Loughborough University

This item was submitted to Loughborough's Research Repository by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

A large-scale survey on finger counting routines, their temporal stability and flexibility in educated adults

PLEASE CITE THE PUBLISHED VERSION

https://doi.org/10.7717/peerj.5878

PUBLISHER

PeerJ

VERSION

VoR (Version of Record)

PUBLISHER STATEMENT

This is an open access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, reproduction and adaptation in any medium and for any purpose provided that it is properly attributed. For attribution, the original author(s), title, publication source (PeerJ) and either DOI or URL of the article must be cited.

LICENCE

CC BY 4.0

REPOSITORY RECORD

Hohol, Mateusz, Kinga Wołoszyn, Hans-Christoph Nuerk, and Krzysztof Cipora. 2018. “A Large-scale Survey on Finger Counting Routines, Their Temporal Stability and Flexibility in Educated Adults”. Loughborough University. https://hdl.handle.net/2134/12210107.v1.

A large-scale survey on finger counting routines, their temporal stability and flexibility in educated adults

Mateusz Hohol[1,2], Kinga Wołoszyn[3], Hans-Christoph Nuerk[4,5,6] and Krzysztof Cipora[4,5]

[1] Copernicus Center for Interdisciplinary Studies, Jagiellonian University, Cracow, Poland
[2] Section of Cognitive Science, Institute of Philosophy and Sociology, Polish Academy of Science, Warsaw, Poland
[3] Psychophysiology Laboratory, Institute of Psychology, Jagiellonian University, Cracow, Poland
[4] Department of Psychology, University of Tuebingen, Tuebingen, Germany
[5] LEAD Graduate School & Research Network, University of Tuebingen, Tuebingen, Germany
[6] Leibnitz-Institut für Wissenmedien, Tuebingen, Germany

ABSTRACT

A strong link between bodily activity and number processing has been established in recent years. Although numerous observations indicate that adults use finger counting (FC) in various contexts of everyday life for different purposes, existing knowledge of FC routines and their use is still limited. In particular, it remains unknown how stable the (default) FC habits are over time and how flexible they can be. To investigate these questions, 380 Polish participants completed a questionnaire on their FC routines, the stability of these routines, and the context of FC usage, preceded by the request to count on their fingers from 1 to 10. Next, the test–retest stability of FC habits was examined in 84 participants 2 months following the first session. To the best of our knowledge, such a study design has been adopted for the first time. The results indicate that default FC routines of the majority of participants (75%) are relatively stable over time. At the same time, FC routines can flexibly adapt according to the situation (e.g., when holding an object). As regards prevalence, almost all participants, in line with previous findings on Western individuals, declared starting from the closed palm and extending consecutive fingers. Furthermore, we observed relations between FC preferences and handedness (more left-handers start from the left hand) and that actual finger use is still widespread in healthy adults for a variety of activities (the most prevalent uses of FC are listing elements, presenting arguments and plans, and calendar calculations). In sum, the results show the practical relevance of FC in adulthood, the relative stability of preferences over time along with flexible adaptation to a current situation, as well as an association of FC routines with handedness. Taken together our results suggest that FC is the phenomenon, which is moderated or mediated by multiple embodied factors.

Subjects Psychiatry, Psychology
Keywords Number processing, Numerical cognition, Finger counting, Embodied cognition, Situated cognition, Handedness

Submitted 28 June 2018
Accepted 5 October 2018
Published 31 October 2018

Corresponding author
Krzysztof Cipora,
krzysztof.cipora@uni-tuebingen.de

Academic editor
Anna Borghi

Additional Information and Declarations can be found on page 17

DOI **10.7717/peerj.5878**

Copyright
2018 Hohol et al.

Distributed under
Creative Commons CC-BY 4.0

OPEN ACCESS

INTRODUCTION

A large proportion of adults use finger counting (henceforth FC) in various contexts, such as calendar calculations, counting perceived objects, enumeration, or to communicate small numbers to other people (e.g., one usually shows two fingers at the same time as saying "two beers please" in a noisy pub; see *Pika, Nicoladis & Marentette, 2009*; *Bender & Beller, 2011*). This observation constitutes the starting point for systematic inquiries into the nature of FC. The human hand is the first computing machine for a number of reasons: our fingers are handy, perceptually distinguishable, and easy to move and manipulate. They can iconically represent discrete values or objects, their ordering is constant over time. A clear one-to-one correspondence between fingers and counted objects is easy to maintain (preserve), and hence, they are suitable for determining both cardinal number and ordinal number (*Butterworth, 1999*). FC is a spontaneous activity that has been present in the vast majority of cultures since prehistoric times (*Göbel, Shaki & Fischer, 2011*; *Overmann, 2014*). It had a great impact on the development of numerical systems and Western mathematics in its current form (*Ifrah, 1981*). Even today, FC appears to have a broader role than its normally ascribed function as a transitory step in the acquisition of numerical competences by individuals (*Piaget, 1942*; *Gelman & Gallistel, 1986*; *Jordan et al., 2008*). Hence, contemporary studies on FC are extensively carried out not only in children, but also in educated adults.

