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Special Thematic Section on "Tracking the Continuous Dynamics of Numerical Processing"

The Influence of Number Magnitude on Continuous Swiping Movements

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Abstract

There is accumulating evidence that numerical information influences the way in which we perform bodily movements. Specifically, the idea that our cognitive representations of numbers and space interact is supported by systematic associations of space with both number magnitude (SNARC effect) and number parity (MARC effect). However, whether this influence is bound to the left or right side of space or to the hand with which we perform the movement remains debated. One novel and interesting way to disentangle these factors is to use movement responses in which hand and movement direction can be dissociated. In the present study, participants moved a central object to the left or right side on a touchscreen with their index fingers as response to a parity judgment and magnitude classification task. We observed significant SNARC effects in both tasks. Number magnitude and response direction interacted, but magnitude and response hand did not. This indicated that the SNARC effect can be independent of the responding hand. Importantly, however, a MARC effect was observed not only in an interaction between response direction and parity, but also in an interaction between response hand and parity, suggesting that response hand plays a role in the interaction between physical space and parity. Additionally, number magnitude influenced the amplitude of participants' response movements, with larger numbers eliciting longer movements. These results indicate that space, magnitude and parity interact on different levels that can be unraveled in a paradigm utilizing continuous movements such as swiping.

Keywords: number magnitude, swiping, SNARC effect, MARC effect

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Numbers are universally present in everyday life. As such, there is increasing research interest in unraveling the processes underlying our abilities to mentally represent and process numbers. Interestingly, our processing of numerical information is associated with physical space, including our bodily movements (Fischer & Brugger, 2011). A basic instance of this concept of *Embodied Numerosity* (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010) is the use of our hands and fingers for counting and calculating (for instance Butterworth, 1999; Fuson & Kwon, 1992). Importantly, empirical evidence points towards a bidirectional association: Not only do we use our fingers to represent numbers and calculate, but the way in which we process numbers also affects hand and finger movements (for a review see Moeller & Nuerk, 2012). For example, the presentation of a number has been observed to influence the size of grasping movements, with larger numbers priming larger grip apertures and smaller numbers priming smaller grip apertures (Andres, Ostry, Nicol, & Paus, 2008).

With the increasing emergence of touchscreens on smartphones and tablets, new response modalities become available for using bodily movements to investigate the interaction between numerical information and physical space. In the present study, we utilized such movements to investigate the origins of spatial-numerical associations. The idea of a bidirectional influence between numerical cognition and physical space finds support from various observations, one of them being the SNARC (Spatial-Numerical Association of Response Codes) effect (Dehaene, Bossini, & Giraux, 1993). This effect describes an association between the magnitude of numbers and physical space. Participants respond faster on their right compared to their left side to large numbers and faster on their left compared to their right side to small numbers in a variety of tasks. The effect is attributed to the congruity between the mental representations of number magnitudes on a spatially oriented number line and of the response locations in physical space.

Another observation, the MARC (Linguistic Markedness Association of Response Codes) effect, describes that odd numbers are associated with the left side and even numbers with the right side of space (Nuerk, Iversen, & Willmes, 2004). The effect is typically attributed to the linguistic markedness of both numerical and spatial concepts: "even" and "right" are both linguistically unmarked while "odd" and "left" are both linguistically marked[i]. Together, SNARC and MARC effects indicate that different aspects of spatial and numerical processing interact.

In most studies, associations of small/odd numbers with the left and larger/even numbers with the right side of space are investigated in reaction time experiments as the difference between left and right hand button presses. As a result, the left and right side of physical space is perfectly confounded with response hand: Every response with the left hand occurs in the left side of physical space, and every response with the right hand occurs in the right side of physical space. Therefore, there have been attempts to dissociate influences of side of physical space and response hand by, for instance, having participants cross their hands. However, so far, results were inconsistent. Dehaene et al. (1993) observed a significant SNARC effect as indicated by an interaction between side of response and number magnitude. This indicated that it is indeed left/right side of space which is associated with smaller/larger numbers and not the left/right hand. However, Wood et al. (2006) did not replicate this finding, and argued that associations with response hand were more relevant to the SNARC effect than physical space.

Novel response modalities like swiping movements on a touchscreen may help us dissociate influences of response hand and response side. In these movements, it is possible to implement left- and rightward response movements with both hands. Thereby, it will be possible to consider SNARC and MARC effects based on both response hand (left or right hand) as well as response direction (left- or rightward movement) to narrow down the origin of these spatial-numerical associations. In the following, we will first discuss previous findings on spatial-numerical effects in bodily movements before outlining the current study.

Spatial Numerical Effects in Bodily Movement

Ever since the link between number semantics and physical space was established, research interest into influences of numerical information on movements in physical space has steadily increased (e.g., Domahs et al., 2010; Faulkenberry, 2014; Fischer & Brugger, 2011; Hartmann, Grabherr, & Mast, 2012; Marghetis, Núñez, & Bergen, 2014). Research mostly focused on different types of discrete movement responses made with either

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one or both arms or hands (e.g., Alibali & DiRusso, 1999; Badets & Pesenti, 2010; Imbo, Vandierendonck, & Fias, 2011), but alternative approaches involving full-body movements have been implemented as well (e.g., Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011; Link, Moeller, Huber, Fischer, & Nuerk, 2013, for a review see Dackermann, Fischer, Cress, Nuerk, & Moeller, 2016).

Spatially continuous responding is a particularly valuable source of information about the real-time activation of number knowledge. In an early study, an association between number magnitude and space was observed in a pointing task requiring lateralized movements (Fischer, 2003). Participants were presented with a parity judgment task and had to move their left or right index finger from a central position to the left or the right side of the screen to a predefined target area. Results revealed a SNARC-like effect: After being presented with small numbers, movements to the left target area were conducted faster than to the right target area, and vice versa for large numbers.

Recently, the investigation of movement trajectories has received increasing research interest. Spivey et al. (Spivey, Grosjean, & Knoblich, 2005) first recorded the continuous displacement of a mouse cursor while participants identified one of two displayed pictures as the target after hearing the target's name. Following their lead, several studies have measured the activation of conceptual knowledge in the domain of number magnitude with continuous movements. Some studies measured movements of a computer mouse while participants decided about number magnitude or parity (Faulkenberry, 2014; Faulkenberry, Cruise, Lavro, & Shaki, 2016; Fischer & Hartmann, 2014; Marghetis et al., 2014) or computed sums or differences (Marghetis et al., 2014; Pinheiro-Chagas, Dotan, Piazza, & Dehaene, 2017). Others analyzed finger movements across a tablet surface when participants located numbers on a number line (Dotan & Dehaene, 2013, 2016), or investigated manual reaching trajectories to a touchscreen when participants made magnitude comparison decisions (Song & Nakayama, 2008).

