength of the axial activities. In line with our expectations, we found a sagittal SNARC effect, but unexpectedly, the hand-based SNARC effect did not reach significance. These results further indicate the influence of the response layout on the mental orientation of the number representation. Meanwhile, purely spatial compatibility effects play a significant role, which we had not considered sufficiently when proposing the study.

Moreover, several of the results should be scrutinized further. For example, it should be investigated whether spatial compatibility effects systematically differ from magnitude-mediated effects. Do they yield respective response biases simply in a weighted, linear manner? Do the sagittal and the hand-based SNARC effect both occur with larger sample sizes? Do they interact? We believe that further experimental studies will help to answer these questions. However, probably only an actual process model implementation will be able to fully explain the observed effects on David Marr's computational and algorithmic levels (Marr, 1982), aiming at generating predictions about sequential trial dynamics (Butz, 2022; Heald et al., 2021; Heald et al., 2023; Steyvers et al., 2019; Zénon et al., 2019) and about the performance in related but different stimulus and response arrangements.

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Data Availability: All research data and materials to replicate the findings are publicly available (see Koch et al., 2023).

Supplementary Materials

The Supplementary Materials include the following items:

- The pre-registration protocol of the current study (see Koch et al., 2021)
- The experimental code, stimuli, participant data, data analysis scripts, additional analyses, and more supplementary material (see Koch et al., 2023)

Index of Supplementary Materials

Koch, N., Lohmann, J., Butz, M. V., & Nuerk, H. (2021). *Supplementary materials to "Embodied magnitude processing: On the relation between the SNARC effect and perceived reachability"* [Pre-registration protocol]. OSF Registries. https://doi.org/10.17605/OSF.IO/53F6X

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References

Aleotti, S., Di Girolamo, F., Massaccesi, S., & Priftis, K. (2020). Numbers around Descartes: A preregistered study on the three-dimensional SNARC effect. *Cognition, 195*, Article 104111. https://doi.org/10.1016/j.cognition.2019.104111

Aleotti, S., Massaccesi, S., & Priftis, K. (2023). The SNARC effect: A preregistered study on the interaction of horizontal, vertical, and sagittal spatial–numerical associations. *Psychological Research, 87*(4), 1256–1266. https://doi.org/10.1007/s00426-022-01721-8

Andres, M., Davare, M., Pesenti, M., Olivier, E., & Seron, X. (2004). Number magnitude and grip aperture interaction. *Neuroreport, 15*(18), 2773–2777.

Bae, G. Y., Choi, J. M., Cho, Y. S., & Proctor, R. W. (2009). Transfer of magnitude and spatial mappings to the SNARC effect for parity judgments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(6), 1506–1521. https://doi.org/10.1037/a0017257

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society of London: Series B. Biological Sciences, 364*(1525), 1831–1840. https://doi.org/10.1098/rstb.2009.0028

Bufacchi, R. J., & Iannetti, G. D. (2018). An action field theory of peripersonal space. *Trends in Cognitive Sciences, 22*(12), 1076–1090. https://doi.org/10.1016/j.tics.2018.09.004

Bull, R., Cleland, A. A., & Mitchell, T. (2013). Sex differences in the spatial representation of number. *Journal of Experimental Psychology: General, 142*(1), 181–192. https://doi.org/10.1037/a0028387

Butz, M. V. (2022). Resourceful event-predictive inference: The nature of cognitive effort. *Frontiers in Psychology, 13*, Article 867328. https://doi.org/10.3389/fpsyg.2022.867328

Canzoneri, E., Magosso, E., & Serino, A. (2012). Dynamic sounds capture the boundaries of peripersonal space representation in humans. *PLoS One, 7*(9), Article e44306. https://doi.org/10.1371/journal.pone.0044306

Cipora, K., Soltanlou, M., Reips, U.-D., & Nuerk, H.-C. (2019). The SNARC and MARC effects measured online: Large-scale assessment methods in flexible cognitive effects. *Behavior Research Methods, 51*(4), 1676–1692. https://doi.org/10.3758/s13428-019-01213-5

