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Is more always up? Evidence for a preference of hand-based associations over vertical number mappings

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ABSTRACT

It has been argued that the association of numbers and vertical space plays a fundamental role for the understanding of numerical concepts. However, convincing evidence for an association of numbers and vertical bimanual responses is still lacking. The present study tests the vertical Spatio-Numerical-Association-of-Response-Codes (SNARC) effect in a number classification task by comparing anatomical hand-based and spatial associations. A mixed effects model of linear spatial-numerical associations revealed no evidence for a vertical but clear support for an anatomical SNARC effect. Only if the task requirements prevented participants from using a number-hand association due to frequently alternating hand-to-button assignments, numbers were associated with the vertical dimension. Taken together, the present findings question the importance of vertical associations for the conceptual understanding of numerical magnitude as hypothesised by some embodied approaches to number cognition and suggest a preference for ego- over geocentric reference frames for the mapping of numbers onto space.

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SNARC effect; embodied numerosity; numerical cognition

Research on number cognition in the last decades has revealed strong evidence for close associations between numerical knowledge and space (Hubbard, Piazza, Pinel, & Dehaene, 2005). For instance, for number classification tasks with bimanual responses, the participant tends to respond faster with the left hand to small numbers and with the right hand to large numbers (Spatio-Numerical-Association-of-Response-Codes, SNARC effect; Dehaene, Bossini, & Giraux, 1993). This horizontal mapping of number onto space has been metaphorically described with the presence of a mental number line. Recent theories suggest, however, that spatio-numerical mappings are not limited to the horizontal dimension and also exist on the vertical dimension (Fischer & Brugger, 2011; Lakoff, 1987; Proctor & Cho, 2006). This idea is based on strong correlations between vertical position and magnitude in the environment (“more is up, less is down”). One might think of actions like pouring water into a glass or piling objects. Accordingly, the ground represents the natural zero-point and gravity serves as a stable

and fundamental reference frame for vertically increasing magnitude, which together provides an intuitive grounding for number concepts (Clark, 1973). Crucially, in contrast to vertical space, there are no physical constants that put constraints on the natural alignment of objects in horizontal space. As a consequence, it has been hypothesised that vertical spatio-numerical associations are more stable and less sensitive to interference than horizontal spatio-numerical associations (Fischer & Brugger, 2011; Lindemann & Fischer, 2015), which have been linked to flexible or strategic task-specific processing (Lindemann, Abolafia, Pratt, & Bekkering, 2008; van Dijck & Fias, 2011). The polarity correspondence principle account predicts the same strength of association along the vertical dimension as along the horizontal dimension, because vertical space is mapped to negative (down) or positive (up) polarities as the horizontal dimension and the numerical magnitudes (Proctor & Cho, 2006). The current study now aims to examine the robustness of the vertical against the horizontal or anatomical mapping.

Evidence for a mapping of number and vertical space has been provided by studies using random number generation (Hartmann, Grabherr, & Mast, 2012; Loetscher, Bockisch, Nicholls, & Brugger, 2010). If participants are instructed to name random numbers while performing upward and downward head or body motions, they tend to generate larger numbers while moving upwards and smaller numbers moving downwards (Hartmann et al., 2012; Winter & Matlock, 2013). Moreover, it has also been observed that participants generate more upward oriented eye movements during the generation of large compared to small numbers (Loetscher et al., 2010).

However, there are merely few studies that directly compared vertical to horizontal spatio-numerical associations (Holmes & Lourenco, 2012; Wiemers, Bekkering, & Lindemann, 2014; Winter & Matlock, 2013). Initial evidence for the predominance of vertical mappings has been provided by Winter and Matlock (2013) who showed that vertical associations in random number generation are stronger than horizontal associations. In the same vein, Wiemers et al. (2014) found that performance in mental arithmetic is stronger influenced by vertical than horizontal eye and arm movements (but see also Knops, Viarouge, & Dehaene, 2009). That is, the authors observed that mental additions are impaired by downward as compared to upward eye movements and subtractions are more impaired by upward as compared to downward eye movements. A comparable effect for the horizontal dimension could not be observed. It is however so far unclear if this spatial effect in mental arithmetic can be generalised to the mere processing of small and large numbers.