Taken together, there is now accumulating evidence suggesting an influence of numerical information on bodily movements such as grasping, pointing, or finger movements (see also Badets, Bidet-Ildei, & Pesenti, 2015 for influences on head turns; or Loetscher, Bockisch, Nicholls, & Brugger, 2010 for influences on eye movements). This influence is not limited to response latencies but extends into movement trajectories. However, designs investigating movement trajectories in previous studies operated with a predefined target area. That is, participants had to move their fingers or a mouse cursor to a predefined location. This limited the amplitude of participants' movements from the starting point to the target area (e.g., touching the response object and moving from there to a position on a number line) and might thus have impaired the sensitivity of the amplitude variable to the processing of numerical information. Therefore, we suggest to not only look at temporal and trajectorial aspects of response movements, but to specifically consider the spontaneously generated amplitude of continuous hand movements in a non-restrictive way. Continuous hand movements become increasingly important as they replace keyboards on devices such as tablets or smartphones. One type of movement that is at the center of touchscreen navigation is swiping, which is a quick movement of a finger across a touchscreen. These swiping movements can be performed when there is no predefined target area and only the direction of the swipe (to the left or right) but not its length is response-relevant. The distance participants choose to travel on a touch screen might then give novel insight into how numbers influence continuous movements.

First studies already made use of finger trajectories on a touchscreen to investigate processing stages during number line estimation or mental arithmetic (Dotan & Dehaene, 2013, 2016; Pinheiro-Chagas et al., 2017).

However, not only have these studies so far not investigated spatial-numerical associations such as the SNARC or MARC effect. Additionally, they also did not make use of the possibility of measuring the amplitude of participants' spontaneous movements. Instead, they focused on the curvature of movement trajectories. Investigating swiping movements without a predefined target area may present a particularly promising approach to investigate spatial-numerical associations, because they allow us to measure not only reaction times, but also the distance traveled in response to a certain stimulus.

The Present Study

The current study aimed at dissociating influences of response hand and response direction on spatial-numerical associations. Participants had to touch and drag a centrally presented object with a lateralized movement to either the left or the right side of the screen. MARC and SNARC effects are typically investigated with parity judgment tasks. But because the SNARC effect might differ when the task requires explicit as opposed to implicit magnitude processing (Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; van Galen & Reitsma, 2008), we used both a parity judgment task (for implicit magnitude processing and explicit parity processing) and a number magnitude classification task, in which participants had to classify a number as smaller or larger than five (for explicit magnitude processing and implicit parity processing). Using these paradigms, we aimed at evaluating the following hypotheses:

Hypothesis 1: Magnitude Effect

In accordance with previous research, we expected to find an influence of number magnitude on the speed with which participants respond, which is also referred to as the size effect (e.g., Buckley & Gillman, 1974; Karolis, Iuculano, & Butterworth, 2011). In particular, this effect predicts that overall, small numbers should be classified faster than large numbers independently of task requirements (magnitude classification or parity judgment). Furthermore, we expected a similar effect on spontaneous movement amplitude: Participants should make longer movements on the screen the larger the magnitude of a given number. This would present a novel finding, considering that previous studies (e.g., Dotan & Dehaene, 2013; Fischer, 2003) with a predefined target area did not allow for measuring spontaneous movement amplitude. An effect of number magnitude on movement amplitude would also lend support to theories assuming common processing mechanisms for number and space, with greater numbers being associated with greater distances (i.e., A Theory of Magnitude; Walsh, 2003, 2015)

Hypothesis 2: SNARC Effect

In addition to number magnitude influencing responses, we expected a SNARC effect reflective of a directed association between numbers and space. Depending on the origins of the effect, it should either be observed in an interaction between number magnitude and physical space as operationalized by response direction (with small numbers being associated with the left and large numbers with the right side of space), or an interaction between number magnitude and response hand (with small numbers being associated with the left hand and large numbers being associated with the right hand). As in previous studies, the SNARC effect should be found in both the magnitude classification as well as the parity judgment task in RT (i.e., faster reaction to small/large numbers for movements to the left/right). Additionally, we expected a SNARC effect in spontaneous movement amplitude, with participants moving further to the left for small than large numbers and further to the right for large than small numbers.

Hypothesis 3: MARC Effect

We also expected a MARC effect indicative of an association between numerical parity and space. The MARC may also be bound to either response direction or response hand. Accordingly, it should be reflected in an interaction between parity and physical space operationalized by response direction (with odd numbers being associated with the left side of space and even numbers with the right side of space), or an interaction between parity and response hand (with odd numbers being associated with the left hand and even numbers being associated with the right hand). Because the MARC effect has previously been investigated exclusively in parity judgement tasks, we also expected a MARC effect specifically in this task, where parity is response relevant. However, parity was also considered in the magnitude classification task. We expected a MARC effect as indicated by faster RTs and larger movement amplitudes for responses to the left for odd and to the right for even numbers.

Materials and Methods

Participants

Twenty-four participants, mostly students (21 female), aged between 20 and 59 years (*M* = 26 years, *SD* = ± 9.9 years), participated in the study. An a priori power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) suggested that 24 participants should allow for detecting a medium sized effect of $f = .25$ with sufficient power of .90 for the present within-participant design. All participants gave their informed consent. The study was approved by the local Ethics Committee.

Apparatus

Both tasks were presented on an Acer Multitouch Monitor T231 23 inch touch sensitive screen with a resolution of 1920 x 1080 pixels and a display size of 50.9 cm x 28.6 cm. The screen was placed horizontally on a table top, lying flat in front of the participants in landscape orientation. Digits and response object were presented in black Arial font, size 120, on a white background. The Experiment was programmed in C# using Microsoft Visual Studio 2010 (Microsoft Corporation). In both tasks, the response object in the shape of an ‘x’ was positioned 85 mm below the digit (see Figure 1) which was positioned at the horizontal center of the screen.

Design

Participants were tested individually in two sessions, one for each task. The sessions were conducted on separate days, with the interval between them not exceeding 9 days. Each session lasted about one hour.

Participants had to swipe to the right or left side of the screen to indicate whether a number was odd/even (in the parity judgement task) or larger/smaller than five (in the magnitude classification task). As in most SNARC experiments, the assignment of response direction to the right or left for larger/smaller or odd/even was changed after the first half of the experiment. Additionally, participants performed each task twice: once with their left and once with their right hand. This resulted in four conditions per task, counterbalancing responding hand and response direction. The order of task (parity/magnitude), response hand (left/right), and response assignment (left side for even/smaller numbers vs. right side for even/smaller numbers) was counterbalanced across participants using a Latin square design.

Each number from 1 to 9 (excluding 5) was presented 25 times per condition, resulting in 200 items per condition, and a total of 800 items per session. The same number never appeared twice in a row, and response direction stayed the same for no more than three consecutive trials. After every 50 items participants were given the opportunity to take a break. Throughout the entire study, no text was displayed on the screen.

Procedure

Prior to each condition, participants were instructed orally on which task to perform (magnitude classification or parity judgment), which hand to use, and on the direction of the response. They were instructed that they would see numbers between 1-4 and 6-9 and that they were to decide whether 1) the number was odd or even (parity judgment) or whether 2) the number was larger or smaller than five (magnitude classification). Participants were instructed to decide as quickly and accurately as possible, but there was no instruction as to the amplitude of the required movement. In both sessions, instructions were followed by 8 practice trials during which each of the eight digits appeared once.

