NUMBER-SPACE ASSOCIATIONS IN SYNAESTHESIA ARE NOT INFLUENCED BY FINGER-COUNTING HABITS

Clare N. Jonas[1,2*] and Jamie Ward[3,4]

[1]School of Psychology and Neuroscience, University of St Andrews, U.K.

[2]School of Psychology, University of East London, U.K.

[3]School of Psychology, University of Sussex, U.K.

[4]Sackler Centre for Consciousness Science, University of Sussex, U.K.

Short title: Role of finger-counting in synaesthesia

*Corresponding author:

Clare N. Jonas,

School of Psychology

University of East London

Stratford Campus

Water Lane

London E15 4LZ

Tel: +44 (0) 20 8223 4659

Fax: +44 (0) 20 8223 4937

Email: c.n.jonas@uel.ac.uk

Abstract

In many cultures, one of the earliest representations of number to be learned is a finger-counting system. Although most children stop using their fingers to count as they grow more confident with number, traces of this system can still be seen in adulthood. For example, an individual's finger-counting habits appear to affect the ways in which numbers are implicitly associated with certain areas of space, as inferred from the spatial-numerical association of response codes (SNARC) effect. In this study, we questioned the finger-counting habits of 98 participants who make explicit, idiosyncratic associations between number and space, known as number-space synaesthesia. Unexpectedly, neither handedness nor finger-counting direction (left-to-right or right-to-left) was associated with the relative positions of 1 and 10 in an individual's number-space synaesthesia. This lack of association between finger-counting styles and number-space synaesthesia layout may result from habitual use of synaesthetic space rather than fingers when learning to count; we offer some testable hypotheses that could assess whether this is the case.

Keywords: embodiment; number; manumerical cognition; synaesthesia

Introduction

There are multiple ways in which number can be represented. In the Western world, the most common representation system is based on the Arabic numerals 1, 2, 3, etc. (Dehaene, 1997). Among other systems, it is also possible to represent numbers using the fingers. Finger-counting is likely to be one of the evolutionary roots of human numeracy, giving us a ready-made tally on which to count (Wiese, 2007) and providing us with names for numbers (e.g. Ifrah, 1987). Developmentally, fingers are a useful tool in learning to count and calculate, potentially aiding the understanding of many aspects of number such as magnitude comparison and calculation (Baroody & Wilkins, 1999; Levine, Jordan & Huttenlocher, 1992; but see Crollen, Seron, & Noël, 2011). This habitual co-opting of fingers to aid in counting is known as *manumerical cognition* (Wood & Fischer, 2008). Fingers and numbers are so strongly tied together that the extent to which a child is able to discriminate the fingers by unseen touch – an ability known as finger gnosia – is highly predictive of certain numerical skills (Costa et al., 2011), and training finger gnosia can improve numerical skills (Gracia-Bafalluy & Noël, 2008). Even in adulthood, traces of manumerical cognition can be seen in some numerical tasks (Badets, Pesenti, & Olivier, 2010; Imbo, Vandierendonck, & Fias, 2011; Klein, Moeller, Willmes, Nuerk, & Domahs, 2011).

The manner in which finger-counting is carried out is highly inter-culturally variable. In many cultures, fingers are considered the units to be counted, but other features of the hands may be used instead, such as the creases on the glabrous surface of the fingers (e.g. the Indian counting system; Guha, 2006). Some counting systems extend beyond the fingers to encompass the toes, arms or other body parts (e.g. the Oksapmin counting system; Saxe, 1981). In cases where only the fingers are used, the fingers of different hands or different parts of hands may be used to represent bases and powers of numbers (e.g. the Babylonian counting system; Bender & Beller, 2012), or some numbers may be represented symbolically (e.g. the Chinese counting system; Domahs, Moeller, Huber, Willmes, & Nuerk, 2010). In the most widely studied variant of finger-counting, each finger represents one number, meaning that the total quantity that can be counted on the fingers is ten. Even here, there is some inter- (and intra-) cultural variation: in the United Kingdom there is a preference to start counting on the left thumb, but in France the preferred starting digit is the right thumb and in Iran it is the right little finger (Fischer, 2008; Lindemann, Alipour, & Fischer, 2011; Sato & Lalain, 2008).