Another approach to test the predicted predominance of vertical spatio-numerical couplings is by means of bimanual number classification tasks with vertically aligned response buttons and a systematic manipulation of the hand-to-button assignment. This way, vertical and hand-based anatomical numerical associations, that is, a mapping of number size with the left or right hand, can be directly tested against each other. If the task requires to press the upper response button with the right hand and the lower button with left hand, effects of vertical and anatomical associations of individuals are confounded with a left-to-right oriented mental number line and can thus not be distinguished. However, if the left hand is linked to the upper button effects of anatomical and vertical

associations operate in opposite directions. Hand-to-button assignments have been examined in studies on the spatial association of numbers along the sagittal dimension (Hung, Hung, Tzeng, & Wu, 2008; Ito & Hatta, 2004; Müller & Schwarz, 2007; Shaki & Fischer, 2012; Viarouge, Hubbard, & Dehaene, 2014). In these experiments, participants were required to classify numbers by pressing one of two sagittally aligned response buttons, that is, responses were characterised by either a button press close or far from the body. Ito and Hatta (2004) as well as Shaki and Fischer (2012) performed two separate analyses for each hand-to-button assignment to prove the presence of a sagittal SNARC effect. That is, both analyses revealed that pressing the button far away from the body was faster in response for large digits and pressing the button close to the body faster in response to small digits. Another approach to statistically test the two conflicting associations was chosen by Müller and Schwarz (2007). The authors used a single multi-factorial analysis that showed the presence of the sagittal SNARC effect coinciding with an absence of the anatomical SNARC effect (see also Hung et al. (2008) for a similar approach). Moreover, evidence for number associations along the sagittal dimension has also been found for unimanual movements away or towards the body (Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006).

Crucially, as mentioned above an embodied approach to number cognition (Lindemann & Fischer, 2015) suggests stronger spatial mappings of numerical magnitude representations along the vertical dimension, because gravity and the ground as zero-point are natural constants in the environment which put constraints on the alignment of objects in vertical space (Fischer & Brugger, 2011; Lakoff, 1987). Importantly, as pointed out by Winter, Matlock, Shaki, and Fischer (2015), cognitive associations with sagittal and vertical dimensions have to be distinguished conceptually. As a consequence, effects of sagittal number-response mappings do not necessarily reflect a potential coupling of vertical spatio-numerical association. Research on spatial cognition distinguishes between representations based on an egocentric and allo- or geocentric frame of reference (see Klatzky, 1998). A location might be coded in relation to the own body (egocentric) or with respect to another object (allocentric) or, in the case of the vertical dimension, to the ground (geocentric). According to this classification, we interpret a sagittal spatial-numerical association as an

egocentric mapping of numbers with distances towards the own body (Gevers et al., 2006). Vertical associations, however, need to be conceived as distance-based with respect to the ground and do therefore represent a geocentric mapping. Taken together this illustrates that effects of sagittally aligned responses as reported previously are not suited to test the presence of vertical spatio-numerical associations.

Surprisingly, a closer look at the literature reveals that there is no convincing evidence for a vertical SNARC effect from number classification tasks. While Schwarz and Keus (2004) reported an interference between vertical saccades and small and large numbers, so far only two studies investigated SNARC effects using bimanual responses which allows a direct comparison of horizontal or anatomical associations with vertical associations (Hartmann, Gashaj, Stahnke, & Mast, 2014; Holmes & Lourenco, 2012). Holmes and Lourenco (2012) compared horizontal and vertical couplings with touchscreen responses and did not observe evidence for the presence of vertical SNARC effect. However, since hand positions and hand-to-response mappings were not controlled in this study, a conclusive interpretation of the absence of vertical associations might be difficult. One experiment reported by Hartmann et al. (2014; Experiment 1) examined true vertical number associations by using two vertically aligned buttons placed in front of the standing participants. The hand-to-button assignment was varied and evidence for a vertical spatial-numerical association was observed by showing a vertical SNARC effect in the absence of an anatomical effect. That is, in line with an embodied view on number cognition, small numbers were associated with “down” and large numbers were associated with “up” responses. Surprisingly, however, this down-to-up spatial mapping could not be replicated and reversed if participants indicated the judgments with hand and foot responses (Experiments 2–4). The change of the mapping for different motor effectors might be related to an association between number size and the different body parts but might also suggest that the mapping along the vertical dimension is not as robust as along the sagittal or horizontal dimension.

