Experiential Origins of the Mental Number Line

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Abstract

People map numbers onto horizontal space, forming an implicit mental number line (MNL). The direction of the MNL, which varies across cultures, has often been attributed to the direction of reading and writing words. Yet, this proposal is neither clearly motivated nor well supported by experimental data. Here we tested the hypothesis that finger-counting habits can determine the direction of the MNL. Americans were trained to count on their fingers from left to right or from right to left. After rightward counting, participants showed implicit associations of small numbers with left space and large numbers with right space, typical for Americans. After leftward counting, this space-number association was extinguished, overall, and was qualitatively reversed in a significant proportion of the individual participants. A few minutes of finger counting experience can redirect the MNL, supporting a causal role for finger counting in the acquisition and maintenance of culture-specific mental number lines.

Keywords: SNARC; finger counting; embodied cognition; numerical cognition; motor experience

Introduction

Across many cultures, people use space to think about number. In English speaking cultures, small numbers are associated with the left side of an implicit mental number line (MNL), and large numbers with the right side (Restle, 1970). The most abundant source of evidence for this MNL is the Spatial-Numerical Association of Response Codes, or SNARC effect: People tend to respond faster to small numbers with their left hand and to large numbers with their right hand, even when the magnitude of the number is irrelevant to their response (Dehaene, Bossini, & Giraux, 1993). Although the MNL has been the subject of more than 100 experiments (Wood, Willems, Nuerk, & Fischer, 2008), there is little consensus about its developmental origins (de Hevia & Spelke, 2009; 2010; cf., Gebuis & Gevers, 2011).

Where does this spatial mapping of number come from? Cross-cultural variation in the MNL provides clues to the origin of its directionality. According to one account, still widely accepted, the direction of reading and writing in a culture determines the direction of the MNL. In general, people from left-to-right reading cultures show MNLs that increase from left to right (e.g. French; Dehaene et al., 1993; Scots: Fischer, 2008; Canadians; Shaki, Fischer, & Petrusic, 2009), whereas people from some Arabic cultures show MNLs in the opposite direction (i.e. small numbers on the right, large numbers on the left), consistent with the right-to-left direction of reading in their cultures (Palestinians: Shaki et al., 2009; Lebanese: Zebian, 2005).

Yet, overall, the available evidence calls into question the role of reading experience in determining the direction of the MNL. In their seminal study, Dehaene and colleagues (1993) found "no evidence" of a reversed SNARC effect in Iranian immigrants living in France who had extensive exposure to a right-to-left orthography. Another study found a reversed SNARC effect among Arabic-speaking Palestinians but no SNARC effect among Hebrew-speaking Israelis, who also read text from right to left (Shaki et al., 2009). Across cultures, the direction of people's MNL appears to be only loosely correlated with the direction in which they read and write text. Furthermore, evidence of a culture-specific MNL has been found in preliterate children as young as 3 years old (Hoffmann, Hornung, Martin, & Schiltz, 2013; Opfer, Thompson, & Furlong, 2010; Shaki, Fischer, & Göbel, 2012). Finally, the only direct experimental test of the effect of reading experience on the direction of the MNL produced a null result. French participants responded to number words in either standard or mirror-reversed orthography. Orthography had no effect on the strength or direction of the SNARC (Dehaene et al., 1993; Experiment 8). Although Dehaene and colleagues concluded that, "[t]he particular direction of the spatial-numerical association seems to be determined by the direction of writing," (1993, pg. 394) there is little empirical support for this claim. *Some* cultural practices appear to determine the direction of the MNL, but which ones?

Does Finger Counting Shape the MNL?

The direction of the MNL has also been attributed to finger counting. People whose finger-counting routines start with the left hand (habitual left-starters) were found to be more likely to show a standard SNARC effect than those who started with their right hand (habitual right-starters; Fischer, 2008). Across cultures, finger-counting habits appear to covary with writing direction. Reportedly, Americans and western Europeans tend to be left-starters, whereas Persian-speaking Iranians tend to be right-starters (Lindemann, Alipour, & Fischer, 2011; but see Di Luca, Granà, Semenza, Seron, & Pesenti, 2006; Sato, Cattaneo, Rizzolatti, & Gallese, 2007; Sato & Lalain, 2008). Could differences in finger-counting habits contribute to the observed cross-cultural variation in the MNL?