Though finger-counting is an obvious and intuitive way of mapping numbers onto (bodily) spatial locations, it is one of several associations that humans are known to make between number and space. The first of these alternate associations is the tendency to implicitly associate large numbers with one part and small numbers with another part of bodily space. These associations are typically tested using a parity judgement task: a number is presented in the centre of a screen in front of the participant, who judges whether the number is odd or even, and makes a key-press response with her left or right hand to indicate her decision. The resulting pattern of response times shows that certain numbers are more easily categorized with one hand than with another. This is known as the spatial-numerical association of response codes (SNARC) effect (Dehaene, 1992). Among the French-speaking sample who took part in the original study, the SNARC effect was such that small numbers in the stimulus set were categorized more quickly with left responses and large numbers more quickly with right responses (Dehaene, Bossini, & Giraux, 1993). However, among Palestinian participants categorising Arabic-Indic numbers, the association is small-right/large-left (Shaki, Fischer, & Petrusic, 2009), and in Taiwanese participants categorising simple-form Chinese numbers it is small-top/large-bottom (Hung, Hung, Tzeng, & Wu, 2008). Evidently, there is a cultural component to the SNARC effect, though there is also some intracultural variation: Fischer and Campens (2009) asked blindfolded participants to point to the location of various numbers and found that while most produced the dominant cultural mapping of small-left/large-right, a subset of participants produced linear responses in other dimensions (e.g. small-near/large-far). This overall tendency for participants to produce certain mappings in certain cultural contexts was initially attributed to the direction in which written language is read (Dehaene et al., 1993), but recently several researchers have begun to explore other effects that may be at work, including teaching methods and finger-counting (Göbel, Shaki, & Fischer, 2011). In the largest study so far which has directly examined the link between finger-counting and SNARC effects, Fischer (2008) performed a large-scale study of the finger-counting habits of people in a British city, and then tested a subset of these participants on a parity judgement task. He found that the SNARC effect was significantly weaker in those who started counting on their right hand than those who started on their left hand - that is, when an individual's finger-counting direction was in conflict with the general tendency in the United Kingdom to map small numbers to the left and large numbers to the right, the SNARC effect was diminished. However, Tschentscher, Hauk, Fischer, and Pulvermüller (2012) failed to replicate this result in left- and right-starters in another English-speaking sample, instead finding that both groups showed a significant large-left/small-right SNARC effect. Furthermore, Fabbri (2013) failed to replicate this finding in an Italian-speaking sample, finding that the culturally-dominant right-starters showed a non-significantly *stronger* SNARC effect than left-starters.

Generally, the SNARC effect is presumed to indicate an implicit, linear association between number and space known as the mental number line (Dehaene et al., 1993; but see Santens & Gevers, 2008). However, parity judgement tasks have also been used to assess explicit associations in the small percentage of the population who have number-space synaesthesia, a third way in which number and space can be associated. Among this group, numbers 'belong to' certain locations in the mind's eye or in the space around the body, and those locations are apparent to the synaesthete. These number-space associations are called number forms. Interestingly, while the synaesthete exists as part of a culture in which most people have a mental number line oriented in a particular direction, his/her number form may or may not reflect those cultural pressures. Though number forms are often linear, they do not necessarily have the same orientation as the cultural mental number line. Further, they may take on highly individualised shapes with curves, breaks, loops or spirals (Sagiv, Simner, Collins, Butterworth, & Ward, 2006). Work with parity judgement tasks in these synaesthetes has found mixed results: in some synaesthetes, the SNARC effect conforms to the shape of the number form (Jarick, Dixon, Maxwell, Nicholls, & Smilek, 2009), while in others it does not (Hubbard, Ranzini, Piazza, & Dehaene, 2009; Piazza, Pinel, & Dehaene, 2006). Recently, it has been suggested that the parity judgement task may not be an appropriate means of measuring synaesthetic experience, potentially because number forms are not involved in such judgements (Jonas & Jarick, in press ; Jonas, Spiller, Jansari, & Ward, submitted; Price & Mattingley, in press).

Number-space synaesthesia is just one of a larger group of sequence-space synaesthesias in which ordinal sequences such as days of the week, letters of the alphabet, or even pure-breed dog naming conventions or signs of the zodiac are laid out in space (Hubbard et al., 2009; Seymour, 1980). Body specificity (differences in cognition resulting from differences in interaction with the environment, in turn resulting from differences in bodily characteristics such as handedness; Casasanto, 2009, 2011) and experience are known to play roles in these, and other, synaesthesias. For example, right-handed time-space synaesthetes with circular month forms tend to perceive the months as being laid out in a clockwise format, while left-handed synaesthetes' circular layouts are more commonly anticlockwise (Brang, Teuscher, Miller, Ramachandran, & Coulson, 2011). Similarly, the need to take a breath at certain points when reciting the alphabet seems to have shaped the breaks, bends and other features seen in alphabet-space synaesthesia (Jonas, Taylor, Hutton, Weiss, & Ward, 2011).