Taken together, evidence for vertical spatio-numerical couplings is exclusively based on studies on random number generation or mental arithmetic, since strong support for the dominance of vertical associations over anatomical mappings in bimanual

number classifications has not been shown yet. Since a test of the grounding hypothesis of vertical spatio-numerical couplings requires responses coded in a vertical geocentric reference frame, a SNARC effect with sagittal responses, which yields an egocentric reference frame, does not provide evidence for vertical spatio-numerical associations in number classifications. Considering the few studies that exist on the truly vertical SNARC effect and the mixed findings they have produced, we believe that an additional test of the robustness of the vertical SNARC effect in bimanual parity judgments is necessary (Aarts et al., 2015). Since the study by Hartmann et al. (2014) reflects the first report of a bimanual vertical SNARC effect, we set out to provide a replication of its findings. In order to do this, we instructed participants to perform speeded single-digit parity judgments with vertically aligned responses. As mentioned above, the only two previous studies that tested SNARC effects in parity judgment with vertically aligned responses provided conflicting results (Hartmann et al., 2014; Holmes & Lourenco, 2012). Since Holmes and Lourenco did not control the hand-to-response mapping, which makes the results difficult to interpret, we predict, based on the findings from Hartmann et al., a vertical SNARC effect, that is, a facilitation of down/up responses by small/large numbers.

General method

Participants

Sixty-six students from the Radboud University Nijmegen (53 female, mean age 22.16 years) took part in the experiment, in return for course credits or vouchers. All were naive regarding the purpose of the experiment, had normal or corrected-to-normal vision and were free of any motor problems that could affect performance on the tasks being used in the experiment.

Stimuli and procedure

Experimental software, raw data and analysis scripts are available via the OSF platform: <http://osf.io/5bc7v/>. In all experiments, participants were instructed to indicate the parity of a number with a button press as fast as possible without making errors. The hand-to-button (left-up or right-up) and parity-to-button mappings (up-odd or up-

even) were presented on the screen at the start of the experiment and once when mappings changed. The stimuli consisted of Arabic digits ranging from 1 to 9 (except 5) plotted in black serif font and a black fixation cross which all were of a size of approximately 1.00° visual angle each plotted on a light grey background.

Each trial started with the presentation of the fixation cross for a random interval of 1000 to 1500 ms. Afterwards, the digit was presented and disappeared after response detection or after a maximum duration of 1500 ms. Following a correct response, a blank screen was presented for 1000 ms. After an erroneous or missing response, the words “wrong” or “too slow” were presented in red capital letters for 4 s. Feedback on average accuracy and speed of responding was provided at the end of each block.

Apparatus

The experiment was controlled using the Python software package Expyriment (Krause & Lindemann, 2014). Stimuli were presented on a 19" TFT monitor placed at approximately 70 cm viewing distance in front of the participant. For response detection, we used two custom-made buttons, which were placed at approximately 20 cm vertical distance, respectively. For any further details on the exact setup, see the method section of each experiment. We refer to Figure 1 for a visual illustration of the two setups.

Design

For each hand-to-button mapping, each digit was presented eight times per parity-response mapping yielding 128 trials per hand-to-button mapping and a total of 256 trials. Trials were split into blocks of 16, containing each digit twice in a randomised order. Participants could decide when to continue after each block. The parity-response mapping (i.e. upper button for odd or lower button for even) changed after each eighth block. The orders of the hand-to-button and parity-response mappings were counterbalanced across participants.

Analysis

Erroneous trials and trials with reaction times faster than 250 ms or slower than 1500 ms were excluded.

The anatomical and vertical SNARC effects for reaction times were analysed using linear mixed effects models (Bates, Mächler, Bolker, & Walker, 2015). Mixed effect models of the reaction times have already been used previously to examine the spatial-numerical association (see Zorzi et al., 2012). Here, spatial-numerical associations were modelled as the linear interaction between Digit and Response Hand and Digit and Response Position, respectively.

For the analyses of the error rates, we calculated for each participant and digit the differences in the error rates between right and left hand responses and the error rate differences between upper and lower responses. Afterwards, individual linear regressions were calculated between the digits and these differences. These resulting regressions slopes served as estimates for the individual vertical and anatomical SNARC effects, which could be tested for significance using one-sample *t*-tests (cf. Fias, Brysbaert, Geypens & d'Ydewalle 1996).

All statistical analyses were performed with the R software package lme4 (Bates et al., 2015) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2016). The *p*-values for linear mixed-effects model (LME) were calculated using the Satterthwaite approximation for degrees of freedom available.

To select a parsimonious but sufficient random effect structure (cf. Barr, Levy, Scheepers, & Tily, 2013; Bates, Kliegl, Vasishth, & Baayen, 2015), we fitted a linear mixed effects model with the described fixed factors and the by-participant random intercept only and added in a stepwise manner the random slopes for all factors. χ^2 -tests of the log likelihoods of the previous model and the model containing the additional random slope were calculated to determine whether a random slope was entered in the model or not (Baayen, Davidson, & Bates, 2008).