Finger counting and numerical processing

There is a growing consensus that FC is not an immature strategy which serves only for assistance (*Dupont-Boime & Thevenot, 2017*), but affects number processing more directly (*Previtali, Rinaldi & Girelli, 2011*; *Crollen & Noël, 2015*; *Newman, 2016*; *Newman & Soylu, 2014*). It has been shown that FC reduces working memory load and provides control over the correctness of calculations (*Wiese, 2004*; *Beller & Bender, 2011*). Furthermore, the structure of finger-number relations affects basic symbolic number comparison (*Domahs et al., 2010*), where differences between different cultures could be traced back to different finger-number relations (see also *Domahs et al., 2012*).
The direction of FC has also been claimed to affect spatial-numerical associations (or SNA; *Fischer, 2008*; *Fischer & Brugger, 2011*; *Cipora, Patro & Nuerk, 2015*; *Lindemann, Alipour & Fischer, 2011*) with the space-number relation (aka the mental number line) following the direction of FC.

What is more, finger-number relations seem to influence complex arithmetic in children and adults. *Domahs, Krinzinger & Willmes (2008)* showed that split-5 errors—namely, errors with a difference of plus-minus 5 from the correct result—are disproportionally frequent in children's mental calculation and argued that this is due to underlying finger representations. Similarly, *Klein et al. (2011)* showed that not only carrying over unit sums beyond a base-10 quantity (e.g., 29 + 4), but also carrying over sub-base-5 thresholds (23 + 4) slows down responses in adults. Again, in the context of other sub-base-5 effects, they attributed these results to embodied finger number representations. What is more, there are several studies suggesting that early finger-related habits are positively related to later arithmetic skill

(*Willems, Feeters-Erenay & Depuydt-Bcrte, 1980*; *Fayol, Barrouillet & Marinthe, 1998*; *Noël, 2005*; *Jordan et al., 2008*; *Reeve & Humberstone, 2011*; *Chinello et al., 2013*; *Penner-Wilger & Anderson, 2013*; *Wasner et al., 2016*; *Fischer et al., 2017*; *Soylu, Lester & Newman, 2018*). Because of this reason, some researchers suggested that FC may be considered as the missing link—in both ontogenetic and historical timescales—between the hardwired "number sense" (*Dehaene, 2011*) and culture-dependent, and more symbolical, numerical systems (*Butterworth, 2005*; *Andres, Di Luca & Pesenti, 2008*).

Finger counting as a hallmark of embodied cognition

From a theoretical perspective, FC is often considered within the embodied cognition framework. Despite the fact that "the embodiment" is a label for different, and in some cases incoherent, approaches, most of its proponents agree that concepts—including abstract ones—are not arbitrary, amodal, and language-like symbols, as representatives of classic cognitive science typically assumed (*Fodor, 1975*; *Jackendoff, 2002*). Instead, they are to emerge from the bodily interactions of individuals with their environments (*Clark, 1998*; *Barsalou, 1999*, *2008*; *Wilson, 2002*; *Borghi et al., 2018*). Although some amodal models of number processing have been proposed in the past (*Groen & Parkman, 1972*; *Banks, Fujii & Kayra-Stuart, 1976*), recently, there is growing agreement that mathematical concepts are indeed constrained by bodily activity and anchored, or systematically mapped, in sensorimotor systems (*Lakoff & Núñez, 2000*; *Moeller et al., 2012*; *Landy, Allen & Zednik, 2014*; *Dackermann et al., 2017*; *Wołoszyn & Hohol, 2017*; *Fischer, 2012*, *2018*; *Fischer & Shaki, 2018*). The embodied approach to numerical cognition is supported, inter alia, by the results of neuroimaging studies which suggest that representations of fingers and numbers are shared. For instance, *Zago et al. (2001)* discovered that carrying out simple arithmetic operations involves activation of the same brain areas as those which are active during learning of finger movements sequences or during manual manipulation of three-dimensional objects. In line, *Tschentscher et al. (2012)* found that individuals' habits regarding FC (specifically starting hand) is linked to neural activation during number processing. It has been suggested that simple counting is implemented through embodied, or off-line, simulation of finger movements (*Andres, Seron & Olivier, 2007*). There is also some evidence indicating that influences of FC routines on number processing go beyond simple arithmetic, and can also be observed in more elementary numerical processing (*Fischer, 2008*; *Riello & Rusconi, 2011*).