In the current study, we used a questionnaire study to investigate whether there was an association between the layout of a number form and the handedness and finger-counting habits of the synaesthete it belonged to. Based on the above tentative evidence of the link between the SNARC effect and finger-counting in non-synaesthetes as well as the roles of body specificity and experience in other forms of synaesthesia, it was predicted that participants who started counting on the left hand would generally locate 10 to the right of 1 in their number form (i.e. the two forms of counting would be laid out in space in a similar way), while participants who started counting on the right hand, would generally locate 10 to the left of 1 in their number form. However, the ambiguous evidence on the link between the SNARC effect and finger-counting as well as the link between the SNARC effect and number forms meant that we approached these predictions with caution. Synaesthetes were also predicted to show an effect of handedness, as in time-space synaesthetes' month forms. Given that Brang et al. (2011) looked at circular month forms, but the number lines we examined were mainly linear, exactly what form this effect would take was unclear. Since handedness and finger-counting habits do not appear to be related (Fischer, 2008), we did not expect an interaction between these two effects in terms of the relative locations of 1 and 10.

Methods

All synaesthetes registering with the Sussex-Edinburgh Synaesthete Database are asked to fill out a questionnaire on their synaesthesia. Those who gave an answer of 'agree' or 'strongly agree' to the question 'Do you think about the numbers being arranged in a specific pattern in space (e.g. in a line, or circle)?' and/or had provided a diagram or description of their number-space synaesthesia were eligible to take part in this experiment (N = 405). We also asked participants whether they were left-handed, right-handed or ambidextrous in this questionnaire using a single self-report question. Of our eligible participants, 278 had provided working email addresses through which we contacted them to request that they fill out a short web-hosted questionnaire (based on Fischer, 2008; see Appendix) on how they would use their fingers to count to ten, and 127 completed this questionnaire[1]. At the time of completing the Database questionnaire, the demographic data of this group were as follows: 105 female, 20 male; mean age = 38.66 years, S.D. = 14.89, range = 9-76; 89 of whom were native speakers of English living in the UK (N.B. Six synaesthetes did not provide sufficient information to calculate their age at questionnaire completion, and another two did not state their gender). Forty-two (33% of) participants had completed and passed a consistency test on at least one form of synaesthesia that they reported. Our cut-off criterion was to have at least one of the following: a consistency score lower than 1 on the Eagleman synaesthesia battery (www.synesthete.org; Eagleman, Kagan,

[1] Fischer (2008), Lindemann et al. (2011) and Tschentscher et al. (2012) have all used this questionnaire method to assess finger-counting habits and report it to be both valid and reliable.

Nelson, Sagaram, & Sarma, 2007), a Stroop accuracy score of 85% or more on the same battery, or over 75% consistency in verbal descriptions (e.g. “A is red”) of at least one variant of synaesthesia over a minimum of two months. Seven participants who had completed consistency tests did not meet this criterion and were excluded from further analysis. Furthermore, 27 participants had not provided a clear description or diagram of their synaesthesia. We contacted these participants by email to request clarification and received responses from ten, of whom six provided clarifications, one was unable to clarify her number form, one reported an inconsistent number form, one reported that though he associated numbers with spaces, the numbers were located in space near the objects he was counting, and one reported that he had no number form (we assume that he had mistakenly circled the ‘strongly agree’ option in the questionnaire). We excluded the last four of these participants and the seventeen who had not responded to our emails as well as two participants who reported that they did not use all ten of their digits to count to ten, leaving us with 98 participants, of whom 37 had passed a consistency test.

We ran analyses with and without the synaesthetes who had not completed a consistency test and as the results from these two analyses generally did not differ in significance, we report the results based on all participants and note where these differ in the consistency-checked group.

Results

Handedness and start hand when counting

As Table 1 shows, 60% of participants always start counting on the left hand (left-starters), 33% always start counting on the right hand (right-starters), and the remainder vary the start hand (varying-starters). Looking solely at left- and right-starters (in order to facilitate comparison with Fischer, 2008, and to avoid violating the chi-square assumption that no more than 20% of cells have a predicted value of less than 5), this difference is significant ($\chi^2(1) = 8.01$, $p = .005$, $\varphi = 0.29$). Among consistency-checked participants, 19 (51% of) participants always start on their left hand, and 16 (43%) always start on the right hand. This difference is not significant ($\chi^2(1) = 0.26$, $p = .61$, $\varphi = 0.09$).