A variety of behavioral, neuropsychological, and brain-imaging studies reveal tight links between fingers and numbers. In many numerate cultures, children learn to count on their fingers (Butterworth, 2000). Their ability to differentiate fingers predicts later numerical abilities (Fayol, Barrouillet, & Marinthe, 1998; Noël, 2005) and training this ability improves their performance on some numerical reasoning tasks (Gracia-Bafallu & Noël, 2008). In adults, passively viewing hands in canonical finger-counting postures facilitates processing of the corresponding Arabic numerals (Badets, Pesenti, & Olivier, 2010; Di Luca & Presenti, 2008). Likewise, people are fastest to respond to single digits when the response mapping between numbers and fingers matches their own finger-counting routine (DiLuca et al., 2006). The influence of the hands is also evident in arithmetic, where both children and adults commit a disproportionate number of *split-five errors*: answers that differ from the correct answer by exactly five (e.g. 18 – 7 = 6; Domahs, Krinzinger, & Willmes 2008; Domahs, Moeller, Huber, Willmes, & Nuerk, 2010). Neurostimulation studies support functional relationships beteween hands and numbers. In participants who habitually count on their fingers from left to right, transcranial magnetic stimulation (TMS) to motor cortex increased excitability in right (but not left) hand muscles in response to small numbers (1-4) relative to large numbers (6-9) and controls; this pattern was found even when number magnitude was irrelevant to the task (Sato et al., 2007).

These associations between fingers and numbers in healthy participants are reflected in patients with brain damage, as well. Patients with Gerstmann syndrome show both severe acalculia (mathematical impairment) and finger agnosia (inability to distinguish the fingers of one's hand), often as a result of damage to the left angular gyrus of the parietal lobe (Gerstmann, 1940). Producing transient lesions in this brain region using repeated transcranial magnetic stimulation (rTMS) produces the same deficits in finger differentiation and numerical processing as Gerstmann observed, suggesting a functional overlap between representations of numbers and fingers in the parietal cortex (Rusconi, Walsh, & Butterworth, 2005). Likewise, fMRI data show overlap in the BOLD signal pattern in bilateral parietal cortex during simple arithmetic and finger-discrimination tasks (Andres, Michaux, & Pesenti, 2012; but see Andres, Seron, & Olivier, 2007).

Together, these findings lend support to "manumerical" accounts of numerical cognition, which posit a critical functional role for the fingers in the representation and manipulation of numbers (Fischer & Brugger, 2011; Wood & Fischer, 2008; see also Di Luca & Presenti, 2011). Yet, despite a wealth of data linking number representations with the fingers, there has been no experimental test of the relationship between finger counting and the construction of the MNL. On the basis of the data reviewed above, it is not possible to determine whether culture-specific finger-counting habits are a *cause* or an *effect* of culture-specific mental number lines.

To test for effects of finger counting on the direction of the MNL, here we trained participants to count on their fingers in one of two randomly-assigned patterns, one increasing from left to right (rightward) and the other increasing from right to left (leftward). After training, we assessed the strength and direction of participants' mental number lines as indexed by the SNARC effect. We reasoned that if finger-counting habits can play a causal role in determining the direction of the MNL, then manipulating the direction of finger counting should cause corresponding differences in the direction of the MNL.

Method

Participants

Thirty-two right-handers from the New School for Social Research and the New York City area participated for payment. Half were randomly assigned to the leftward counting condition (n = 16) and the other half to the rightward counting condition (n = 16).

Materials and Procedure

Participants performed a two-part experiment in which a training phase was followed by a test phase. In the training phase, participants counted on their fingers according to one of two randomly-assigned patterns. In the test phase, participants performed two standard tests of the SNARC effect, a parity-judgment task and a magnitude-judgment task, with the order of these tasks counterbalanced across subjects using a Latin square design.

During both the training and test phases participants sat at a desk in front of an Apple iMac computer (Apple Inc., Cupertino, CA). Instructions and stimuli were presented in white text on a black background in the center of the screen, approximately at eye level. All numbers were displayed as Arabic numerals.