Experiment 1

Method

Twenty-three students (20 female, mean age: 22.75) participated in the experiment. The two response buttons were aligned in the vertical dimension. The lower button was placed on the table top and a monitor pedestal was centred on top of the lower button serving as a platform for the upper button. The monitor shelf was approximately 30 cm wide, 20 cm deep and 15 cm high. The monitor was also elevated by approximately 15 cm in order to be

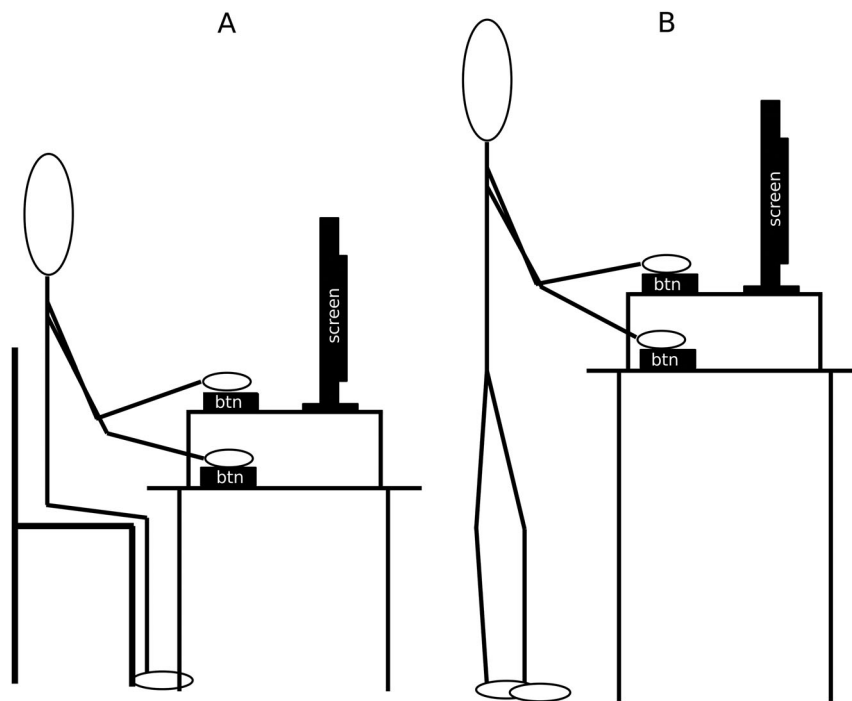


Figure 1. Schematic depiction of the experimental setups. The two setups only differed regarding the participant's posture. Experiment 1 and 3: sitting posture (a); Experiment 2: standing posture (b).

completely visible. Participants were sitting in front of the table top. The hand-to-button mapping changed within subjects once halfway through the experiment.

Results

First, the random-effects were determined. The by-participant adjustments for Digit, $\chi^2(2) = 2.08$, $p = .35$, Response Hand, $\chi^2(2) = 2.71$, $p = .26$ or Response Position, $\chi^2(2) < 1$, did not improve the model substantially. The resulting random effect structure of the final model thus comprised only the random slopes for the intercept.

Reaction times

Figure 2 depicts the average reaction times. Surprisingly, the analysis revealed no evidence for a vertical SNARC effect, as indicated by the non-significant interaction between Digit and Response Position, $\beta = 0.49$, standard error (SE) = 0.54, $t < 1$. Importantly, the interaction between Digit and Response Hand was significant, reflecting the presence of an anatomical SNARC effect, that is a facilitation of left hand responses for small digits and a facilitation for right hand responses for large digits, $\beta = 2.42$, SE = 0.54, $t = 4.48$, $p < .001$. In addition, there was a significant main effect of Response Hand, $\beta = -9.09$, SE = 3.08, $t = -2.95$. On average participants responded faster

with the right (467 ms) as compared to the left hand (472 ms). Moreover, on average even digits were responded to faster (463 ms) than odd digits (479 ms), as indicated by the significant main effect of Parity, $\beta = 15.28$, SE = 2.95, $t = 5.174$, $p < .001$.

Error rates

Despite the low average error rate (3.41%), we performed one-sample *t*-tests of the individual error rate regression slopes, which revealed neither a significant vertical SNARC effect or anatomical SNARC effect, both $t(22) < 1$.