Cultural embedding of finger counting habits

A comparison of Western and Middle Eastern adults reveals that the starting preference in FC is associated with the SNA direction. Specifically, Western two-hand counters start counting with their left hand, whereas Middle Eastern ones with their right hand (*Lindemann, Alipour & Fischer, 2011*). However, there is some evidence showing both within-individual variation in FC routines, as well as considerable variation within cultures, even in Western Europe, which share the same directions of SNAs. For instance, some left-to-right readers, such as French and Belgian participants, predominantly start counting with their right hand (*Sato & Lalain, 2008*; *Lindemann, Alipour & Fischer, 2011*).

Several studies showed the same behavioral pattern in Italian adults (*Di Luca et al., 2006*; *Di Luca & Pesenti, 2008*, *2010*; *Sato et al., 2007*; *Fabbri, 2013*; *Fabbri & Natale, 2015*; *Fabbri & Guarini, 2016*). On the other hand, the study by *Newman & Soylu (2014)* revealed no preference in starting habits among American right-handed adults. Therefore, even in countries that share a left-to-right reading/writing direction, FC habits differ between studies. The cause of observed diversity may, at least partially, lie in differences in FC assessment[1].

[1] Note that there are cultural differences between left-to-right writing/reading countries even when the assessment is identical (*Lindemann, Alipour & Fischer, 2011*). These differences are not entirely surprising considering that there are multiple other mechanisms, which are possibly also responsible for left-to-right SNAs (*Nuerk et al., 2015*; *Patro, Nuerk & Cress, 2016*). Such non-reading/writing mechanisms have been shown to influence other SNAs (*Patro et al., 2016*), and their extent and prevalence might also differ between cultural contexts. However, since cultural differences are not the main topic of this article, a more detailed discussion goes beyond the scope of this introduction.

Situatedness of finger counting habits

Besides embodiment, some evidence suggests that FC may also be prone to situational influences and that testing conditions largely affect FC routines used by participants. For instance, a series of experiments conducted by *Lucidi & Thevenot (2014)* showed that verbal reports of roughly a quarter of participants on FC routines were inconsistent with their actual pattern of behavior in the syllable-counting task. *Wasner et al. (2014)* also found that FC routines declared by participants might not always be consistent with their actual practices. As long as both hands were available, they spontaneously counted in line with their declared habits and only 28% of participants began counting with the left hand. When the task required counting with the fingers aligned horizontally (hands in front), 54% of tested persons began counting with the left hand. Finally, when participants were asked to count with the horizontal arrangement, but additionally with the dominant hand full, 62% of them started with the left hand. This was a between-participant design, but the results are significantly inconsistent with the idea that an individual maintains stable FC patterns regardless of the specific situated influences.

Following *Wasner et al. (2014)*, it is essential, how to ask about FC routines. When participants view an image of their fingers in front of them aligned from left-to-right first, seems to influence the report of their FC routines. So, does having a pen in one hand. For these reasons, we asked all participants in our study first to count spontaneously (with two free hands) and memorize how they had counted and then to report their counting routines in the questionnaire. By this assessment, we were hoping to be closer to spontaneous counting procedures, that is, less influenced by horizontally aligned finger images than in previous group or internet studies.

Stability of finger counting habits

The stability of FC routines over time is largely understudied. There is not much data, the existing findings are not conclusive (*Previtali, Rinaldi & Girelli, 2011*), and—to the best of our knowledge—not longitudinal. For instance, in a cross-sectional study by *Sato & Lalain (2008)* considering four age groups (4–5, 6–7, 10–11, and 24–47 years old) of French participants, the same pattern of FC was found regardless of age. Namely, participants were mostly starting with the right and continuing with the left hand. However, while this shows that the general pattern in a whole group does not significantly differ between age groups, the cross-sectional design reveals nothing about individual stability over time. Indeed, P. Räsänen & T. Koponen (2010, unpublished data;

we quote after *Previtali, Rinaldi & Girelli, 2011*) found that although most Finnish right-handers, regardless of age, start counting from their right hand, such a pattern was not observed in left-handers. More precisely, although all left-handed preschoolers tested by Räsänen and Koponen were left-starters, only half of left-handed fourth graders were left-starters. Again, while these data suggest some group variability in development on a group level, little can be said about intraindividual stability. In summary, none of these studies tested the intraindividual temporal stability of FC routines since cross-sectional data have been collected only at the single time point. Therefore, the issue of temporal stability still needs to be addressed. This is the second goal of this study.