Training Phase. The experimenter asked participants to count on their hands from 1 to 10 and documented their spontaneous finger-counting pattern. He then stood to the left of the participant, facing the same direction, and demonstrated the randomly-assigned finger-counting pattern once. Participants then repeated the pattern once in tandem with the experimenter and once on their own before continuing. In the rightward counting condition, participants counted from left to right, starting with the left thumb and ending with the right thumb. In the leftward counting condition, participants counted in the opposite direction, starting with the right thumb and ending with the left thumb. Both hands were kept in the supine position (palms up) during all counting tasks.

After participants were familiarized with the leftward or rightward finger-counting pattern, they practiced the pattern during three computer-based training tasks. In all three tasks, the integers 1 through 10 were presented on the screen. Participants were required to represent the presented number on their fingers using the finger-counting pattern they had just practiced. Instructions appeared on the screen at the beginning of each task. In task A, participants started with their hands closed and counted up to the number displayed, saying each number aloud while extending the corresponding finger. In task B, participants started with their hands closed and extended the set of fingers corresponding to the number displayed on the screen (all at once) while saying the number aloud. In task C, participants held their hands open and wiggled the finger that corresponded to the number displayed while saying the number aloud. After the participant successfully completed each trial, the experimenter advanced to the next trial by pressing a key on a keyboard out of sight of the participant. All ten integers were presented in random order three times in task A and twice in tasks B and C. Participants performed three rounds of this training sequence (i.e. ABC, ABC, ABC), completing a total of 210 training trials. Training lasted about 15 minutes, and was recorded by a digital video camera positioned to the left and out of sight of participants.

Test Phase. After training, participants performed two standard tests of the SNARC effect: a parity judgment task and a magnitude judgment task. The order of these tasks was counterbalanced across participants. For both tasks, they were instructed to respond as quickly and accurately as possible to the numbers on screen by pressing one of two keys (“a” and “’” on the English-US keyboard), each covered by a yellow sticker.

In the parity judgment task, participants were instructed to press the yellow key on the left for odd numbers and the yellow key on the right for even numbers for one block of trials. In a second block this mapping was reversed, and the order of blocks was counterbalanced across participants. Each of eight digits (1 through 9 except 5) was presented eight times in random order, yielding 64 trials per block. Each trial began with a fixation cross for 500ms, after which the digit appeared and remained on the screen until the participant responded. Participants used their left index finger to press the left key and their right index finger to press the right key.

The materials and procedures used in the magnitude judgment task were identical to those used in the parity judgment task, with the exception of the task instructions. In one block, participants were instructed to press the yellow key on the left for numbers less than 5 and the yellow key on the right for numbers greater than 5. In a second block this mapping was reversed and the order of blocks was counterbalanced across participants. In total, each participant completed 256 trials across 4 blocks (2 parity judgment blocks and 2 magnitude judgment blocks). The order of blocks and tasks was counterbalanced across participants using a latin square design.

After testing, participants completed a language history questionnaire and the Edinburgh Handedness Inventory (Oldfield, 1971) and were subsequently debriefed.

Results

Parity Judgment Task

The average error rate was 3.8% and did not differ significantly between training conditions ($\chi^2(1, N = 32) = .02$, $p = .89$). Inaccurate trials were excluded from the reaction time (RT) analyses as were trials with RTs greater than 2.5 standard deviations from the average, which accounted for 2% of accurate responses.

To evaluate the strength of the SNARC effect in each participant, mean RTs for each digit were calculated for participants’ left hand and right hand responses. The difference (right minus left) was then regressed over digit magnitude to obtain non-standardized regression coefficients representing each participant’s mapping of numbers onto space (Fig 1a).