Discussion

Experiment 1 yielded two important findings. First, we could not replicate a vertical SNARC effect with bimanual responses as previously reported in Hartmann et al. (2014). Second, we found evidence for an anatomical SNARC effect, that is, a coupling of the left/right hand and small/large number. The failure to obtain a vertical SNARC effect together with a presence of an anatomical hand-based SNARC indicates that the effector-based anatomical-magnitude associations dominated over the vertical spatio-numerical coupling. In so far, our results add to (1) previous findings that reported evidence for hand-numerical associations (Müller & Schwarz,

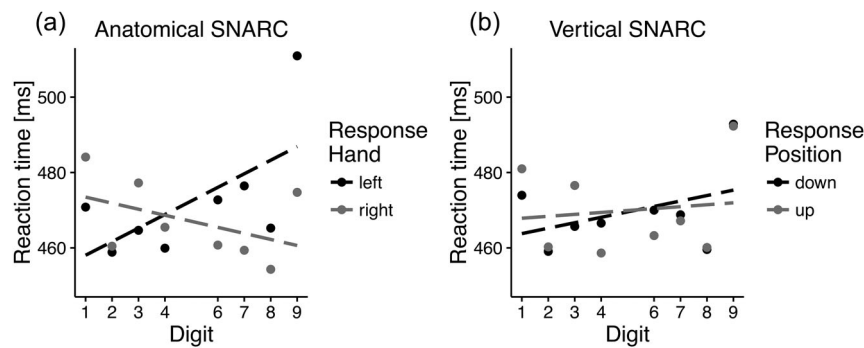


Figure 2. Reaction times in Experiment 1 as a function of Digit and Response Hand (a) and Response Position (b). Linear fitted regression lines are added for each response category. The SNARC is reflected by an interaction between the factors Digit and Response Hand or Response Position.

2007) and (2) to the results from Experiment 2–4 from Hartmann et al., which showed a dominance of effector-based associations over spatial-numerical couplings when using hand and foot responses. While our experimental setup was identical to the one adopted by Hartmann et al., participants in Hartmann et al. performed the parity judgment in a standing posture. A standing posture might have highlighted the vertical spatial feature of the responses, which might have facilitated the vertical spatio-numerical coupling. In order to rule out that participants' posture is responsible for the failure to replicate a vertical SNARC as in Hartmann et al., we instructed participants to perform the parity judgment task in a standing posture in Experiment 2.

Experiment 2

Method

Twenty-three students (18 female, mean age: 23.41) participated in the experiment. Due to technical difficulties during the experiment, however, one participant had to be excluded from the analysis. In

contrast to the previous experiments, participants performed the parity judgment task standing. Participants were standing in front of a high desk on which the button and monitor setup from Experiment 1 was placed. The hand-to-button mapping changed once after the half of the experiment.

Results

The by-participant adjustments for Digit, $\chi^2(2) < 1$, Response Hand, $\chi^2(2) = 1.12$, $p = .55$ or Response Position, $\chi^2(2) < 1$, did not improve the model substantially. The resulting random effect structure of the final model thus comprised only the random slopes for the intercept.

Reaction times

Again, the analysis revealed no evidence for a vertical SNARC effect (see Figure 3), as indicated by the non-significant interaction between Digit and Response Position, $\beta = 0.63$, $SE = 0.59$, $t = 1.07$, $p = .29$. Importantly, the interaction between Digit and Response Hand was again significant, reflecting the presence of an anatomical SNARC effect, $\beta =$

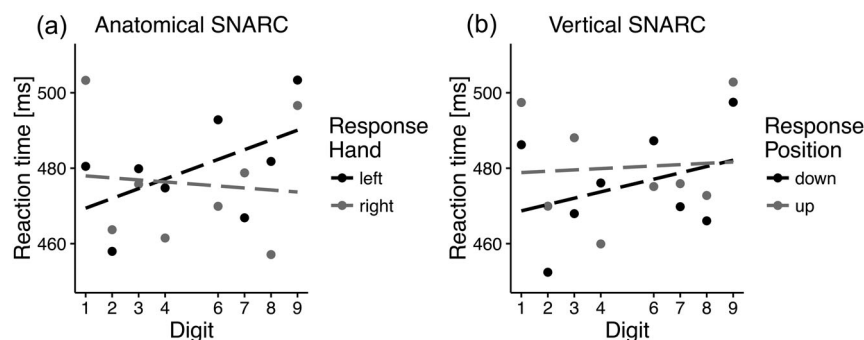


Figure 3. Reaction times in Experiment 2 as a function of Digit and Response Hand (a) and Response Position (b). Linear fitted regression lines are added for each response category.