If split into left- and right-*handers* (again, excluding varying-starters, but this time also ambidextrous participants), the proportions of left- and right-*starters* are not significantly different between the two handedness groups ($\chi^2(1) = 0.22$, $p = .64$, $\varphi = 0.05$). These results are very similar to Fischer (2008), who found that 66% of his participants were left-starters and 34% were right-starters, with no significant difference in those proportions between left- and right-handers.

Table 1: Number of participant responses split by handedness and start hand when counting on fingers (percentages by row in parentheses).

Handedness	**Starting hand when counting**		
	Left	**Right**	**Varies**
Left	7 (58%)	5 (42%)	0 (0%)
Right	49 (60%)	26 (32%)	6 (7%)
Ambidextrous	3 (60%)	1 (20%)	1 (20%)
Total	59 (60%)	32 (33%)	7 (7%)

Handedness and relative lateral positions of 1 and 10

To calculate whether handedness had an effect on the position of 10 relative to 1 in the number form, participant descriptions and diagrams were divided into three categories based on the relative lateral positions of 10 and 1, while ignoring differences in sagittal and vertical positions: 10 is to the left of 1, 10 is to the right of 1, and 10 is neither to the left nor the right of 1 (i.e. 10 is vertically and/or sagittally, but not laterally, displaced, from 1). Overall, 65% of number forms have 10 to the right of 1, 11% have 10 to the left of 1, and the remaining 23% have 10 neither to the left nor the right of 1 (Table 2). A chi-square shows that these differences are significant ($\chi^2(2) = 47.29$, $p < .001$, $\varphi = 0.69$). Based on standardized residuals, participants with 10 to the left of 1 are significantly less frequent than expected ($z = -2.19$, $p < .05$) and participants with 10 to the right of 1 are significantly more frequent than expected ($z = 3.16$, $p < .01$). Participants with 10 neither to the left nor the right of 1 are not significantly more or less frequent than expected ($z = -0.98$, $p > .05$).

Again, we split the data into left- and right-handers, excluding ambidextrous participants, for further analysis. Using the Freeman-Halton extension of Fisher's exact test (Freeman & Halton, 1951), we found no significant difference in left- and right-handers in terms of the relative locations of 1 and 10 ($p = .90$).

Table 2: Number of participant responses split by handedness and relative lateral positions of 1 and 10 (percentages by row in parentheses).

Handedness	**Is 10 to the left or the right of 1?**		
	Left	**Right**	**Neither**
Left	1 (8%)	9 (75%)	2 (17%)
Right	10 (12%)	52 (64%)	19 (23%)
Ambidextrous	0 (0%)	3 (60%)	2 (40%)
Total	11 (11%)	64 (65%)	23 (23%)

Start hand when counting and relative lateral positions of 1 and 10

As shown in Table 3, among left-starters, right-starters, and varying-starters, the most common type of number form has 10 to the right of 1 and the least common type has 10 to the left of 1. A chi-square shows that these differences are non-significant (χ^2 (4) = 3.34, p = .50, φ = 0.19). This chi-square should be interpreted with caution as more than 20% of expected values were less than 5 (the Freeman-Halton extension of Fisher's Exact Test is not possible here due to sample size). However, the problem resulting from this violation of the prerequisites for a chi-square is increased likelihood of a Type II error, and given that the p-value is well above 0.05, the effect size is small, and the second method of testing this association (see below) also gave a non-significant result, the chi-square result is likely to be valid.

Table 3: Number of participant responses split by start hand when counting and relative lateral positions of 1 and 10 (percentages by row in parentheses).

Start hand	**Is 10 to the left or the right of 1?**		
	Left	**Right**	**Neither**
Left	8 (14%)	40 (68%)	11 (19%)
Right	3 (9%)	20 (63%)	9 (28%)
Varies	0 (0%)	4 (57%)	3 (43%)
Total	11 (11%)	64 (65%)	23 (23%)