Participants placed their index finger on the object, which was a lower-case x at the bottom of the screen, and waited 500 milliseconds until the digit appeared at the center of the screen. Participants then had to swipe the object in the instructed direction, depending on either the parity or the magnitude of the presented digit. After each item, participants had to place their finger on the object again (which reappeared at its original centered position after releasing the object by lifting the finger from the screen) in order to see the next digit (see Figure 1).

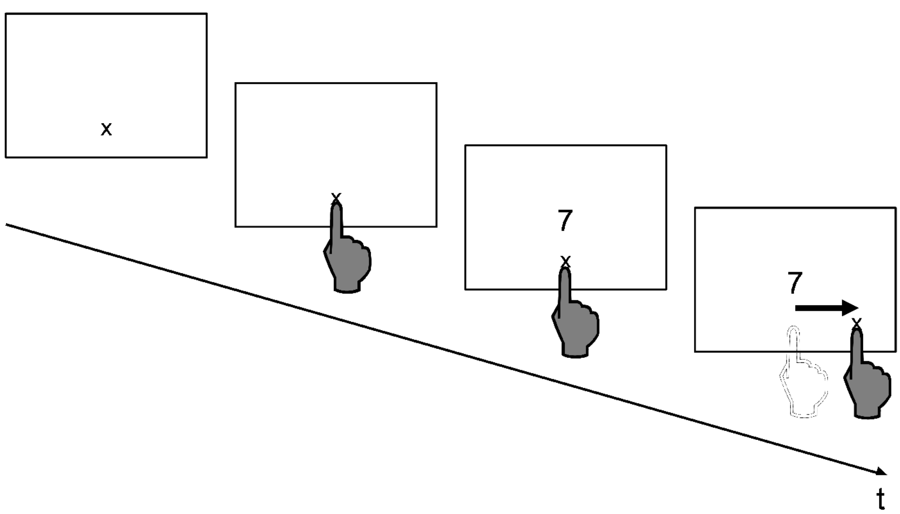

Figure 1. 500 ms after participants placed their finger on the response object, a digit appeared. They responded by swiping the object to the right/left side, depending on the digit's magnitude/parity.

Analysis

Dependent Variables

We analyzed *reaction time* in ms (RT) and *movement amplitude* (MA). RT was defined as the time between the appearance of a digit and the first movement event registered by the computer, indicating a change in x/y coordinates. MA was operationalized as the maximum distance from the starting point in pixels[ii]. Specifically, MA was the largest Euclidean (x and y coordinates) distance in pixels between the starting point and the subsequent swiping trajectory before the participant lifted their finger off the screen at the end of each swiping movement. Data trimming involved removing erroneous trials, RT slower than 200 ms, and RT or MA outside of 3 *SD* of a participants' individual mean. All analyses were conducted using R (R Development Core Team, 2014).

Parameters

Rather than running ANOVAs with all factors and all interactions, only those interactions of interest for analyzing SNARC and MARC effects were included in the analysis to allow for a better fit of the models.

However, in addition to the above described factors, the absolute distance of each number from 5 (which could take on values from 1 to 4) was entered as a continuous parameter in the ANOVAs for the magnitude classification task. This was done to account for the numerical distance effect (the finding that number pairs with larger numerical distances are easier to compare, e.g., Moyer & Landauer, 1967), which is typically observed in number magnitude classification tasks and might therefore explain additional variance.

In sum, in the ANOVA for the magnitude classification task we analyzed main effects of i) number magnitude (1-4 and 6-9), ii) parity status (odd and even), iii) numerical distance from 5 (1-4), iv) response hand (left and right) and v) response direction (left and right). Moreover, we considered three three-way interactions (including all lower level interactions): number magnitude x response hand x response direction; parity status x response hand x response direction; and distance from 5 x response hand x response direction.

For the parity judgment task, we included the main effects of i) number magnitude, ii) parity status (odd and even), iii) response hand, and iv) response direction; as well as two three-way interactions (including all lower level interactions): number x response hand x response direction; as well as parity x response hand x response direction.

The presence of the SNARC effect was indicated by an interaction between number magnitude and response direction (spatial SNARC) or between number magnitude and response hand (hand-based SNARC). Likewise, the MARC effect was indicated by an interaction between parity status and response direction (spatial MARC) or between parity status and response hand (hand-based MARC).

Prior to data analysis, we centered continuous predictors (i.e., number and distance) and effect-coded dichotomous predictors (i.e., parity, response hand and response direction) in order to be able to directly interpret the direction of the respective effects.

Results

Magnitude Classification Task

RT Results

All results for the magnitude classification task are presented in Table 1. For RT, the ANOVA revealed significant main effects of number magnitude and numerical distance from 5. This indicated that RT increased with the size of numbers (with a linear increase of 1.58 ms per number) and decreased as the distance to the standard 5 increased (with a linear decrease of -13.62 ms per unit) in accordance with previous research (e.g., Moyer & Landauer, 1967). The significant spatial SNARC effect, as indicated by the interaction between response direction and number, showed that participants responded faster with movements to the left when responding to small compared to large numbers, but faster with movements to the right when responding to large compared to small numbers. This difference in RT (dRT = right hand RT minus left hand RT) is depicted in Figure 2A.

Table 1

Estimated Effects and Statistics for Dependent Variables of the Magnitude Classification Task

Effect	Estimate	*SD*	*F*(1, 23)	*p*	η_p^2
DV: RT in ms					
Response direction	-4.30	13.30	2.51	.127	.10
Number magnitude	1.58	1.68	21.18	< .001	.48
Response Hand	13.80	41.06	2.71	.113	.11
Distance from 5	-13.62	8.18	81.77	< .001	.78
Parity	-3.59	10.82	2.64	.118	.10
Response direction x Number magnitude (spatial SNARC)	-7.59	13.60	7.47	.012	.25
Response direction x Response hand	-15.55	41.46	3.38	.079	.13
Number magnitude x Response hand (hand-based SNARC)	-0.75	4.17	0.78	.387	.03
Response direction x Distance from 5	2.30	10.29	0.83	.371	.03
Response hand x Distance from 5	-3.13	9.91	2.08	.163	.08
Response direction x Parity (spatial MARC)	2.43	18.27	0.42	.521	.02
Response hand x Parity (hand-based MARC)	-2.20	18.02	0.36	.555	.02
Response direction x Number magnitude x Response hand	0.76	21.35	0.03	.863	< .01
Response direction x Response hand x Distance from 5	1.38	13.53	0.18	.676	.01
Response direction x Response hand x Parity	12.42	24.84	6.00	.022	.21
DV: MA in px					
Response direction	-1.48	13.78	0.28	.605	.01
Number magnitude	0.80	1.51	6.72	.016	.23
Response hand	-3.03	52.98	0.08	.782	< .01
Distance from 5	1.16	2.08	8.96	.006	.28
Parity	-0.10	3.81	0.02	.898	< .01
Response direction x Number magnitude (spatial SNARC)	3.26	12.46	1.64	.213	.07
Response direction x Response hand	35.91	58.16	9.15	.006	.28
Number magnitude x Response hand (hand-based SNARC)	-0.16	1.88	0.17	.685	.01
Response direction x Distance from 5	-0.35	2.63	0.15	.705	.01
Response hand x Distance from 5	0.40	3.41	0.08	.775	< .01
Response direction x Parity (spatial MARC)	-0.58	5.63	0.26	.617	.01
Response hand x Parity (hand-based MARC)	2.94	6.67	4.67	.041	.17
Response direction x Number magnitude x Response hand	1.22	19.62	0.09	.764	< .01
Response direction x Response hand x Distance from 5	-1.22	6.77	1.13	.299	.05
Response direction x Response hand x Parity	1.72	10.83	0.61	.444	.03

Note. DV = dependent variable; RT = Reaction time; MA = movement amplitude. η_p^2 = partial eta squared.