1.71, $SE = 0.59$, $t = 2.90$, $p < .01$. In addition, there was a significant effect of Response Hand, $\beta = -6.52$, $SE = 3.37$, $t = -1.94$, $p = .05$. On average participants responded faster with the right (476 ms) as compared to the left hand (480 ms). Moreover, on average even digits were responded to faster (470 ms) than odd digits (488 ms), as indicated by the significant main effect of Parity, $\beta = 17.19$, $SE = 3.22$, $t = 5.342$, $p < .001$.

Error rates

One-sample t -tests on the individual error rate regression slopes revealed neither a significant vertical SNARC effect or anatomical SNARC effect, both $t(22) < 1$.

Discussion

Experiment 2 rules out that a difference in the participant's posture was responsible for the failure to obtain a vertical SNARC effect in Experiment 1 and provides a replication of the hand-numerical coupling found in Experiment 1. Importantly, the task set in Experiment 1 and 2 was response-based, that is, the hand placement did not consistently change with the parity-to-response mapping. Therefore, the task design as such did not prime a coding of the task set at the hand-level in any way. The fact that, nevertheless, a dominance of the hand-numerical mapping was found with this task design suggests that participants spontaneously adopted a horizontal/hand-based spatio-numerical coding.

The goal of Experiment 3 was to provide another test for the existence of vertical associations in number classifications. Assuming a cognitive mapping of vertical space and number, this coupling might only be adopted when a horizontal/hand-based coding is rendered inefficient by task constraints. Therefore, we designed Experiment 3 in a way to interfere with a coding of the responses at the hand-level. In order to do so, we instructed participants to alter the hand-to-button mapping after each block of 16 trials, while changing the parity-to-button mapping only after every eighth block. This manipulation was expected to interfere with a coding of the parity status at the hand-level, since it would require a re-coding after each block. This manipulation should substantially reduce the horizontal/hand-numerical association and thereby enhance the vertical SNARC.

Experiment 3

Method

Twenty students (15 female, mean age: 20.31) participated in the experiment. The setup was identical to Experiment 1. In contrast to Experiment 1 the hand-to-button mapping changed after each block of 16 trials, which was done in order to prevent participants from memorising the parity-to-response mapping at the hand-level.

Results

We applied the same analysis as in the previous experiments. Again, we first determined a parsimonious but sufficient random effect structure. The by-participant adjustments for Digit, $\chi^2(2) = 1.32$, $p = .52$, Response Hand, $\chi^2(2) = 2.55$, $p = .28$ or Response Position, $\chi^2(2) = 1.92$, $p = .39$, did not improve the model substantially. The resulting random effect structure of the final model thus comprised only the random slopes for the intercept.

Reaction times

Average reaction times are depicted in Figure 4. Importantly, in line with our hypothesis, the analysis revealed a vertical SNARC effect, as indicated by the significant interaction between Digit and Response Position, $\beta = 2.60$, $SE = 0.68$, $t = 3.81$, $p < .001$. Moreover, the interaction between Digit and Response Hand was not significant, reflecting the absence of an anatomical SNARC effect, $\beta = 1.57$, $SE = 0.68$, $t = 1.69$, $p = .09$. In addition, on average even digits were responded to faster (495 ms) than odd digits (516 ms), as indicated by the significant main effect of Parity, $\beta = 20.41$, $SE = 3.73$, $t = 5.46$, $p < .001$.

Between-experiments comparison

In order to test whether the size of the anatomical and vertical SNARC were affected by the manipulation in the last experiment, we directly compared Experiments 1 and 3 by included the additional factor Experiment (1/3). As predicted, the vertical SNARC effect was enhanced, as suggested by the significant interaction between Digit, Response and Experiment, $\beta = -2.98$, $SE = 0.86$, $t = -2.45$, $p < .05$. However, the anatomical SNARC effect was not modulated, as the interaction between Digit, Hand and Experiment failed to reach significance, $\beta = 1.27$, $SE = 0.86$, $t = 1.48$, $p = .14$.