For the 66 participants who had provided information about the position of their hands during finger-counting, it was possible to test this association in a different way by calculating the ordinal position (from left to right, during finger-counting) of the digits designated 1 and 10. For example, if a participant counted with palms facing up, starting on the left hand thumb, the ordinal position of 1 is 1. If the same participant finished counting to 10 on the right hand little finger, the ordinal position of 10 is 6. We subtracted the second of these numbers from the first to create an ordinal distance score between 1 and 10. The minimum distance score was -9 and the maximum was +9, with a negative number indicating that the ordinal position of 10 was to the right of the ordinal position of 1, and a positive number indicating the inverse. For the 41 participants with 10 to the right of 1 in their number forms, the mean distance score is –2.95 (*SD* = 5.79). For the 8 participants with 10 to the left of 1 in their number forms, the mean distance score is -3.13 (*SD* = 6.24). For the 17 participants with no lateral difference between 10 and 1 in their number forms, the mean distance score is -0.76 (*SD* = 7.14). That is, in each of the participant groups there is a tendency of varying strength to begin counting on a finger further to the left than the finger on which counting is finished. A Kruskal-Wallis test showed that the differences in distance score between the groups were not significant (χ^2 (2) = 2.02, p = .37, η^2 = 0.03).

Discussion

We assessed handedness, preferred start hand for counting, and number form shape among 98 number-space synaesthetes. We found similar proportions of left- and right-starters in this population as Fischer (2008) did in the general population, indicating that synaesthetes are not unusual with respect to their finger-counting behaviours. Since finger-counting is culturally variable, the slight differences in proportions between our study and his may be due to differences in participant nationality or ethnicity. Fischer did not record participant nationality, but his sample is likely to have been mainly native English speakers living in the UK due to his sampling method. The majority of our participants are also native English speakers living in the UK, but as we cannot assess the relative proportions of such participants in our study and his, it is impossible to tell whether our study or his reflects more influence from non-native speakers. This potential difference in participant nationality/ethnicity may also explain why, in the consistency-checked participant group, there is no significant difference in the numbers of left- and right-starters.

Our second result, that handedness is not associated with the relative locations of 1 and 10 in a synaesthete's number form, was not predicted and is rather unexpected given that Brang et al. (2011) reported that handedness *does* affect whether a time-space synaesthete's month form proceeds clockwise or anticlockwise. This may indicate that there are two separate underlying mechanisms for number-space and time-space synaesthesia. However, this explanation is debateable given the phenomenological similarity of the two types of synaesthesia and the finding that, in the general population, 40% of time-space synaesthetes also have number-space synaesthesia and 67% of number-space synaesthetes also have time-space synaesthesia (Sagiv et al., 2006; but note that these may be overestimates of both types of synaesthesia due to the lenient criteria for consistency over time in this study). These results should be interpreted with some caution since we asked participants to self-report handedness with a single question rather than using a handedness inventory or observing hand use, potentially reducing the validity of the measure.

Lastly, our results show that the direction of finger-counting is not associated with the relative locations of 10 and 1 in a number form. This finding is not entirely unexpected, as outlined in the Introduction: the direction of finger-counting is likely to be related to the strength of the SNARC effect (Fischer, 2008, but see Tschentscher et al., 2012 and Fabbri, 2013), which putatively reveals the non-synaesthetic, implicit mental number line of the general population. However, SNARC paradigms are not necessarily a good means of investigating number-space synaesthesia since the number form does not appear to be automatically activated during these tasks (Jonas & Jarick, in press; Jonas, Spiller, Jansari, & Ward, submitted; Price & Mattingley, in press). The lack of association between number-space synaesthesia and finger-counting habits that we have shown is further, though indirect, evidence for this argument against the use of SNARC paradigms as a means of measuring characteristics of number-space synaesthesia. Given that Tschentscher et al. (2012) and Fabbri et al. (2013) also found no role for finger-counting styles in SNARC effects, it may in fact be that neither implicit nor synaesthetic number-space associations are related to this behaviour. However, to be certain about the strength of the association between SNARC and finger-counting will require more investigation.

A point of more general interest that this result raises is the apparent disconnect between finger-counting and synaesthesia. Fingers are fundamental to counting and numeracy development, yet they do not appear to influence number-space synaesthesia. One possible explanation for this finding is that number-form synaesthetes make much less use of finger-counting than their peers as children because they are more reliant on their synaesthesia, and so do not make use of manumerical cognition in the same way as the general population. Inversely, number-form synaesthetes may have some attribute that makes them unlikely to use their fingers to count, for example poor finger gnosis, and consequently develop synaesthesia as a strategy to overcome this problem – in this case, number-space synaesthesia could initially be a form of mental imagery that eventually becomes automatic (perhaps arising from the strong mental imagery abilities of synaesthetes; Simner, Mayo, & Spiller, 2009). Both of these explanations fit well with a previous finding that adult number-space synaesthetes tend to be slower at multiplication and addition than others (Ward, Sagiv, & Butterworth, 2009). For synaesthetes, early learning of these techniques is not based in finger-counting, so number-space synaesthetes are hypothetically at a slight disadvantage compared to those who do use finger-counting when learning about number for the first time. This is supported by spontaneous comments from some synaesthetes in this study that they rarely used their fingers to count but instead relied on their number form.