Finally, a significant three-way interaction between response direction, response hand, and parity suggested that the MARC effect in RT differed depending on both response direction and hand. This was investigated by conducting separate ANOVAs for the two movement directions and the two hands. The separate ANOVAs for responses to the left and to the right revealed a marginally significant interaction between response hand and parity for responses to the left, $F(1,23) = 3.29$, $p = .083$, but no significant interaction for responses to the right, *F*(1,23) = 0.87, *p* = .360. The separate ANOVAs for the left and right hand revealed a marginally significant interaction between response direction and parity for the right hand, *F*(1,23) = 3.45, *p* = .076, but none for the left hand, *F*(1,23) = 0.75, *p* = .395. These results indicate a marginal hand-based MARC effect for responses to the left side as well as a marginal spatial MARC effect for responses with the right hand. The differences between RTs to odd and even numbers (dRT = RT odd numbers minus RT even numbers) for both response directions and response hands are depicted in Figure 3.

No other effects reached significance (see Table 1).

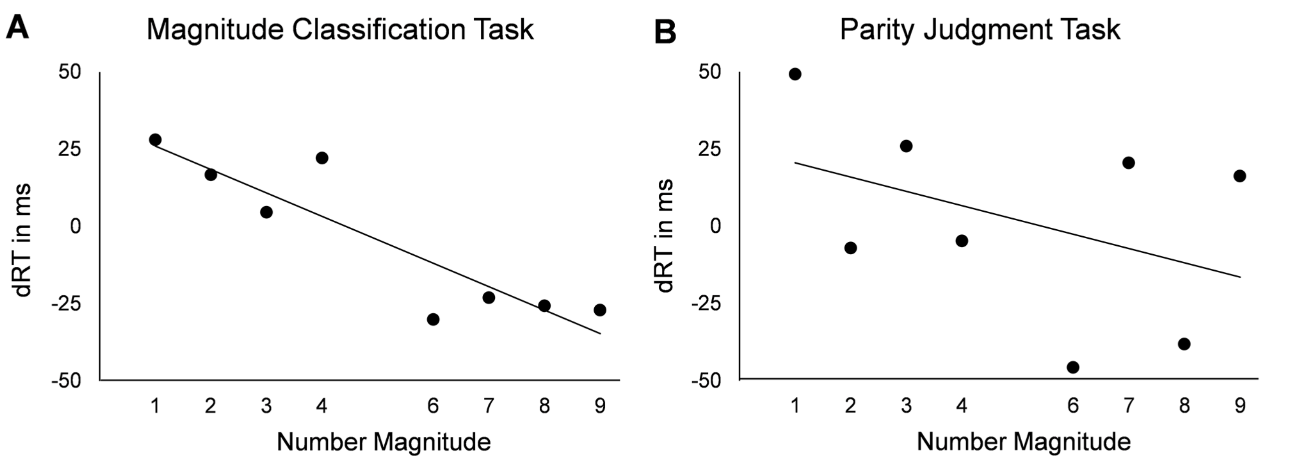

Figure 2. SNARC effects (i.e., interaction between response direction and number magnitude) for differences between RTs for movements to the right and movements to the left (dRT = right hand RT minus left hand RT) (**A**) in the magnitude classification task and (**B**) in the parity judgment task.

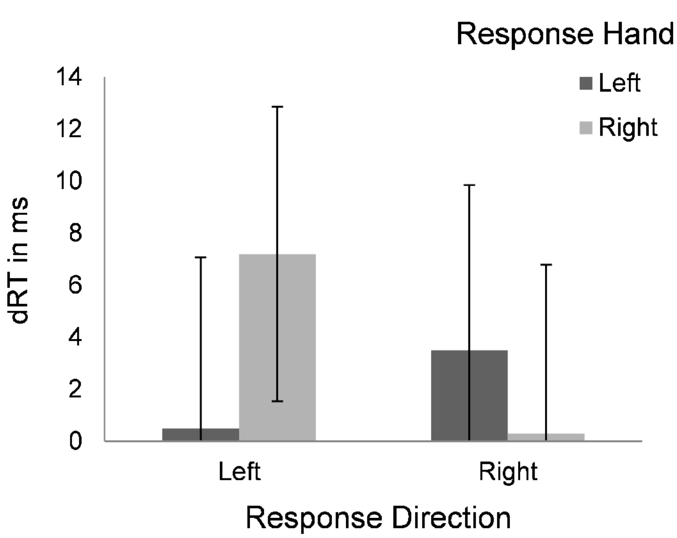

Figure 3. MARC effects for RTs in the magnitude classification task separated by response direction and response hand. The MARC effects are depicted as differences between odd and even numbers (dRT = RT odd numbers minus RT even numbers). Positive values indicate a regular MARC effect (faster responses to even compared to odd numbers).

MA Results

MA results again revealed an effect of number magnitude, with movement amplitude increasing with the magnitude of the to-be-classified number (i.e., a linear increase in movement amplitude of 0.80 px per number). A numerical distance effect was also observed, indicating larger movements the larger the numerical distance to the standard 5 (with a linear increase in movement size of 1.16 px per unit). In contrast to the RT results, the interaction between response direction and hand was significant for MA. It indicated an ipsilateral advantage: larger movements to the left with the left hand (movement to the left: *M* = 286 px, *SD* = 30 px; movement to the right: *M* = 267 px, *SD* = 38 px) and to the right with the right hand (movement to the left: *M* = 265 px, *SD* = 39 px; movement to the right: *M* = 282 px, *SD* = 36 px). Furthermore, we observed an interaction between parity and hand, indicating a hand-based MARC effect. Participants responded with larger movements of their left hand to odd numbers (*M* = 278 px, *SD* = 30 px) compared to even numbers (*M* = 275 px, *SD* = 32 px), whereas there was no difference in movement amplitude for response movements with their right hand to odd (*M* = 273 px, *SD* = 32 px) and even numbers (*M* = 273 px, *SD* = 30 px; see Figure 4).