Objectives of the present study

If FC routines play a role in the formation of directional SNA, as *Fischer (2008)* suggested, they should be stable, so that a given hand/finger occupying the particular relative position (e.g., third from the left) always corresponds to the same number. This would also imply that FC routines are stable within certain cultural contexts, which have been observed to share the same directions of SNAs (*Shaki, Fischer & Petrusic, 2009*). However, most previous reports on FC routines, as we have mentioned above, did not consider the temporal stability of FC routines. Furthermore, it should be noted that studies on FC are typically conducted only at a single time point.

First of all, we wished to provide quantitative data on FC routines with particular emphasis on their temporal stability, by directly (verbally) asking participants about their habits, and then testing it empirically in the retest study. Moreover, in the questionnaire we asked several questions on the stability of FC routines, which allowed us to cross-check the consistency of participants' answers.

Secondly, *Wasner et al. (2014)* showed that left-to-right alignment of hands, while asking for FC routines, influences results. Therefore, we asked participants to count first without such an alignment, before they reported their FC routine. In that way, we attempted to make prevalence estimates obtained in this study more similar to spontaneous FC routines.

Finally, we wanted to provide data on how and when educated adults actually use FC in everyday life. The latter part of the survey was exploratory and aimed at providing quantitative data on typical FC routines, which would be useful in guiding future investigations.

METHOD

Participants

In the first session, there were 380 native Polish-speaking participants (236 female, 137 male; seven did not report their gender) aged 17–42 years (M = 20.8, SD = 3.6; 14 participants did not report their age) tested. The group consisted mostly of undergraduate students of law (n = 190) and psychology (n = 170); other participants (n = 16) studied math, computer science, cognitive science, or did not report their field of study (n = 4). Data from an additional five participants was excluded from further analysis due to the lack of data on FC direction, which was the main objective of the study.

Two months following the first testing, participants, which we could reach again were invited to participate in the second session (psychology students, n = 84, 66 women, aged 19–42, M = 21.7, SD = 4.1).[2] All participants gave informed consent verbally prior to the procedure. As the study was conducted in large groups of participants, we did not collect written consents to ensure anonymity. The design of the study was approved by the Local Ethics Committee of the Copernicus Center for Interdisciplinary Studies of the Jagiellonian University (decision no. 2 issued on the 30th of September 2015).

[2] Due to organizational constraints (tight schedule at the end of the semester), we were not allowed to visit some lectures for the second time. The majority of the students, who were actually given the opportunity to participate in the second session agreed to do so. Part of the drop-outs may be simply related to students' absences during classes or impossibility to match the pseudonyms from the first session (we did not have a code list, and some students could not recall the pseudonyms they had used in the first session). Thus, the much lower number of participants in the retest session was not due to self-selection.

Materials

FC routines were measured using a paper-and-pencil survey. The questionnaire consisted of the drawing of two palms taken from *Fischer (2008)*, on which the participants were asked to mark their FC sequence, along with the set of questions described below (the original questionnaire in Polish, as well as its English translation, can be accessed at http://doi.org/10.17605/OSF.IO/RQHFK).