In the rightward counting condition, the mean slope was -10.84 ms/digit ($t(15) = -4.02$, $p = .001$), indicating a standard SNARC effect in which small numbers are mapped to the left and large numbers are mapped to the right. By contrast,

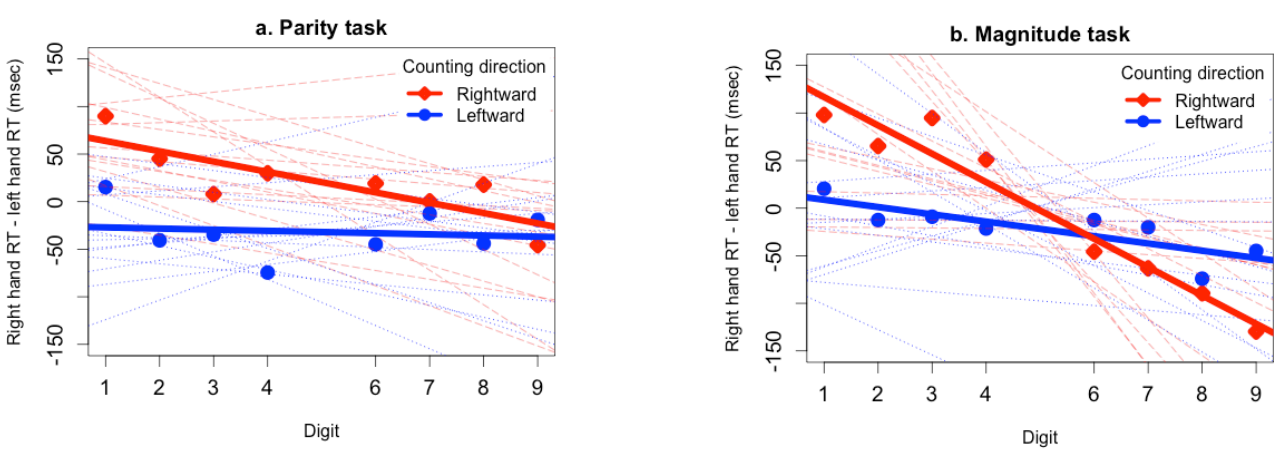

Figure 1. SNARC effects by task and condition. Bold lines show group effects, dashed lines show individual effects in the rightward counting condition, and dotted lines show individual effects in the leftward counting condition.

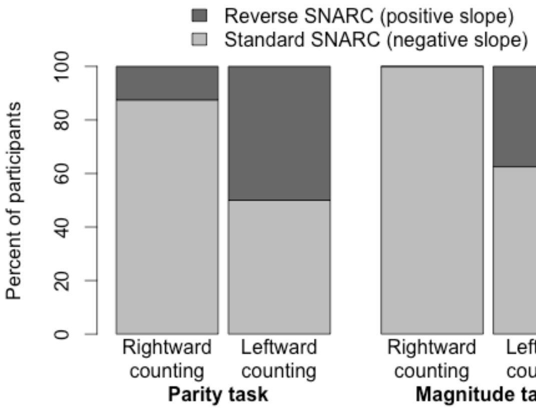

Figure 2. Direction of individual SNARC effects.

the mean slope in the leftward counting condition was only -1.23 ms/digit, and showed no reliable SNARC effect (t(15) = -.42, *p* = .68). Importantly, these slopes differed significantly between training conditions (F(1, 30) = 5.79, *p* = .02), indicating that the finger counting training was sufficient to modulate the strength of the SNARC effect.

The effect of finger-counting training was also evident in a comparison of the proportion of participants in each condition with positive slopes (reversed SNARC effect) vs. negative slopes (standard SNARC effect): only 2 of 16 participants (12.5%) in the rightward counting condition showed a positive slope, whereas 8 out of 16 participants (50%) in the leftward counting condition showed a positive slope, indicating a reversed SNARC effect (one-tailed Fisher's Exact p=.02; fig 2).

Magnitude Judgment Task

Data from one participant who failed to follow instructions were excluded. The average error rate in the remaining 31 participants was 2.9% and did not differ significantly between training conditions (χ^2(1, N = 31) = 2.10, *p* = .15). Inaccurate trials were excluded from RT analyses as were trials with RTs greater than 2.5 standard deviations from the average, which accounted for 2% of accurate responses.

In the rightward counting condition, the mean slope was -29.8 ms/digit (t(14) = -4.11, *p* = .001), indicating a strong SNARC effect. By contrast, the average slope in the leftward counting condition was only -7.66 ms/digit and did not differ from zero (t(15) = -1.63, *p* = .12). As in the parity judgment task, the average SNARC effect differed as a function of finger counting training, as indicated by a significant difference between the mean slopes (F(1, 29) = 6.73, *p* = .01).