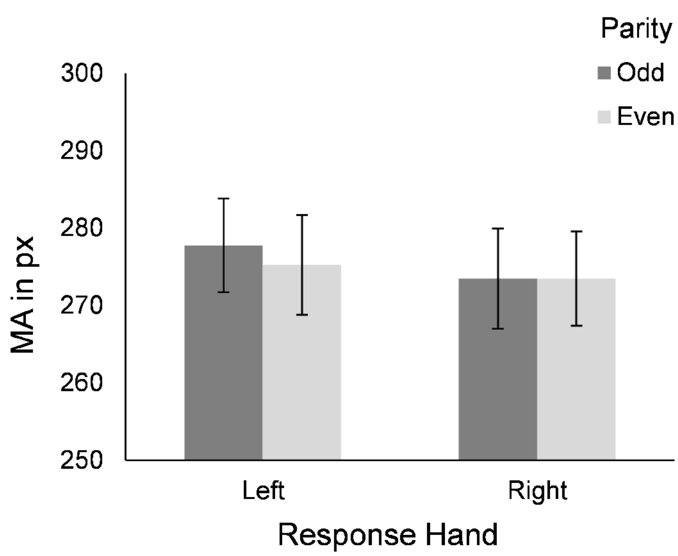

Figure 4. Hand-based MARC effect indicated by an interaction between parity and hand for movement amplitude in the magnitude classification task.

No SNARC effect was observed as indicated by the non-significant interactions between response direction and number magnitude (p = .213), as well as between response hand and number magnitude (p = .685). No other effects reached significance (see Table 1).

Parity Judgment Task

RT Results

Again, we observed a significant effect of number magnitude for RT, indicating that RT increased with the size of the to-be-classified numbers (i.e., a linear increase of 2.22 ms per number). In accordance with previous findings, we also observed a main effect of parity (also termed the odd effect; see Hines, 1990), with participants responding faster to even numbers (*M* = 636 ms, *SD* = 37 ms) than to odd numbers (*M* = 643, *SD* = 36). Moreover, we found a spatial SNARC effect as indicated by a significant interaction between response direction and number magnitude (see Figure 2B for the differences between right hand RT minus left hand RT). This indicated increasingly faster response movements to the right than to the left as the to-be-classified numbers increased in magnitude.

Furthermore, the interaction between response direction and response hand was significant. It indicated significantly faster RT to the left with the left hand (movement to the left: M = 642 ms, SD = 29 ms; movement to the right: M = 653 ms, SD = 29 ms) and faster RT to the right with the right hand (movement to the left: M = 634 ms, SD = 30 ms; movement to the right: M = 627 ms, SD = 29 ms).

Furthermore, we observed a MARC effect as indicated by the significant interaction between response direction and parity. Participants responded faster to odd numbers with movements to the left compared to movements to the right side (movement to the left: M = 630 ms, SD = 35 ms; movement to the right: M = 657 ms, SD = 37 ms), and faster to even numbers with movements to the right compared to movements to the left (movement to the left: M = 647 ms, SD = 36 ms; movement to the right: M = 623 ms, SD = 37 ms; see Figure 5). No other effects reached significance (see Table 2).

Table 2

Estimated Effects and Statistics for Dependent Variables of the Parity Judgment Task

Effect	**Estimate**	***SD***	***F*(1, 23)**	***p***	η_p^2
DV: RT in ms					
Response direction	2.04	14.37	0.48	.493	.02
Number magnitude	2.22	3.11	12.16	.002	.35
Hand	-16.89	46.91	3.11	.091	.12
Parity	-7.96	18.11	4.64	.042	.17
Response direction x Number magnitude (spatial SNARC)	-4.62	6.99	10.48	.004	.31
Response direction x Response hand	-19.69	27.70	12.13	.002	.35
Number magnitude x Response hand (hand-based SNARC)	0.48	3.88	0.37	.546	.02
Response direction x Parity (spatial MARC)	-51.89	117.32	4.70	.041	.17
Response hand x Parity (hand-based MARC)	4.54	23.84	0.87	.361	.04
Response direction x Number magnitude x Response hand	2.25	7.06	2.44	.132	.10
Response direction x Response hand x Parity	13.46	152.57	0.19	.670	.01
DV: MA in px					
Response direction	-0.72	10.47	0.11	.741	< .01
Number magnitude	0.64	0.95	10.69	.003	.32
Response hand	2.00	59.21	0.03	.870	< .01
Parity	-3.10	8.83	2.97	.098	.11
Response direction x Number magnitude (spatial SNARC)	-0.42	1.33	2.39	.136	.09
Response direction x Response hand	43.39	49.07	18.76	< .001	.45
Number magnitude x Response hand (hand-based SNARC)	-0.15	1.32	0.31	.580	.01
Response direction x Parity (spatial MARC)	17.61	84.85	1.03	.320	.04
Response hand x Parity (hand-based MARC)	0.26	12.65	0.01	.920	< .01
Response direction x Number magnitude x Response hand	0.61	2.11	1.99	.172	.08
Response direction x Response hand x Parity	-50.12	82.01	8.96	.006	.28

Note. DV = dependent variable; RT = Reaction time; MA = movement amplitude. η_p^2 = partial eta squared.

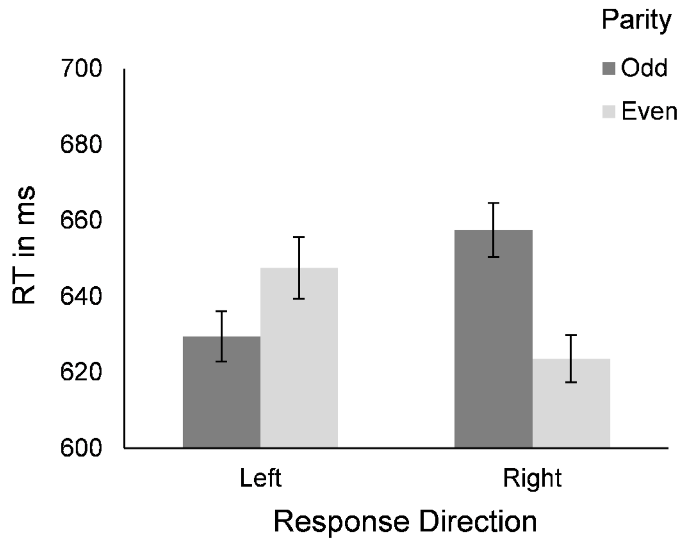

Figure 5. Interaction between response direction and parity (MARC effect) for reaction times in the parity judgment task.

MA Results

We observed a significant effect of number magnitude on MA, which increased with the size of the to-be-classified numbers (0.64 px per number).

As in magnitude classification, the two-way interaction between response direction and response hand was significant, and was qualified by the significant three-way interaction between response direction, response hand, and parity. This again indicated different MARC effects depending on both hand and response direction (see Figure 6). We therefore conducted separate ANOVAs for the two movement directions and the two hands.

The separate ANOVAs for responses to the left and to the right revealed a significant interaction between response hand and parity (i.e., a hand-based MARC) for responses to the left, $F(1,23) = 6.73$, $p < .05$, as well as for responses to the right, $F(1,23) = 8.47$, $p < .01$. However, the directions of the hand-based MARC were reversed: While movements to the right showed a regular MARC effect, with larger movements in response to even compared to odd numbers, the direction of the MARC effect was reversed for responses to the left, with larger movements in response to odd compared to even numbers (see Figure 6). The separate ANOVAs for the left and right hand revealed a marginally significant interaction between response direction and parity for the left hand, $F(1,23) = 3.45$, $p = .076$, but none for the right hand, $F(1,23) = 0.21$, $p = .648$. This indicates that left hand responses were marginally sensitive to interactions between parity and movement, whereas right hand responses were not (see Figure 6).