Usually, finger-counting during arithmetic is seen relatively early in numeracy development, but begins to tail off between 7 and 8 years of age as children become more confident in their mathematical abilities (Jordan, Kaplan, Locuniak, & Ramineni, 2007). Jordan et al. also found that finger use during arithmetic problems is positively associated with accuracy at the beginning of first grade, but by the end of second grade this association is negative, indicating that habitual or extensive use of finger-counting to solve arithmetic problems may not be helpful when developmentally inappropriate. Unlike finger-counting, number-space synaesthesia cannot be seen by others; therefore, if it is used in place of finger-counting, there is no cue to stop using it. For example, there is no evidence that your peers are using or not using number-space synaesthesia to aid mental arithmetic, so you cannot compare your technique with others. Furthermore, if a teacher cannot tell that you are using number-space synaesthesia in place of finger-counting, he cannot prompt you to try other, more mature techniques for mental arithmetic (and during very early schooling may even assume that you are more advanced than your peers if you do not use finger-counting at all). For these reasons, an important direction for future research is assess whether and why the slowing of mental arithmetic in adult number-space synaesthetes occurs, particularly since number-space synaesthetes likely comprise a significant minority of the population, up to 12% (Sagiv et al., 2006; please note our earlier caveat that this is potentially an overestimate of prevalence). Specifically, if number-space synaesthetes have poor finger gnosis generally, this should be easily testable using standard assessments of finger gnosis (e.g. the unseen-finger-naming task used by Gracia-Ballafuy & Noël, 2008) – though we wish to highlight that finger gnosis tests such as this do not directly assess the use of fingers in counting. However, if number-space synaesthetes are no different from others in their finger gnosis but simply choose to use their synaesthesia instead of finger-counting, one would predict that passive movement of the hand during mental arithmetic (as in Imbo et al., 2009) would have much less impact on this group than it does in the rest of the population.

In sum, our study indicates that unlike time-space synaesthesia, number-space synaesthesia is not affected by the handedness of synaesthetes. Further, unlike the implicit mental number line, the explicit synaesthetic number form is not influenced by the direction in which the fingers are counted upon. These findings may indicate decreased use of fingers in young synaesthetes learning to count as compared to their peers, either by choice or because of deficits in finger gnosis.

Acknowledgements

Our thanks to Kate Cross, Andy Mealor, and two anonymous reviewers for providing feedback on earlier versions of this manuscript.

References

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. doi: 10.1080/17470210903134385

Baroody, A. J., & Wilkins, J. L. M. (1999). The development of informal counting, number, and arithmetic skills and concepts. In J. Copeley (Ed.), *Mathematics in the early years, birth to five.* Reston, VA: National Council of Teachers of Mathematics.

Bender, A., & Beller, S. (2012). Nature and culture of finger counting: diversity and representational effects of an embodied cognitive tool. *Cognition, 124,* 156-182. doi: 10.1016/j.cognition.2012.05.005

Brang, D., Teuscher, U., Miller, L. E., Ramachandran, V. S., & Coulson, S. (2011). Handedness and calendar orientations in time–space synaesthesia. *Journal of Neuropsychology*, *5*(2), 323-332. 10. doi: 111/j.1748-6653.2011.02012.x

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

Casasanto, D. (2011). Different Bodies, Different Minds: The Body Specificity of Language and Thought. *Current Directions in Psychological Science*, *20*(6), 378-383. doi: 10.1177/0963721411422058

Costa, A. J., Lopes Silva, J. B., Pinheiro Chagas, P., Krinzinger, H., Lonneman, J., Willmes, K., Wood, G., & Haase, V. G. (2011). A hand full of numbers: a role for offloading in arithmetics learning? *Frontiers in Psychology*, *2*. doi: 10.3389/fpsyg.2011.00368

Crollen, V., Seron, X., & Noël, M. P. (2011). Is finger-counting necessary for the development of arithmetic abilities? *Frontiers in Psychology*, *2*. doi: 10.3389/fpsyg.2011.00242

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*(1), 1-42. doi: 10.1016/0010-0277(92)90049-N

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. Oxford: Oxford University Press.