This effect of finger counting training was also reflected in an analysis of the polarity of the SNARC effect slopes in the individual participants:,whereas 0 of 15 participants (0%) in the rightward counting condition showed a positive slope, 6 of 16 participants (37.5%) in the leftward counting condition did so (one-tailed Fisher's Exact *p* = .03; fig 2).

In summary, on the basis of the averaged data, it appears that the SNARC effect was extinguished after rightward finger counting, but not reversed. Yet, analyses of the individual participants' slopes suggest that group averaging was obscuring an informative pattern. After rightward finger counting, most participants showed the standard negative SNARC effect slope; very few participants showed a positive slope (12.5% in the Parity task; 0% in the Magnitude task). By contrast, after leftward finger counting, a significantly greater proportion of the participants showed a qualitatively reversed SNARC effect (i.e., a positive slope: 50% in the Parity task; 37.5% in the Magnitude task). If about 15 minutes of rightward finger counting can cause up to 50% of participants to show qualitatively reversed SNARC effects, perhaps more sustained leftward finger-counting experience would cause not only a modulation of the SNARC effect but also a significant reversal in the group-averaged data.

Discussion

Ordinarily, native English speakers' implicit mental number line increases from left to right (e.g. Fischer, 2008; Shaki et al., 2009). Yet, just a few minutes of finger counting dramatically changed this space-number mapping. Whereas training with a rightward finger-counting routine produced a standard SNARC effect, training with a leftward finger-counting routine abolished this effect at the group level. At the individual level, leftward finger counting caused more participants to show a qualitatively reversed SNARC effect than rightward finger counting. These results provide the first evidence that finger counting can play a causal role in determining the direction of the mental number line.

How experience shapes mental metaphors

Number is one of several abstract concepts people associate with left-right space, but different concepts are spatialized on the basis of different kinds of experience. Like left-right spatial mappings of time (Tversky, Kugelmass, & Winter, 1991) and emotional valence (Casasanto, 2009), space-number mappings can be considered to be a *mental metaphor*: an implicit association between analog continuums in two different conceptual domains, in which the *source domain* (e.g., space) serves as a scaffold for representations in the *target domain* (e.g., number), which is typically more abstract (Casasanto, 2010; Lakoff & Johnson, 1980). The specifics of these mental metaphors are established through correlations in particular kinds of experience. In the case of time, the act of reading establishes a correlation between progress through space and time in one direction or the other. When reading each line of an English text, the reader's eyes begin on the left side (at an earlier time) and end up on the right side (at a later time). This correlation between space and time results in a culture-specific mental timeline in which earlier events are on the left and later events are on the right, which can be transiently reversed when people are exposed to mirror-reversed text (Casasanto & Bottini, 2014).

In the case of emotion, people experience a correlation between space and motor fluency: We tend to act more fluently on our dominant side of space, and more clumsily on our non-dominant side. Since fluent actions are associated with positive emotions, right-handers come to implicitly associate "good" with "right" and "bad" with "left," whereas left-handers show the opposite associations. These body-specific associations can be reversed by making the non-dominant hand temporarily more fluent than the domiant hand (Casasanto & Chrysikou, 2011).

How are space and number related in experience? In finger counting, each number in the count list corresponds to the spatial position of one finger. For rightward finger counters, low numbers are on the left and high numbers are on the right, and vice versa for leftward counters. In contrast with finger counting, the process of reading written words does not seem to provide any correlation between space and number (unless people count words as they read, which seems doubtful). The direction of the MNL is not likely to be conditioned by the direction of reading and writing, *per se* (cf., Dehaene, et al., 1993), but rather by other culture-specific conventions like finger counting.