In the first question (henceforth Q1) participants were asked to indicate whether they (a) always follow the same sequence as they marked on the drawing, (b) usually do so, or (c) do not have any stable tendency in terms of the order of FC. In Q2 participants were asked to mark those out of six sentences, which described their FC routines (multiple answers were allowed). They were chosen based on an informal pilot procedure, in which several people naive to the purpose of the questions were asked how they count on their fingers and what they use FC for. Sentences were as follows: (a) I begin with a closed hand and extend the consecutive fingers; (b) I begin with a closed hand and extend the consecutive fingers touching fingers which have been already extended with the other hand; (c) I begin with an open hand and fold the consecutive fingers inwards; (d) I make gentle movement of consecutive fingers with a hand put on some object (e.g., a desk, a cup); (e) I make gentle movements of consecutive fingers keeping the hand open; (f) other way (specify). In Q3 participants were asked whether they would continue the FC sequence for numbers 6–10 by using the other hand (response alternative (a)), or by repeating the sequence with the starting hand (response alternative (b)). In Q4 participants were asked about their FC routine when the preferred hand is full. Three alternatives were presented: (a) I use the other hand without any problem; (b) I try to count on the preferred hand despite holding an object in it; (c) I put the object away or move it to the other hand. In Q5 participants were first asked to count on fingers of the hand opposite to the one they declared to begin with. Subsequently, they were asked how (a) natural; and (b) comfortable the counting was using a 5-point Likert-type scale with one representing very unnatural/uncomfortable and five—very natural/comfortable, respectively. The last question (Q6) concerned the circumstances in which participants use FC. Participants were asked to mark how often they use FC in each of the listed situations: (a) simple arithmetical operations, (b) calendar calculations, (c) listing elements (e.g., how many pairs of shoes/cousins do I have?), (d) describing plans/presenting arguments (e.g., First we will make repairs and next we will go for vacation), (e) multiplication, (f) communicating quantity, that is, finger montring

(e.g., ordering three cups of coffee), (g) other (specify). Responses were given on a 5-point Likert-type scale from one (labelled with "never") to five (labelled with "very often").

The handedness was measured with the *Edinburgh Handedness Inventory* (*Oldfield, 1971*). The questionnaire consists of 10 questions in which participants declare their preferred hand in performing daily activities.

Procedure

Data was collected during regular academic classes. Participants were tested in a group setup in lecture halls/seminar rooms. After providing general information about the study, participants, who agreed to volunteer, were orally instructed to have their hands free and keep their arms down (thus, they were not holding the hands in front of them and they did not see them), and then count on their fingers from 1 to 10 and memorize the order. Subsequently, the questionnaires were distributed, and participants were asked to mark the sequence on the palm drawing on the questionnaire (i.e., the schematic hands drawings were not visible to the participants while counting). Note that this procedure differs from *Fischer (2008)* in that participants first counted freely and then marked their preferred FC scheme. According to *Wasner et al. (2014)*, this makes a meaningful difference (see Introduction). After marking the order of FC on the schematic hands, participants were asked to respond to items of the questionnaire. Participants were free not to return the questionnaires to ensure their freedom to withdraw from their participation in the study. They were also free to omit some items if they wished to. Thus, in some analyses the reported number of participants does not sum up to 380. The procedure lasted approximately 15 min.

RESULTS

Handedness

The laterality quotient (LQ) could range from −100 to +100. According to *Oldfield's (1971)* recommendations, the participants were categorized as right-handers (LQ > 40; n = 328, i.e., 86.3% of the sample), ambidextrous (40 ≤ LQ > 0; n = 22, i.e., 5.8%), or left-handers (LQ ≤ 0; n = 30, i.e., 7.9%)[3].

Finger counting routines

Results regarding the FC routines and patterns are summarized in Table 1.
More participants declared starting with their right than with their left hand. Interestingly, the proportion of right- and left-starters differed significantly depending on handedness (chi_2^2 = 12.56; p = 0.002). This effect was driven by the difference between left-handers and two other groups. Left-handers were more likely to start FC from the left hand than from the right hand. The opposite was true for right-handers and ambidextrous (Table 2).

Irrespective of the starting hand, nearly all participants declared starting with their thumb. A few participants declared starting with their pinkie, and only one—with the index finger. Vast majority of participants used both hands to count to ten.

[3] There is no consensus nor golden standard in the field (*Lahita 1988*; *Tan 1991*; *Beratis et al., 2009*; *Arning et al., 2015*). To check whether adopting alternative criteria actually would not change the results regarding handedness, we rerun the analyses using the following ranges: (A) LQ ≤ 0; 0 < LQ ≥ 50; LQ > 50 and (B) LQ < −40; −40 ≥ LQ ≥ 40; LQ > 40 for left-handers, ambidextrous, right-handers respectively. Disregarding the cut-offs adopted (A or B), the number of participants categorized as ambidextrous increased. Specifically, when we used the (A) criteria, 25 participants who—according to the initial cut-offs—were categorized as right-handed, now they felt into the ambidextrous group. When we used the (B) criteria, 10 out of 30 participants who were previously categorized as left-handers, felt into the ambidextrous category. These changes, however, did not change the major results of our study substantially. For instance, the relationship between handedness and starting hand was still significant (chi_2^2 = 12.62, p = 0.002; chi_2^2 = 12.63, p = 0.002; for A and B respectively). Moreover, all data, including the raw LQ values, are available at http://doi.org/10.17605/OSF.IO/RQHFK. So, every interested reader can conduct the analyses using handedness cut-off criteria she/he prefers to see whether adopting yet another handedness cut-off criterion makes a substantial difference for the handedness—FC relation.