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

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

Eagleman, D. M., Kagan, A. D., Nelson, S. S., Sagaram, D., & Sarma, A. K. (2007). A standardized test battery for the study of synesthesia. *Journal of Neuroscience Methods*, *159*(1), 139-145. doi: 10.1016/j.jneumeth.2006.07.012

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

Fischer, M. H., & Campens, H. Pointing to numbers and grasping magnitudes. *Experimental Brain Research*, *192*(1), 149-153. doi: 10.1007/s00221-008-1622-3

Freeman, G.H. and Halton, J.H. (1951). Note on exact treatment of contingency, goodness of fit and other problems of significance. *Biometrika, 38*, 141-149.

Göbel, S. M., Shaki, S., & Fischer, M. H. (2011). The cultural number line: A review of cultural and linguistic influences on the development of number processing. *Journal of Cross-Cultural Psychology*, *42*(4), 543-565. doi: 10.1177/0022022111406251

Gracia-Bafalluy, M., & Noël, M. P. (2008). Does finger training increase young children's numerical performance? *Cortex*, *44*(4), 368-375. doi: 10.1016/j.cortex.2007.08.020

Guha, S. (2006). Using mathematics strategies in early childhood education as a basis for culturally responsive teaching in India. *International Journal of Early Years Education*, *14*(1), 15-34. doi: 10.1080/09669760500446374

Hubbard, E. M., Ranzini, M., Piazza, M., & Dehaene, S. (2009). What information is critical to elicit interference in number-form synaesthesia? *Cortex*, *45*(10), 1200-1216. doi: 10.1016/j.cortex.2009.06.011

Hung, Y. H., Hung, D. L., Tzeng, O. J. L., & Wu, D. H. (2008). Flexible spatial mapping of different notations of numbers in Chinese readers. *Cognition*, *106*(3), 1441-1450. doi: 10.1016/j.cognition.2007.04.017

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

Ifrah, G. (1987). *From one to zero: A universal history of numbers*. New York: Viking.

Jarick, M., Dixon, M. J., Maxwell, E. C., Nicholls, M. E., & Smilek, D. (2009). The ups and downs (and lefts and rights) of synaesthetic number forms: Validation from spatial cueing and SNARC-type tasks. *Cortex*, *45*(10), 1190-1199. doi: 10.1016/j.cortex.2009.04.015

Jonas, C., & Jarick, M. (in press). Synaesthesia, sequences, and space. In J. Simner & E. Hubbard (Eds.), *Oxford Handbook of Synaesthesia*. Oxford: Oxford University Press.

Jonas, C. N., Spiller, M. J., Jansari, A., & Ward, J. (submitted). Comparing implicit and explicit number-space associations: visuospatial and verbal SNARC effects. *Quarterly Journal of Experimental Psychology.*

Jonas, C. N., Taylor, A. J., Hutton, S., Weiss, P. H., & Ward, J. (2011). Visuo-spatial representations of the alphabet in synaesthetes and non-synaesthetes. *Journal of Neuropsychology*, *5*(2), 302-322. doi: 10.1111/j.1748-6653.2011.02010.x

Jordan, N. C., Kaplan, D., Locuniak, M. N., & Ramineni, C. (2007). Predicting first-grade math achievement from developmental number sense trajectories. *Learning Disabilities Research & Practice*, *22*(1), 36-46. doi: 10.1111/j.1540-5826.2007.00229.x

Klein, E., Moeller, K., Willmes, K., Nuerk, H. C., & Domahs, F. (2011). The influence of implicit hand-based representations on mental arithmetic. *Frontiers in Psychology*, *2*. doi: 10.3389/fpsyg.2011.00197

Levine, S. C., Jordan, N. C., & Huttenlocher, J. (1992). Development of calculation abilities in young children. *Journal of Experimental Child Psychology*, *53*(1), 72-103.

Lindeman, 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. doi: 10.1177/0022022111406254

Piazza, M., Pinel, P., & Dehaene, S. (2006). Objective correlates of an unusual subjective experience: A single-case study of number–form synaesthesia. *Cognitive Neuropsychology*, *23*(8), 1162-1173. doi: 10.1080/02643290600780080

Price, M. C., & Mattingley, J. B. (in press). Automaticity in sequence-space synaesthesia: A critical appraisal of the evidence. *Cortex*.