Cléry, J., Guipponi, O., Wardak, C., & Hamed, S. B. (2015). Neuronal bases of peripersonal and extrapersonal spaces, their plasticity and their dynamics: Knowns and unknowns. *Neuropsychologia, 70*, 313–326. https://doi.org/10.1016/j.neuropsychologia.2014.10.022

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

Fabbri, M. (2013). Finger counting habits and spatial-numerical association in horizontal and vertical orientations. *Journal of Cognition and Culture, 13*(1–2), 95–110. https://doi.org/10.1163/15685373-12342086

Fagioli, S., Hommel, B., & Schubotz, R. I. (2007). Intentional control of attention: Action planning primes action-related stimulus dimensions. *Psychological Research, 71*(1), 22–29. https://doi.org/10.1007/s00426-005-0033-3

Fischer, M. H. (2005). Perceived reachability: The roles of handedness and hemifield. *Experimental Brain Research, 160*(3), 283–289. https://doi.org/10.1007/s00221-004-2007-x

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

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., & Moeller, B. (2020). Binding and retrieval in action control (BRAC). *Trends in Cognitive Sciences, 24*(5), 375–387. https://doi.org/10.1016/j.tics.2020.02.004

Gamberini, L., Seraglia, B., & Priftis, K. (2008). Processing of peripersonal and extrapersonal space using tools: Evidence from visual line bisection in real and virtual environments. *Neuropsychologia, 46*(5), 1298–1304. https://doi.org/10.1016/j.neuropsychologia.2007.12.016

Georges, C., Hoffmann, D., & Schiltz, C. (2017). How and why do number-space associations co-vary in implicit and explicit magnitude processing tasks? *Journal of Numerical Cognition, 3*(2), 182–211. https://doi.org/10.5964/jnc.v3i2.46

Gevers, W., Lammertyn, J., Notebaert, W., Verguts, T., & Fias, W. (2006). Automatic response activation of implicit spatial information: Evidence from the SNARC effect. *Acta Psychologica, 122*(3), 221–233. https://doi.org/10.1016/j.actpsy.2005.11.004

Gevers, W., Santens, S., Dhooge, E., Chen, Q., Van den Bossche, L., Fias, W., & Verguts, T. (2010). Verbal-spatial and visuospatial coding of number–space interactions. *Journal of Experimental Psychology: General, 139*(1), 180–190. https://doi.org/10.1037/a0017688

Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: A computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance, 32*(1), 32–44. https://doi.org/10.1037/0096-1523.32.1.32

Göbel, S. M. (2015). Up or down? Reading direction influences vertical counting direction in the horizontal plane–A cross-cultural comparison. *Frontiers in Psychology, 6*, Article 228. https://doi.org/10.3389/fpsyg.2015.00228

Gronau, N., Izoutcheev, A., Nave, T., & Henik, A. (2017). Counting distance: Effects of egocentric distance on numerical perception. *PLoS One, 12*(4), Article e0174772. https://doi.org/10.1371/journal.pone.0174772

Hartmann, M., Gashaj, V., Stahnke, A., & Mast, F. W. (2014). There is more than "more is up": Hand and foot responses reverse the vertical association of number magnitudes. *Journal of Experimental Psychology: Human Perception and Performance, 40*(4), 1401–1414. https://doi.org/10.1037/a0036686

Heald, J. B., Lengyel, M., & Wolpert, D. M. (2021). Contextual inference underlies the learning of sensorimotor repertoires. *Nature, 600*(7889), 489–493. https://doi.org/10.1038/s41586-021-04129-3

Heald, J. B., Lengyel, M., & Wolpert, D. M. (2023). Contextual inference in learning and memory. *Trends in Cognitive Sciences, 27*(1), 43–64. https://doi.org/10.1016/j.tics.2022.10.004

Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory & Cognition, 10*(4), 389–395. https://doi.org/10.3758/BF03202431

Hesse, P. N., & Bremmer, F. (2017). The SNARC effect in two dimensions: Evidence for a frontoparallel mental number plane. *Vision Research, 130*, 85–96. https://doi.org/10.1016/j.visres.2016.10.007

Hoffmann, D., Mussolin, C., Martin, R., & Schiltz, C. (2014). The impact of mathematical proficiency on the number-space association. *PLoS One, 9*(1), Article e85048. https://doi.org/10.1371/journal.pone.0085048

Hoffmann, J. (1993). *Vorhersage und Erkenntnis: Die Funktion von Antizipationen in der Menschlichen Verhaltenssteuerung und Wahrnehmung*. Hogrefe.