Table 1 Finger counting patterns and finger counting habits.

					N	%
(a) Counting pattern						
1	2	3	4	5		
RT	RI	RM	RR	RP	215	56.6
RT	RI	RM	RP	RR	3	0.8
LT	LI	LM	LR	LP	159	41.8
LT	LI	LM	LP	LR	2	0.5
LI	LM	LR	LP	LT	1	0.3
(b) Starting hand						
Right					218	57
Left					162	43
(c) Starting finger						
Thumb					371	97.6
Pinkie					8	2.1
Index					1	0.3
(d) Hands used > 5						
One					11	2.9
Both					369	97.1
(e) Technique						
Extending					288	75.8
Moving					21	5.5
Folding					5	1.3
Various					66	17.4

Note:
Counting patterns: each letter pair points at hand (R = right; L = left) and finger (T = thumb; I = index finger; M = middle finger; R = ring finger; P = pinkie) used to indicate the number at the top of its column. Data from items (a) to (d) are based on participants' marks on the palm drawing. Data from item (e) are from the question.

Table 2 Handedness vs. starting hand.

Handedness	**Starting hand**				**Total**
	Right		**Left**		
	N	**%**	***N***	**%**	***N***
Right-handed	197	60	131	40	328
Ambidextrous	13	59	9	41	22
Left-handed	8	27	22	73	30

Interestingly, when participants were explicitly asked whether they use the other hand or continue with the same one (i.e., Q3), four times more individuals declared using only one hand.

Out of 369 participants who declared using both hands, 353 declared they continued from the thumb of the other hand. Other participants declared starting from the pinkie of the other hand. Eight participants reported sequences not following the anatomical order in any direction.

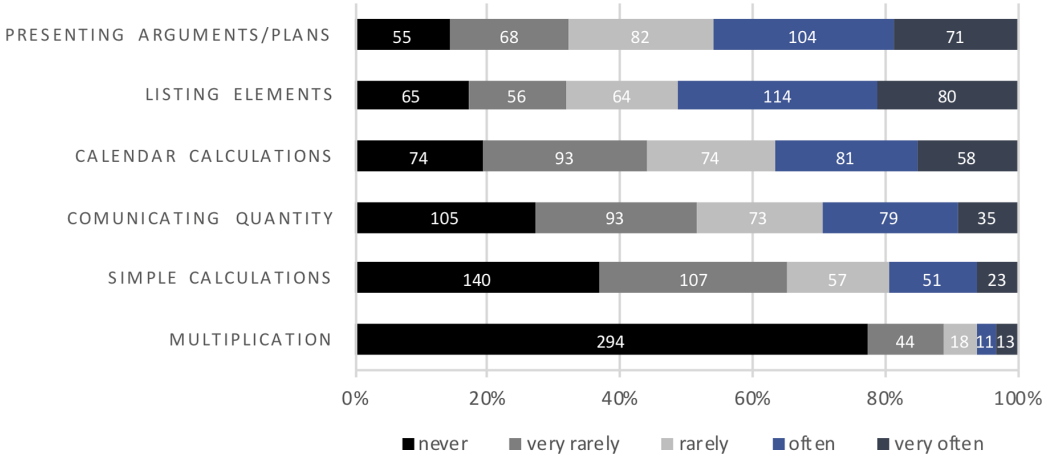


Figure 1 Circumstances in which finger counting is used. Full-size DOI: 10.7717/peerj.5878/fig-1

The most prevalent FC technique reported by participants was extending their fingers. A total of 288 participants declared this as their only strategy. Out of these, 45 participants reported that they additionally touch the inner side of the other palm. The other techniques were far less common, with 21 participants declaring that they counted by making small movements either against a surface or against an item held in their hand. Only five participants declared that they start from an open palm and fold their fingers consecutively. Another five participants declared using "other" techniques only. The remaining 66 participants marked answers that were somehow contradictory with each other (e.g., both spreading and using an item). Most likely, these participants were using varied routines and did not reveal very strong preferences toward any of them.

The most common use of FC declared by participants was listing elements and presenting arguments and plans. A considerable proportion of participants used FC for calendar calculations. Communicating quantity and making simple calculations were somehow less prevalent. By far the least common use of FC reported by the participants was for multiplication (Fig. 1).