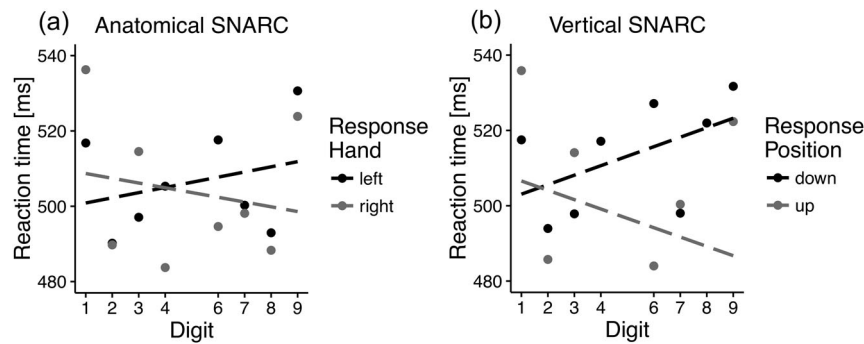


Figure 4. Reaction times in Experiment 3 as a function of Digit and Response Hand (a) and Response Position (b). Linear fitted regression lines are added for each response category.

Error rates

One-sample *t*-tests on the individual error rate regression slopes did neither reveal a significant vertical SNARC effect or anatomical SNARC effect, both $t(22) < 1$.

Discussion

Results from Experiment 3 suggest that when a coding of the responses at the hand-level is cognitively inefficient, participants switch from the preferred horizontal to the more efficient vertical spatio-numerical representation. Therefore, vertical spatio-numerical mappings can be investigated more reliably when button-to-hand mapping are changed frequently throughout the experiment.

General discussion

The present study examined the association of number and vertical space in a numerical classifications task. If the hand-to-button assignment was changed once, the pattern of effects in the reaction times revealed no evidence for a mapping of number onto vertical space but clear support for an association of numerical magnitude and the left or right hand of the body (anatomical SNARC effect; Experiments 1 and 2). Importantly, participants seemed to adopt another number mapping, when the hand-to-button assignment was alternated frequently (Experiment 3). That is, under these conditions participants associated small numbers with the lower response button and large numbers with the upper response button. Beside the emergence of a vertical association of number in Experiment 3, the data revealed no indication for an anatomical mapping of numbers with the hands if hand position is varied continuously. The

present findings suggest that individuals only map numbers onto vertical space if anatomical mappings are rendered inefficient due to the frequent change of the hand-to-button mapping. This preference for an anatomical or horizontal mapping of numbers compared to a cognitive mapping with vertical space argues against the predominance of vertical over anatomical or horizontal mappings of numerical magnitude information.

While previous studies have yielded initial support for vertical associations in mental arithmetic (Wiemers et al., 2013; Lugli et al., 2013) and random number generation (Hartmann et al., 2012; Winter & Matlock, 2013), there is so far inconclusive evidence for the existence of a vertical SNARC effect (Hartmann et al., 2014). The present study now extends this line of research by examining the presence of vertical spatial-numerical association in a bimanual number classification task and by directly comparing hand-based (horizontal) and vertical associations in a mixed model of linear spatial-numerical associations. The pattern of effects in the reaction time analysis revealed a preference of anatomical over vertical number associations.

This dominance of hand-based couplings might be explained by a preference for ego- over geocentric reference frames for the mapping of number onto space. While our results suggest a dominance of anatomical over vertical associations, sagittal and horizontal mappings have both been found to dominate over hand-based numerical associations (Dehaene et al., 1993; Fischer & Hill, 2004; Ito & Hatta, 2004; Shaki & Fischer, 2012; Viarouge et al., 2014). Interestingly, whereas vertical responses provide a geocentric reference frame, sagittally and horizontally aligned responses yield an egocentric frame of reference, which codes for distance or laterality with respect to the body-centre, respectively.

As we know for instance from cross-cultural comparisons of spatial language, Western subjects use the words “left” and “right” exclusively to refer to space left and right relative to the own body and not in terms of an absolute spatial reference frame (Levinson, Kita, Haun, & Rasch, 2002). The dominance of sagittal and horizontal spatio-numerical associations might therefore be explained by a preference for an egocentric reference frame. At this point, we can only speculate about the reasons for a preference for egocentric reference frames. For instance, it might be envisioned that using a bodily reference frame to spatially represent numerical information is computationally more efficient. In fact, the parietal cortex, which is the candidate region for a mapping of numerical magnitude and space (Hubbard et al., 2005), also provides multiple egocentric representations of spatial locations for the control of movements (Colby & Goldberg, 1999). In addition, geocentric compared to egocentric representations appear to engage a larger network of brain regions and involve not only parietal areas but also the ventral visual stream and bilateral hippocampal regions (Zaehle et al., 2006).