Hommel, B., Musseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24*(5), 849–878. https://doi.org/10.1017/S0140525X01000103

Jordan, J. S., Stork, S., Knuf, L., Kerzel, D., & Muesseler, J. (2002). Action planning affects spatial localization. In W. Prinz & B. Hommel (Eds.), *Attention and performance XIX: Common mechanisms in perception and action* (pp. 158–176). Oxford University Press.

Kirsch, W. (2015). Impact of action planning on spatial perception: Attention matters. *Acta Psychologica, 156*, 22–31. https://doi.org/10.1016/j.actpsy.2015.01.002

Li, M., Zhang, E., Zhang, Y., Fanga, X., & Li, Q. (2017). Flexible verbal–spatial mapping in the horizontal and vertical SNARC effects of mainland Chinese readers. *The American Journal of Psychology, 130*(3), 339–351. https://doi.org/10.5406/amerjpsyc.130.3.0339

Lindemann, O., Abolafia, J. M., Girardi, G., & Bekkering, H. (2007). Getting a grip on numbers: Numerical magnitude priming in object grasping. *Journal of Experimental Psychology: Human Perception and Performance, 33*(6), 1400–1409. https://doi.org/10.1037/0096-1523.33.6.1400

Linkenauger, S. A., Bulthoff, H. H., & Mohler, B. J. (2015). Virtual arm's reach influences perceived distances but only after experience reaching. *Neuropsychologia, 70*, 393–401. https://doi.org/10.1016/j.neuropsychologia.2014.10.034

Lohmann, J., Schroeder, P. A., Nuerk, H.-C., Plewnia, C., & Butz, M. V. (2018). How deep is your SNARC? Interactions between numerical magnitude, response hands, and reachability in peripersonal space. *Frontiers in Psychology, 9*, Article 622. https://doi.org/10.3389/fpsyg.2018.00622

Marghetis, T., & Youngstrom, K. (2014). Pierced by the number line: Integers are associated with back-to-front sagittal space. In P. Bello, M. Guarini, M. McShane, & B. Scassellati (Eds.), *Proceedings of the 36th Annual Meeting of the Cognitive Science Society* (pp. 946–951). Cognitive Science Society.

Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual Information.* MIT press.

Mohler, B. J., Buelthoff, H. H., Thompson, W. B., & Creem-Regehr, S. H. (2008). A full-body avatar improves egocentric distance judgments in an immersive virtual environment. In S. H. Creem-Regehr & K. Myszkowski (Eds.), *Proceedings of the 5th Symposium on Applied Perception in Graphics and Visualization, APGV 2008, Los Angeles, California, USA, August 9-10, 2008* (pp. 194–197). https://doi.org/10.1145/1394281.1394323

Mourad, A., & Leth-Steensen, C. (2017). Spatial reference frames and SNARC. *Journal of Cognitive Psychology, 29*(2), 113–128. https://doi.org/10.1080/20445911.2016.1249483

Müller, D., & Schwarz, W. (2007). Is there an internal association of numbers to hands? The task set influences the nature of the SNARC effect. *Memory & Cognition, 35*(5), 1151–1161. https://doi.org/10.3758/BF03193485

Nuerk, H.-C., Wood, G., & Willmes, K. (2005). The universal SNARC effect: The association between number magnitude and space is amodal. *Experimental Psychology, 52*(3), 187–194. https://doi.org/10.1027/1618-3169.52.3.187

Prinz, W. (1990). A common coding approach to perception and action. In D. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167–201). Springer.