Finger counting routine stability

Four questions referred to the declared stability of FC routines. Specifically, Q1 (explicitly asking about the stability), Q4 (actions taken when one needs to count on fingers, but the preferred hand is full), Q5 (a) and (b) (how natural/comfortable it was to start counting with the non-preferred hand; 5-point Likert-type scale). The majority of participants declared having a stable or partly stable FC routine (n = 186, i.e., 49% and n = 141, i.e., 37%, respectively) as opposed to not having such a routine (n = 52, i.e., 14%). Roughly half (n = 186, i.e., 49%) of the participants declared having no problem with using the non-preferred hand while having their preferred hand full, whereas the rest of them declared using the preferred hand anyway, or putting away or moving to the other hand the object being held in order to count on the preferred hand (n = 114, i.e., 30% and n = 79, i.e., 21%, respectively). Notably, participants' responses to questions on how comfortable and natural it was to count with the non-preferred hand were

Table 3 Reported finger counting routine stability vs. declared actions taken when one needs to count with fingers but the preferred starting hand is full.

Declared stability	Actions taken when preferred hand busy						Total
	Use other hand		Count anyway		Put away		
	N	%	*N*	%	*N*	%	*N*
Always	69	37	72	39	45	24	185
Usually	83	59	32	23	26	18	141
No preference	34	65	10	19	8	15	52

rather high (i.e., participants were generally using the upper part of the scale). The mean response to the question how comfortable it was, was 3.5 (SD = 1.1) and to the question on how natural it was, was 3.69 (SD = 1.06).

Right- and left-starters did not differ in respect of any measure of declared FC routine stability (for Q1, $chi_2^2 = 2.47$, $p = 0.291$, for Q4, $chi_2^2 = 0.77$, $p = 0.681$, for Q5 (a), $t_{377} = 1.03$, $p = 0.306$ for Q5 (b), $t_{377} = 0.41$, $p = 0.682$).

Consistency of the stability measures

The further analyses investigated the consistency between the four measures of stability. Congruency between Q1 (reported stability of FC routines) and Q4 (actions taken when preferred hand is full) was estimated by means of chi^2 statistic. With increasing declared stability, the proportion of participants who claimed that they easily use the other hand systematically decreased, whereas the proportion of those who declared that they try to count anyway, or put away the object being held increased ($chi_4^2 = 23.34$, $p < 0.001$; Table 3).

Congruencies between responses to Q1 (reported stability of FC routines) and Q5 (a) (how natural was FC with non-preferred hand) and Q5 (b) (how comfortable was counting with non-preferred hand) were estimated by means of Jonckheere–Terpstra (J–T) test for a monotone trend. This statistic tests whether means in the dependent variable change monotonically as a function of an independent variable. The declared stability was coded in increasing order. Higher declared stability was related to responses referring to feeling less natural and comfortable (observed J–T's 16036.5 and 17371.0, respectively; *p's* < 0.001; Table 4, upper part).

Relations between Q4 (actions taken when preferred hand is full) and Q5 (a) (how natural was FC with non-preferred hand) and Q5 (b) (how comfortable was counting with non-preferred hand) were investigated by means of a nonparametric Kruskal–Wallis (K–W's) test. Individuals who declared no problems with using the non-preferred hand also marked that counting against their typical routine was more natural and comfortable (see Table 3, lower part). In both cases the differences were significant (K–W's 44.38 and 20.68 for Q5 (a) and Q5 (b), respectively; $p < 0.001$).

The consistency of responses to Q5 (a) (how natural was FC with non-preferred hand) and Q5 (b) (how comfortable was counting with non-preferred hand), evaluated by means of polychoric correlation, was 0.66. This method is aimed to test correlations

Table 4 Relations between finger counting stability measures.

Dependent variable	Group	*N*	Mean	SD
	Reported stability			
	No preference	52	4.70	0.91
Natural	Usually	141	3.74	0.98
	Always	185	3.48	1.07
	No preference	52	4.00	1.19
Comfortable	Usually	141	3.53	0.98
	Always	185	3.32	1.13
	Actions taken when preferred hand busy			
	Use other hand	185	4.04	0.92
Natural	Count anyway	114	3.54	1.07
	Put away	79	3.13	1.06
	Use other hand	185	3.72	1.10
Comfortable	Count anyway	114	3.36	1.10
	Put away	79	3.15	1.03

Table 5 Observed vs. declared finger counting routine stability.