The current findings have moreover strong implications for embodied approaches to number cognition (Fischer & Brugger, 2011; Lindemann & Fischer, 2015). The dominance of hand-based over vertical associations suggests a preference for ego- over geocentric spatial coding of number, and thereby casts doubt on the idea that a mapping of vertical space and magnitude is crucial for the understanding of number concepts. It rather indicates that a spatial coding of numbers with reference to the body provides a stronger enrichment of numerical meaning than a coding of numbers with reference to the ground. While our findings indicate a preference for hand-based over vertical associations, previous research has shown that sagittal and horizontal codings dominate over hand-based mappings (Ito & Hatta, 2004; Shaki & Fischer, 2012). This points to a potential hierarchical organisation of reference frames for the spatial mapping of numbers, with the preferred mapping being sagittal and horizontal egocentric codings that use the body-centre as a reference frame. The subordinate effector-based (hand-based) egocentric mappings then seem to be preferred over vertical geocentric codings.

The present study also extends earlier reports of the high flexibility with which adults can map numerical information onto space (Bächtold,

Baumüller, & Brugger, 1998, van Dijck & Fias, 2011; Lindemann et al., 2008; Viarouge et al., 2014). Although in the current study, anatomical number mappings dominated, participants adopted vertical associations when a hand-based representation of the task set was rendered cognitively inefficient by a frequent change of the hand-to-button assignment. While in earlier studies numerical associations were actively induced by instructing participants to adopt a certain spatial coding of numbers (Bächtold et al., 1998; Lindemann et al., 2008; van Dijck & Fias, 2011), the present findings suggest that when a specific mapping is inhibited, participants spontaneously switch to another representation. Viarouge et al.’s (2014) finding that participants adopted a horizontal mapping when a coding at the hand level was cognitively demanding suggests a similar flexibility for horizontal mappings. These findings lend further support to a high flexibility of numerical representations as it suggests that adults easily select from a variety of mappings between numerical and sensorimotor representations without being instructed to do so. The high flexibility of spatio-numerical mappings can be elegantly explained by the working memory account of associations between number and space, which does not assume any stable representations in long-term memory but proposes a spontaneous mapping of digits and space in working memory (van Dijck & Fias, 2011).

In contrast to Experiment 1 in Hartmann et al. (2014), we did not observe any evidence for a spontaneous vertical association with bimanual responses in Experiment 1. Therefore, we set out Experiment 2 to provide a conceptual replication of Hartmann et al., that is, a bimanual number classification task in a standing posture. Again, we observed no evidence for a spontaneous vertical association, and instead replicated our own findings from Experiment 1. One potential contributing factor for the divergent findings might be that while in the present study the hand-to-button assignment was varied within participants, Hartmann et al. varied the hand-to-button assignment between participants. It has previously been argued that a fixed mapping of hands and responses might render a hand-based number coding less salient (Wood, Nuerk, & Willmes, 2006). However, the fact that only when the hand-to-button mapping was changed frequently a significant vertical SNARC effect was observed argues against this idea (Experiment 3). In contrast to Hartmann et al.,

we used a monitor shelf to vertically elevate the higher response button above the lower response button. As a consequence, the lower response button and the lower hand were partly covered by the shelf and not fully visible. This might have facilitated hand-based representations due to a bias towards tactile or proprioceptive over visual response coding. Still, this suggests that the vertical SNARC effect is highly fragile, which argues against a dominance of vertical number associations.

The frequent alternations of the hand-to-button mapping in Experiment 3 was predicted to enhance the mapping of numbers and vertical space since it was expected to interfere with the coding of responses at the hand level. In line with our hypothesis, the results of Experiment 3 revealed a significant vertical SNARC and no evidence for an anatomical SNARC. However, an analysis of variance failed to provide an indication of the reduction of the anatomical SNARC as indexed by the interaction between the factors Digit, Response and Experiment. Thus, it appears that while the vertical SNARC benefits from this manipulation, the anatomical SNARC is not equally diminished.

To summarise, the current study set out to test the dominance of vertical over anatomical hand-based associations as predicted by the embodied approaches to number cognition (Fischer & Brugger, 2011; Lindemann & Fischer, 2015). Importantly, the occurrence of an anatomical SNARC effect together with a simultaneously absent vertical SNARC effect, as found in two experiments, suggests a preference of hand-based over vertical associations and is therefore in conflict with this idea. Our findings question the importance of vertical mappings for the conceptualisation of numbers. The observed dominance of the anatomical over the vertical SNARC effect together with the robustness of sagittal SNARC effect shown by previous research, seems to suggest a preference for ego-over geocentric reference frames for the mapping of numbers onto space.

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