Reed, C. L., Grubb, J. D., & Steele, C. (2006). Hands up: Attentional prioritization of space near the hand. *Journal of Experimental Psychology: Human Perception and Performance, 32*(1), 166–177. https://doi.org/10.1037/0096-1523.32.1.166

Sambo, C. F., & Iannetti, G. D. (2013). Better safe than sorry? The safety margin surrounding the body is increased by anxiety. *The Journal of Neuroscience, 33*(35), 14225–14230. https://doi.org/10.1523/JNEUROSCI.0706-13.2013

Santens, S., & Gevers, W. (2008). The SNARC effect does not imply a mental number line. *Cognition, 108*(1), 263–270. https://doi.org/10.1016/j.cognition.2008.01.002

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence, 10*(3), 266–281. https://doi.org/10.1162/105474601300343603

Shaki, S., & Fischer, M. H. (2014). Random walks on the mental number line. *Experimental Brain Research, 232*(1), 43–49. https://doi.org/10.1007/s00221-013-3718-7

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

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review, 16*(2), 328–331. https://doi.org/10.3758/PBR.16.2.328

Simon, J. R., & Rudell, A. P. (1967). Auditory SR compatibility: The effect of an irrelevant cue on information processing. *The Journal of Applied Psychology, 51*(3), 300–304. https://doi.org/10.1037/h0020586

Sixtus, E., Lonnemann, J., Fischer, M. H., & Werner, K. (2019). Mental number representations in 2D space. *Frontiers in Psychology, 10*, Article 172. https://doi.org/10.3389/fpsyg.2019.00172

Steyvers, M., Hawkins, G. E., Karayanidis, F., & Brown, S. D. (2019). A large-scale analysis of task switching practice effects across the lifespan. *Proceedings of the National Academy of Sciences of the United States of America, 116*(36), 17735–17740. https://doi.org/10.1073/pnas.1906788116

Tschentscher, N., Hauk, O., Fischer, M. H., & Pulvermüller, F. (2012). You can count on the motor cortex: Finger counting habits modulate motor cortex activation evoked by numbers. *NeuroImage, 59*(4), 3139–3148. https://doi.org/10.1016/j.neuroimage.2011.11.037

Tseng, P., Bridgeman, B., & Juan, C.-H. (2012). Take the matter into your own hands: A brief review of the effect of nearby-hands on visual processing. *Vision Research, 72*, 74–77. https://doi.org/10.1016/j.visres.2012.09.005

van Dijck, J.-P., & Fias, W. (2011). A working memory account for spatial–numerical associations. *Cognition, 119*(1), 114–119. https://doi.org/10.1016/j.cognition.2010.12.013

van Dijck, J.-P., Gevers, W., & Fias, W. (2009). Numbers are associated with different types of spatial information depending on the task. *Cognition, 113*(2), 248–253. https://doi.org/10.1016/j.cognition.2009.08.005

Viarouge, A., Hubbard, E. M., & Dehaene, S. (2014). The organization of spatial reference frames involved in the SNARC effect. *Quarterly Journal of Experimental Psychology, 67*(8), 1484–1499. https://doi.org/10.1080/17470218.2014.897358

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483–488. https://doi.org/10.1016/j.tics.2003.09.002

Wasner, M., Moeller, K., Fischer, M. H., & Nuerk, H.-C. (2014). Aspects of situated cognition in embodied numerosity: The case of finger counting. *Cognitive Processing, 15*(3), 317–328. https://doi.org/10.1007/s10339-014-0599-z

Weis, T., Nuerk, H.-C., & Lachmann, T. (2018). Attention allows the SNARC effect to operate on multiple number lines. *Scientific Reports, 8*(1), Article 13778. https://doi.org/10.1038/s41598-018-32174-y

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record, 58*(3), 475–482. https://doi.org/10.1007/BF03395630

Wiemers, M., Bekkering, H., & Lindemann, O. (2017). Is more always up? Evidence for a preference of hand-based associations over vertical number mappings. *Journal of Cognitive Psychology, 29*(5), 642–652. https://doi.org/10.1080/20445911.2017.1302451

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

Wood, G., Nuerk, H.-C., & Willmes, K. (2006). Crossed hands and the SNARC effect: A failure to replicate Dehaene, Bossini and Giraux (1993). *Cortex, 42*(8), 1069–1079. https://doi.org/10.1016/S0010-9452(08)70219-3

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

Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture, 5*(1-2), 165–190. https://doi.org/10.1163/1568537054068660

Zénon, A., Solopchuk, O., & Pezzulo, G. (2019). An information-theoretic perspective on the costs of cognition. *Neuropsychologia, 123*, 5–18. https://doi.org/10.1016/j.neuropsychologia.2018.09.013

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