Neither the SNARC effect nor any other effects reached significance (see Table 2).

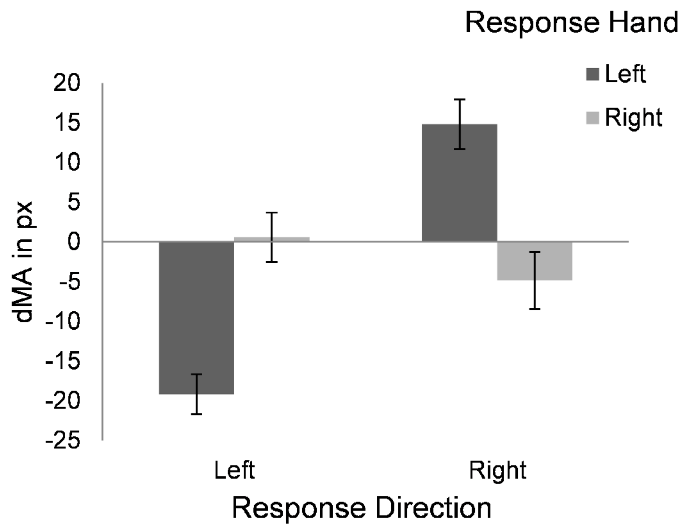

Figure 6. MARC effects for MA in the parity judgment task separated by response direction and response hand. The MARC effects are depicted as differences in MA between odd and even numbers (dMA = MA even numbers minus MA odd numbers). Positive values indicate a regular MARC effect (larger responses to even compared to odd numbers), whereas negative values indicate a reversed MARC effect (larger responses to odd compared to even numbers).

Discussion

The aim of the present study was to dissociate potential influences of response hand and response direction on spatial-numerical associations (i.e., the SNARC and MARC effect) by means of continuous swiping movements on a touchscreen. We employed parity judgment and number magnitude classification tasks and expected to find effects of number magnitude, as well as SNARC and MARC effects as indicators for spatial-numerical associations. To this end, we analyzed reaction times and also considered a novel dependent variable, namely the maximal amplitude participants moved their hand during their swiping movements. Interestingly, the data corroborated our hypotheses in an unexpected pattern. All significant effects are summarized in Table 3. In the following, we discuss our hypotheses on magnitude, SNARC and MARC effects in turn.

Table 3

Summary of Significant Effects in Both Tasks

Effect	*F* RT results	*F* MA results
Magnitude classification		
Number magnitude	21.18***	6.72*
Numerical distance	81.77***	8.96**
Response direction x Number magnitude (spatial SNARC effect)	7.47*	1.64
Response direction x Response hand	3.38	9.15**
Response hand x Parity (hand-based MARC effect)	0.36	4.67*
Response direction x Response hand x Parity	6.00*	0.61
Parity judgment		
Number magnitude	12.16**	10.69**
Parity	4.64*	2.97
Response direction x Number magnitude (spatial SNARC effect)	10.48**	2.39
Response direction x Response hand	12.13**	18.76***
Response direction x Parity (spatial MARC effect)	4.70*	1.03
Response direction x Response hand x Parity	0.19	8.96**

Note. RT = Reaction time; MA = movement amplitude.

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

Magnitude Effects

As predicted, we observed effects of number magnitude in both tasks and on both dependent measures. In line with previous studies (Buckley & Gillman, 1974; Karolis et al., 2011), participants' reaction times increased with the *magnitude of the number* they had to classify. Importantly, this magnitude effect generalized to movement amplitude: participants' response movements increased in physical amplitude as the numerical magnitude of the to-be-classified numbers increased. To the best of our knowledge, this is the first time such a direct scaling of movement amplitude by numerical magnitude has been observed. This finding lends further evidence to theories suggesting common underlying cortical structures for the processing of numbers and space (Walsh, 2003, 2015). Additionally, we observed this effect in both tasks and thus irrespective of whether number magnitude information was task relevant. This suggests that number magnitude influences movement amplitude automatically and does not require explicit processing of number magnitude. The significant effects of numerical *distance from 5* on movement amplitude in the magnitude classification task substantiated this finding. Participants' movement amplitude increased with the numerical distance of the numbers to the standard 5, again indicating internal scaling of the response movement by numerical information.

Importantly, on a methodological level, our data indicate that movement amplitude is a valuable source of information when investigating influences of number magnitude on bodily movements in a paradigm without a predefined target location.

SNARC Effect

We observed a significant SNARC effect in both the magnitude classification and parity task. The SNARC effect was exclusively present in the form of an interaction between number magnitude and response direction (spatial SNARC effect), and not in an interaction between number magnitude and response hand (hand-based

SNARC effect). This provides further evidence that spatial-numerical associations are indeed bound to the spatial representation of magnitudes rather than the responding hand (e.g., Wood, Nuerk, & Willmes, 2006).

Moreover, the SNARC effect was significant for reaction times, but not for movement amplitude. Thus, the interaction between number magnitude and response direction did not influence how far participants moved their hand on a touchscreen. However, as indicated by the above described magnitude effects, number magnitude did influence movement amplitude. This might mean that movement amplitudes are scaled by number magnitude but not by the association between number and physical space. As such, spatial numerical associations seem to be reflected in the temporal dimension of response movements, but not necessarily in their amplitude. However, further research is needed to substantiate this interpretation.

MARC Effect

In contrast to the results for the SNARC effect, the MARC effect was reflected in both tasks by an interaction between response hand and parity (hand-based MARC effect) in movement amplitude. Only in the parity task, an interaction between response direction and parity (spatial MARC effect) was observed in RT.

The hand-based MARC effect (indicated by the interaction in movement amplitude between response hand and parity) in the magnitude classification task corroborates previous findings of a similar interaction. Huber and colleagues (Huber et al., 2015) investigated the assumption that the MARC effect, rather than being an effect of linguistic markedness, might actually stem from a life-long association between positive (or even) things with the dominant hand and of negative (or odd) things with the non-dominant hand. Support for this account comes from the body-specificity hypothesis (Casasanto, 2009), which suggests that response hand, in addition to response direction, plays a role in the processing of parity. Therefore, we might be looking at a different aspect of the MARC effect that is body-specific rather than response-side specific as suggested by Huber et al. (2015). Specifically, because this was observed in the magnitude classification task, in which parity is irrelevant, we suggest that this type of MARC effect might result from an automatic processing of parity rather than the explicit processing of parity in the parity judgement task.

In the parity judgement task, the three-way interaction between response direction, response hand, and parity in movement amplitude suggested that response direction might play a greater role for MARC effects in parity judgment. This is further corroborated by the interaction between response direction and parity in RT in the parity judgement task, indicating a spatial MARC effect. Thus, future studies should take into account that the MARC effect can vary based on task-demands and might be observed in different dependent measures. Further work will be necessary to fully disentangle the origins of the MARC effect.