Finger counting and the MNL across cultures

Although the direction of finger counting covaries with the direction of the MNL, the correlation may not be perfect. In Americans and western European cultures, finger-counting habits have been observed to progress from left to right (Lindemann et al., 2011), consistent with the direction of the standard SNARC effect in those cultures (e.g. Crollen, Dormal, Seron, Lepore & Collignon, 2013; Fischer, 2008; Shaki et al., 2009). However, some studies have found leftward finger-counting habits in participants from cultures where standard SNARC effects have also been observed (Italians: Di Luca et al., 2006; Sato et al., 2007; French: Sato & Lalain, 2008). As none of these studies tested finger-counting habits and the SNARC effect in the same participants, it is possible that such within-subject tests would reveal subject-by-subject covariation between finger counting habits and the direction of the MNL, within cultures (see Fischer, 2008). Discrepencies between the direction of the SNARC and the direction of reported finger-counting habits may also be due to the method by which finger counting was assessed. Self-reported finger-counting habits differ from those produced spontaneously (Lucidi & Thevenot, 2014). Finger-counting habits have not been studied in either of the cultures in which clear reverse SNARC effects have been observed (Palestinians: Shaki et al., 2009; Lebanese: Zebian, 2005); if members of these cultures tend to count from right to left, this finding would support the hypothesis that finger-counting habits can determine the direction of the MNL.

Do other cultural practices shape the MNL?

Numbers are systematically spatialized not just on the fingers but also on calendars, graphs, rulers, keyboards, and on written number lines. Thus, written numbers provide another plausible experiential basis for the MNL. The direction of written numbers varies across cultures. In Hebrew, the direction of written numbers dissociates from the directon of written words. Hebrew speakers, who read words from right to left but read numbers from left to right, show SNARC effects that are reliably shallower than Arabic speakers, who read both words and numbers from right to left (Shaki et al., 2009). The spatial position of numbers on the page has been shown to rapidly modulate the SNARC effect. In a training experiment, reading text in which small numbers appeared on the right and large numbers appeared on the left caused a positive shift in the slope of participants' SNARC effects, even though reading direction was held constant across conditions (Fischer, Mills, & Shaki, 2010). Thus, the direction of written numbers can influence the MNL even when in direct conflict with the direction of written words. The relative contributions of number reading and finger counting to the construction and maintenance of the MNL have yet to be determined.

References

Andres, M., Michaux, N., & Pesenti, M. (2012). Common substrate for mental arithmetic and finger representation in the parietal cortex. *Neuroimage*, *62*(3), 1520-1528.

Andres, M., Seron, X., & Olivier, E. (2007). Contribution of hand motor circuits to counting. *Journal of Cognitive Neuroscience*, *19*(4), 563–76.

Badets, A., Pesenti, M., & Olivier, E. (2010). Response–effect compatibility of finger–numeral configurations in arithmetical context. *The Quarterly Journal of Experimental Psychology*, *63*(1), 16–22.

Butterworth, B. (2000). *The mathematical brain*. London: Macmillan

Casasanto, D. (2009). Embodiment of abstract concepts: good and bad in right-and left-handers. *Journal of Experimental Psychology: General*, *138*(3), 351.

Casasanto, D. (2010). Space for thinking. In V. Evans. & P. Chilton (Eds.), *Language, Cognition and Space*. (453-478). New York: Equinox.

Casasanto, D., & Bottini, R. (2014). Mirror Reading Can Reverse the Flow of Time. *Journal of Experimental Psychology: General*. 143(2), 473-9.

Casasanto, D., & Chrysikou, E. G. (2011). When left is "right" motor fluency shapes abstract concepts. *Psychological Science*, *22*(4), 419-422.

Crollen, V., Dormal, G., Seron, X., Lepore, F., & Collignon, O. (2011). Embodied numbers: The role of vision in the development of number–space interactions. *Cortex*, *49*(1), 276–83.

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

de Hevia, M. D., & Spelke, E. S. (2009). Spontaneous mapping of number and space in adults and young children. *Cognition*, *110*(2), 198-207.

de Hevia, M. D., & Spelke, E. S. (2010). Number-space mapping in human infants. *Psychological Science*, *21*(5), 653-660.

Di Luca, S., Granà, A., Semenza, C., Seron, X., & Pesenti, M. (2006). Finger–digit compatibility in Arabic numeral processing. *The Quarterly Journal of Experimental Psychology*, *59*(9), 1648-1663.

Di Luca, S., & Pesenti, M. (2008). Masked priming effect with canonical finger numeral configurations. *Experimental Brain Research*, *185*(1), 27-39.