Sagiv, N., Simner, J., Collins, J., Butterworth, B., & Ward, J. (2006). What is the relationship between synaesthesia and visuo-spatial number forms? *Cognition*, *101*(1), 114-128. doi: 10.1016/j.cognition.2005.09.004

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

Sato, M., & Lalain, M. (2008). On the relationship between handedness and hand-digit mapping in finger counting. *Cortex*, *44*, 393-399. doi: 10.1016/j.cortex.2007.08.005

Saxe, G. B. (1981). Body parts as numerals: A developmental analysis of numeration among the Oksapmin in Papua New Guinea. *Child Development*, 306-316.

Seymour, P. H. (1980). Internal representation of the months. *Psychological Research*, *42*(3), 255-273. doi: 10.1007/BF00308532

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

Simner, J., Mayo, N., & Spiller, M. J. (2009). A foundation for savantism? Visuo-spatial synaesthetes present with cognitive benefits. *Cortex*, *45*(10), 1246-1260. doi: 10.1016/j.cortex.2009.07.007

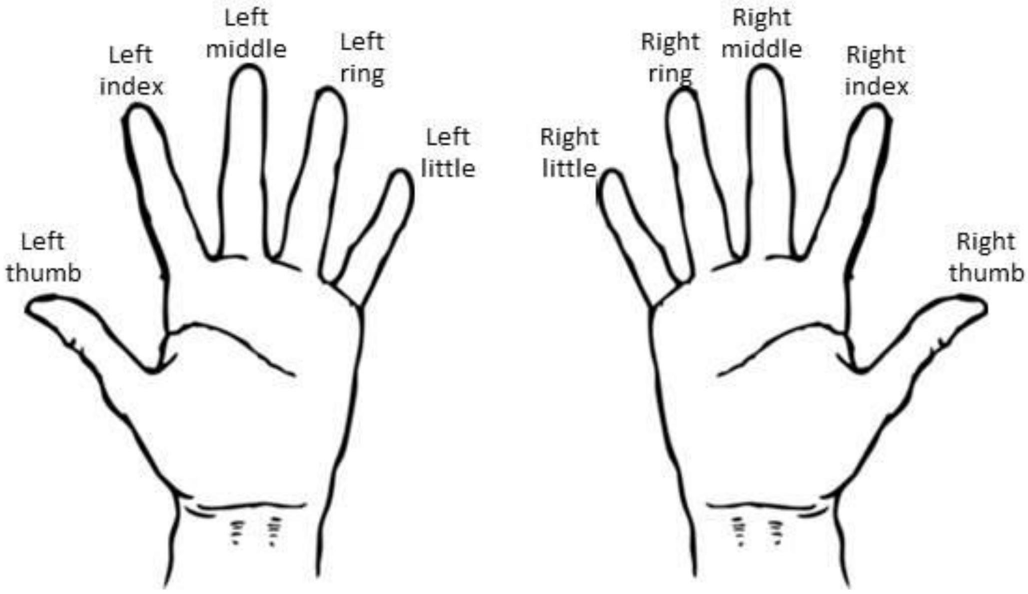
Tschentscher, N., Hauk, O., Fischer, M. H., & Pulvermüller, F. (2012). You can count on the motor cortex: finger counting habits modulate motor cortex activation evoked by numbers. *NeuroImage*, *59*(4), 3139-3148. doi: 10.1016/j.neuroimage.2011.11.037

Ward, J., Sagiv, N., & Butterworth, B. (2009). The impact of visuo-spatial number forms on simple arithmetic. *Cortex*, *45*(10), 1261-1265. doi: 10.1016/j.cortex.2009.03.017

Wiese, H. (2007). The co-evolution of number concepts and counting words. *Lingua*, *117*(5), 758-772. doi: 10.1016/j.lingua.2006.03.001

Wood, G., & Fischer, M. H. (2008). Numbers, space, and action-from finger counting to the mental number line and beyond. *Cortex*, *44*(4), 353. doi: 10.1016/j.cortex.2008.01.002

Appendix: Finger-counting questionnaire



Imagine how you would count with your fingers from 1 to 10. Please write the numbers in the boxes corresponding to the fingers of each hand in the picture above.

Left thumb	
Left index	
Left middle	
Left ring	
Left little	
Right little	
Right ring	
Right middle	
Right index	
Right thumb	

(Optional) Please add any further comments about how you count on your fingers here. For example: Do you count with your palms facing up or down? Do you point to the finger you are counting with the other hand? Do you use more than one order or method to count on your fingers?