Further Results

The consistent interaction between response direction and response hand observed in almost all measures (except for RT in magnitude classification, where the effect was only marginally significant) may be explained by purely biomechanical reasons: Movements to the ipsilateral side (i.e., of the left hand into the left hemispace or of the right hand into the right hemispace) are generally faster and larger, purely because they might be easier to execute than contralateral (i.e., of the left hand into the right hemispace or of the right hand into the left hemispace) movements (e.g., Bradshaw, Bradshaw, & Nettleton, 1988, 1990; for a discussion see Patro, Nuerk, & Cress, 2015).

In sum, our results suggest that the SNARC effect, as previously suggested (Dehaene et al., 1993), originates from an association between numbers and space that influences the speed with which responses are initiated, even in continuous movement responses with no predefined target area. However, the MARC effect might have different origins depending on task demands (explicit or implicit magnitude/parity processing), and might influence numerical processing at different stages during task execution. When operationalized as an interaction between response hand and parity, as suggested by the body-specificity hypothesis, the effect was observed in movement amplitude. Therefore, continuous measures such as movement amplitude, which allow distinguishing between response initiation and response execution, might prove useful for further investigation of the MARC effect.

Difference Between Dependent Measures

The inconsistent results for the two dependent measures RT and movement amplitude suggest that they might also measure different underlying processes. However, we observed magnitude effects on both measures. This suggests that number magnitude information has a substantial effect on touchscreen responses, and not only influences the initial reaction to a number (RT), but also the actual execution of the response movement as indicated by our findings for movement amplitude. However, spatial SNARC and MARC effects as operationalized by the interaction between response direction and magnitude/parity were only observed in RT. This suggests that the associations between numerical information and the left/right side of space rather than an association with response hand drive these effects during response initiation. This finding is in line with similar previous results by Dehaene et al. (1993), who observed a regular SNARC effect when participants crossed their hands in a parity judgment task.

However, our results shed light on the role the response hand plays during the actual execution of the response movement itself (as measured by movement amplitude). Here, not response direction but response hand determined the interactions between number and space. A body-specific MARC effect (reflected by an interaction between response hand and parity) was observed in movement amplitude only. This suggests that the association between parity and the left or right hand may influence later stages of processing, as previously reported by Huber et al. (2015).

Alternative dependent measures, such as velocity and duration of the response movement, could also have been taken into consideration. However, when we analyzed velocity, results were rather similar to those of the movement amplitude data and correlated with $r > .90$. One possible explanation for these similar results for velocity data could be the isochrony principle (Viviani & McCollum, 1983). This principle states that at least in drawing movements (which, although not corresponding to the swiping movements in our study perfectly, share some semblance with our response movement), participants adapt the velocity of their movements to the length of the movement. That is, participants take approximately the same amount of time for drawing figures of different length because they draw smaller figures slower than they draw larger figures.

Taken together, our results indicate that continuous movement measures such as movement amplitude seem to be informative for magnitude processing, as well as spatial numerical associations by means of interactions between bodily movements and number processing. As such, future studies may not only investigate SNARC and MARC effects using such measures, but measures reflecting continuous response movements may also be meaningful for investigating other effects of spatial-numerical associations. This may help further our understanding of spatial-numerical interactions (for recent studies on continuous movements see e.g., Dotan & Dehaene, 2013; Pinheiro-Chagas et al., 2017).

Conclusions

The present study set out to dissociate influences of response hand and response direction on spatial-numerical associations using a swiping paradigm on a touchscreen. Most importantly, we observed the SNARC effect in both tasks exclusively as reflected by the interaction of response direction and number magnitude and not the interaction of response hand and number magnitude. This indicated that this spatial-numerical association seems to be bound to associations of small numbers with the left and larger numbers with the right side of physical space and not primarily its operationalization by left and right hand (similar for the MARC effect in party judgement). Importantly, however, response hand also interacted with parity in both tasks, suggesting that response hand plays a role in the interaction between parity and physical space, but not between number magnitude and physical space.

Additionally, this paradigm introduced a novel measure of responding, namely movement responses without predefined target areas. As such, this study is the first to show that number magnitude scaled the amplitude of participants' spontaneous response movements.

Notes

i) The concept of linguistic markedness states that pairs of antonymous adjectives are often asymmetric, in that one of the adjectives is considered 'positive' and thus 'unmarked' (e.g., 'even'), whereas the other is considered 'negative' and thus 'marked' (e.g., 'odd', Clark, 1969). Positive or unmarked adjectives are stored in memory in a less complex form and can therefore have a processing advantage (Roettger & Domahs, 2015).

ii) Please note that a similar analysis was conducted using movement velocity as a dependent variable. However, because velocity and MA results were fairly similar and correlated with $r > .9$, velocity results are not reported.

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Competing Interests

The authors have declared that no competing interests exist.

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References

Alibali, M. W., & DiRusso, A. A. (1999). The function of gesture in learning to count: More than keeping track. *Cognitive Development, 14*(1), 37-56. doi:10.1016/S0885-2014(99)80017-3

Andres, M., Ostry, D. J., Nicol, F., & Paus, T. (2008). Time course of number magnitude interference during grasping. *Cortex, 44*(4), 414-419. doi:10.1016/j.cortex.2007.08.007

Badets, A., Bidet-Ildei, C., & Pesenti, M. (2015). Influence of biological kinematics on abstract concept processing. *Quarterly Journal of Experimental Psychology, 68*(3), 608-618. doi:10.1080/17470218.2014.964737

Badets, A., & Pesenti, M. (2010). Creating number semantics through finger movement perception. *Cognition, 115*(1), 46-53. doi:10.1016/j.cognition.2009.11.007

Bradshaw, J. L., Bradshaw, J. A., & Nettleton, N. C. (1988). Movement initiation and control: Abduction, adduction and locus of limb. *Neuropsychologia, 26*(5), 701-709. doi:10.1016/0028-3932(88)90005-X

Bradshaw, J. L., Bradshaw, J. A., & Nettleton, N. C. (1990). Abduction, adduction and hand differences in simple and serial movements. *Neuropsychologia, 28*(9), 917-931. doi:10.1016/0028-3932(90)90108-Z

Buckley, P. B., & Gillman, C. B. (1974). Comparisons of digits and dot patterns. *Journal of Experimental Psychology, 103*(6), 1131-1136. doi:10.1037/h0037361

Butterworth, B. (1999). *The mathematical brain*. London, United Kingdom: Macmillan.