Di Luca, S., & Pesenti, M. (2011). Finger numeral representations: more than just another symbolic code. *Frontiers in Psychology*, *2*, 272.

Domahs, F., Krinzinger, H., & Willmes, K. (2008). Mind the gap between both hands: Evidence for internal finger-based number representations in children's mental calculation. *Cortex*, *44*(4), 359-367.

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), 251–66.

Fayol, M., Barrouillet, P., & Marinthe, C. (1998). Predicting arithmetical achievement from neuro-psychological performance: a longitudinal study. *Cognition*, *68*(2), 63–70.

Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex*, *44*(4), 386–92.

Fischer, M. H., Mills, R. A., & Shaki, S. (2010). How to cook a SNARC: number placement in text rapidly changes spatial–numerical associations. *Brain and Cognition*, *72*(3), 333-336.

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*, 260.

Gebuis, T., & Gevers, W. (2011). Numerosities and space; indeed a cognitive illusion! A reply to de Hevia and Spelke (2009). *Cognition*, *121*(2), 248-252.

Gerstmann, J. (1940). Syndrome of finger agnosia, disorientation for right and left, agraphia and acalculia: local diagnostic value. *Archives of Neurology and Psychiatry*, *44*(2), 398.

Gracia-Bafalluy, M., & Noël, M.-P. (2008). Does finger training increase young children's numerical performance? *Coretx*, *44*(4), 368–375.

Hoffmann, D., Hornung, C., Martin, R., & Schiltz, C. (2013). Developing number-space associations: SNARC effects using a color discrimination task in 5-year-olds. *Journal of Experimental Child Psychology*, *116*(4), 775–91.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago, IL: University of Chicago Press.

Lindemann, O., Alipour, a., & Fischer, M. H. (2011). Finger Counting Habits in Middle Eastern and Western Individuals: An Online Survey. *Journal of Cross-Cultural Psychology*, *42*(4), 566–578.

Lucidi, A., & Thevenot, C. (2014). Do not count on me to imagine how I act: behavior contradicts questionnaire responses in the assessment of finger counting habits. *Behavior Research Methods*, 1-9.

Noël, M. P. (2005). Finger gnosia: a predictor of numerical abilities in children?. *Child Neuropsychology*, *11*(5), 413-430.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113.

Opfer, J. E., Thompson, C. a, & Furlong, E. E. (2010). Early development of spatial-numeric associations: evidence from spatial and quantitative performance of preschoolers. *Developmental Science*, *13*(5), 761–71.

Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology*, *83*(2), 274-278.

Rusconi, E., Turatto, M., & Umiltà, C. (2007). Two orienting mechanisms in posterior parietal lobule: an rTMS study of the Simon and SNARC effects. *Cognitive Neuropsychology*, *24*(4), 373–92.

Rusconi, E., Walsh, V., & Butterworth, B. (2005). Dexterity with numbers: rTMS over left angular gyrus disrupts finger gnosis and number processing. *Neuropsychologia*, *43*(11), 1609-1624.

Riello, M., & Rusconi, E. (2011). Unimanual SNARC Effect: Hand Matters. *Frontiers in Psychology*, *2*, 372.

Sato, M., Cattaneo, L., Rizzolatti, G., & Gallese, V. (2007). Numbers within our hands: modulation of corticospinal excitability of hand muscles during numerical judgment. *Journal of Cognitive Neuroscience*, *19*(4), 684–93.

Sato, M., & Lalain, M. (2008). On the relationship between handedness and hand-digit mapping in finger counting. *Cortex*, *44*(4), 393–9.

Shaki, S., Fischer, M. H., & Göbel, S. M. (2012). Direction counts: a comparative study of spatially directional counting biases in cultures with different reading directions. *Journal of Experimental Child Psychology*, *112*(2), 275–81.

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review*, *16*(2), 328–31.

Tversky, B., Kugelmass, S., & Winter, A. (1991). Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology*, *23*(4), 515-557.

Wood, G., & Fischer, M. H. (2008). Numbers, space, and action - from finger counting to the mental number line and beyond. *Cortex*, *44*(4), 353–8.

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

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