Casasanto, D. (2009). Embodiment of abstract concepts: Good and bad in right- and left-handers. *Journal of Experimental Psychology: General, 138*(3), 351-367. doi:10.1037/a0015854

Clark, H. H. (1969). Linguistic processes in deductive reasoning. *Psychological Review, 76*(4), 387-404. doi:10.1037/h0027578

Dackermann, T., Fischer, U., Cress, U., Nuerk, H.-C., & Moeller, K. (2016). Bewegtes Lernen numerischer Kompetenzen [Movement learning of numerical competencies]. *Psychologische Rundschau, 67*(2), 102-109. doi:10.1026/0033-3042/a000302

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

Domahs, F., Moeller, K., Huber, S., Willmes, K., & Nuerk, H.-C. (2010). Embodied numerosity: Implicit hand-based representations influence symbolic number processing across cultures. *Cognition, 116*(2), 251-266. doi:10.1016/j.cognition.2010.05.007

Dotan, D., & Dehaene, S. (2013). How do we convert a number into a finger trajectory? *Cognition, 129*(3), 512-529. doi:10.1016/j.cognition.2013.07.007

Dotan, D., & Dehaene, S. (2016). On the origins of logarithmic number-to-position mapping. *Psychological Review, 123*(6), 637-666. doi:10.1037/rev0000038

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191. doi:10.3758/BF03193146

Faulkenberry, T. J. (2014). Hand movements reflect competitive processing in numerical cognition. *Canadian Journal of Experimental Psychology, 68*(3), 147-151. doi:10.1037/cep0000021

Faulkenberry, T. J., Cruise, A., Lavro, D., & Shaki, S. (2016). Response trajectories capture the continuous dynamics of the size congruity effect. *Acta Psychologica, 163*, 114-123. doi:10.1016/j.actpsy.2015.11.010

Fischer, M. (2003). Spatial representations in number processing – Evidence from a pointing task. *Visual Cognition, 10*(4), 493-508. doi:10.1080/13506280244000186

Fischer, M. H., & Brugger, P. (2011). When digits help digits: Spatial-numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in Psychology, 2*, Article 260. doi:10.3389/fpsyg.2011.00260

Fischer, M. H., & Hartmann, M. (2014). Pushing forward in embodied cognition: May we mouse the mathematical mind? *Frontiers in Psychology, 5*, Article 1315. doi:10.3389/fpsyg.2014.01315

Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H.-C. (2011). Sensori-motor spatial training of number magnitude representation. *Psychonomic Bulletin & Review, 18*(1), 177-183. doi:10.3758/s13423-010-0031-3

Fuson, K. C., & Kwon, Y. (1992). Korean children's understanding of multidigit addition and Subtraction. *Child Development, 63*(2), 491-506. doi:10.2307/1131494

Hartmann, M., Grabherr, L., & Mast, F. W. (2012). Moving along the mental number line: Interactions between whole-body motion and numerical cognition. *Journal of Experimental Psychology: Human Perception and Performance, 38*(6), 1416-1427. doi:10.1037/a0026706

Hines, T. M. (1990). An odd effect: Lengthened reaction times for judgments about odd digits. *Memory & Cognition, 18*(1), 40-46. doi:10.3758/BF03202644

Huber, S., Klein, E., Graf, M., Nuerk, H.-C., Moeller, K., & Willmes, K. (2015). Embodied markedness of parity? Examining handedness effects on parity judgments. *Psychological Research, 79*(6), 963-977. doi:10.1007/s00426-014-0626-9

Imbo, I., Vandierendonck, A., & Fias, W. (2011). Passive hand movements disrupt adults' counting strategies. *Frontiers in Psychology, 2*, Article 201. doi:10.3389/fpsyg.2011.00201

Karolis, V., Iuculano, T., & Butterworth, B. (2011). Mapping numerical magnitudes along the right lines: Differentiating between scale and bias. *Journal of Experimental Psychology: General, 140*(4), 693-706. doi:10.1037/a0024255

Link, T., Moeller, K., Huber, S., Fischer, U., & Nuerk, H.-C. (2013). Walk the number line – An embodied training of numerical concepts. *Trends in Neuroscience and Education, 2*(2), 74-84. doi:10.1016/j.tine.2013.06.005

Loetscher, T., Bockisch, C. J., Nicholls, M. E. R., & Brugger, P. (2010). Eye position predicts what number you have in mind. *Current Biology, 20*(6), R264-R265. doi:10.1016/j.cub.2010.01.015

Marghetis, T., Núñez, R., & Bergen, B. K. (2014). Doing arithmetic by hand: Hand movements during exact arithmetic reveal systematic, dynamic spatial processing. *Quarterly Journal of Experimental Psychology, 67*(8), 1579-1596. doi:10.1080/17470218.2014.897359

Moeller, K., & Nuerk, H.-C. (2012). Zählen und Rechnen mit den Fingern: Hilfe, Sackgasse oder bloßer Übergang auf dem Weg zu komplexen arithmetischen Kompetenzen? [Finger counting and calculation: Support, dead end, or transition on the way to complex arithmetic competencies]. *Lernen und Lernstörungen, 1*(1), 33-53. doi:10.1024/2235-0977/a000004

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature, 215*, 1519-1520. doi:10.1038/2151519a0

Nuerk, H.-C., Iversen, W., & Willmes, K. (2004). Notational modulation of the SNARC and the MARC (linguistic markedness of response codes) effect. *The Quarterly Journal of Experimental Psychology, 57A*(5), 835-863. doi:10.1080/02724980343000512

Patro, K., Nuerk, H.-C., & Cress, U. (2015). Does your body count? Embodied influences on the preferred counting direction of preschoolers. *Journal of Cognitive Psychology, 27*, 413-425. doi:10.1080/20445911.2015.1008005

Pinheiro-Chagas, P., Dotan, D., Piazza, M., & Dehaene, S. (2017). Finger tracking reveals the covert processing stages of mental arithmetic. *Open Mind: Discoveries in Cognitive Science, 1*, 30-41. doi:10.1162/OPMI_a_00003

Priftis, K., Zorzi, M., Meneghello, F., Marenzi, R., & Umiltà, C. (2006). Explicit versus implicit processing of representational space in neglect: Dissociations in accessing the mental number line. *Journal of Cognitive Neuroscience, 18*(4), 680-688. doi:10.1162/jocn.2006.18.4.680

R Development Core Team. (2014). *R: A Language and Environment for Statistical Computing.* Vienna, Austria: R Foundation for Statistical Computing.

Roettger, T. B., & Domahs, F. (2015). Grammatical number elicits SNARC and MARC effects as a function of task demands. *Quarterly Journal of Experimental Psychology, 68*(6), 1231-1248. doi:10.1080/17470218.2014.979843

Song, J.-H., & Nakayama, K. (2008). Numeric comparison in a visually-guided manual reaching task. *Cognition, 106*(2), 994-1003. doi:10.1016/j.cognition.2007.03.014

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). From the cover: Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences of the United States of America, 102*(29), 10393-10398. doi:10.1073/pnas.0503903102

van Galen, M. S., & Reitsma, P. (2008). Developing access to number magnitude: A study of the SNARC effect in 7- to 9-year-olds. *Journal of Experimental Child Psychology, 101*(2), 99-113. doi:10.1016/j.jecp.2008.05.001

Viviani, P., & McCollum, G. (1983). The relation between linear extent and velocity in drawing movements. *Neuroscience, 10*(1), 211-218. doi:10.1016/0306-4522(83)90094-5

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

Walsh, V. (2015). A theory of magnitude: The parts that sum to number. In R. Cohen Kadosh & A. Dowker (Eds.), *The Oxford handbook of numerical cognition* (pp. 552–565). doi:10.1093/oxfordhb/9780199642342.013.64

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. doi:10.1016/S0010-9452(08)70219-3

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