Observed stability	Declared stability						Total
	Always		Usually		No preference		
	N	%	*N*	%	*N*	%	*N*
Stable	37	58.7	22	34.9	4	6.4	63
Unstable	6	28.5	10	47.7	5	23.8	21

between discrete measures of continuous dimensions, like in Likert-like scales (*Gadermann, Guhn & Zumbo, 2012*).

Temporal stability

Out of 84 participants for whom we obtained the data in the second measurement, 63 (i.e., 75%) were stable in their FC sequence. Note that on a group level, this is remarkably consistent with the self-report data. In self-report about 50% declared to be stable. The other 50% declared to be flexible. Thus, if they started counting randomly about half of this other flexible 50% (namely 25%) should start with the same hand and the other half with the different hand. Together, this corresponds to the 75% participants actually showing stability.

Interestingly, individuals who were right-starters in the first measurement were more stable than the left-starters ($chi_1^2 = 7.04$, $p = 0.008$). Notably, participants who declared that their FC routines are stable were, indeed, more stable over time ($chi_2^2 = 7.95$, $p = 0.019$; Table 5), supporting the validity of the verbal reports.

We obtained the retest data only from four left-handed participants (three being stable and one unstable), and three ambidextrous (two being unstable and one stable) thus this analysis should be treated with caution. The Fisher's exact test did not reveal any

Table 6 Polychoric correlations between responses to items regarding for finger counting frequency in different contexts.

	1	2	3	4	5
1. Simple calculation	–				
2. Calendar calculation	0.41	–			
3. Listing	−0.23	0.51	–		
4. Arguments/plans	0.09	−0.23	−0.24	–	
5. Multiplication	0.48	0.30	−0.22	−0.21	–
6. Montring	0.05	0.13	−0.21	0.24	0.08

significant differences in stability related to handedness ($p = 0.194$ two-sided), but due to the low n, the power here is too low to draw reliable conclusions.

Participants whose FC was stable did not significantly differ from those whose FC was unstable regarding the description of their FC techniques (responses to question 2a-2e, $p > 0.20$). They also did not differ in terms of actions taken if they were to count with their fingers while their preferred hand was full ($p = 0.317$). The same is true regarding the responses to questions on how comfortable and natural it was to count with a non-preferred hand (Mann–Whitney's-U 558.5 and 627.0 and p 0.312 and 0.794, respectively). Furthermore, these groups did not significantly differ in overall FC use index (see below; $p = 0.505$).

Finger counting use and its correlates

We tested whether reported frequencies of FC use (questions 6a–6f) correlate with each other. Note that only 39 participants marked any answer to question 6g (other situations), for this reason we did not consider this question anymore. As responses were given on a Likert scale, polychoric correlations were used (cf. Table 6). Correlations were low to moderate, and sometimes even negative. It thus seemed that the FC use is heterogeneous and situation-dependent, and cannot be considered as an individual characteristic.

To check for potential differences in terms of FC use in each of the listed situations, K–W's (for declared stability and handedness) and Mann–Whitney (for starting hand and gender) nonparametric tests were carried out for each item. The tests did not yield any significant differences for declared stability, handedness and starting hand. However, there were differences in the case of gender. Namely, females declared significantly more FC use than men in case of simple calculation ($p = 0.023$), calendar calculation ($p = 0.005$), listing ($p < 0.001$), and multiplication ($p = 0.047$). There were no differences as regards presenting plans and arguments ($p = 0.492$). On the other hand, men declared using more finger montring than women ($p = 0.003$).

DISCUSSION

Overview

In a large-scale survey we aimed at investigating FC habits and their temporal stability among adult participants to provide relevant quantitative data, which—to the best of

our knowledge—was still lacking in the existing literature. Replicating previous studies (*Wasner et al., 2014*), we observed that most of the Polish speaking students started FC from their right hand, when asked to count freely first and subsequently to report their FC preferences in the questionnaire. This proportion was modulated by handedness (starting with a left hand was more prevalent in left-handers). The most prevalent uses of FC were listing elements, presenting arguments/plans, and calendar calculations. Most participants declared in a questionnaire that their FC routines were stable, and we observed congruency in responses to different items asking about this consistency. However, here we also tested the stability of FC routines for the first time: Crucially, 75% participants of the retest session in fact repeated the same FC sequence when tested 2 months following their initial measurement. Furthermore, we provide some exploratory data on the uses of FC in everyday life situations.

Starting hand and the finger counting direction

The majority of participants started FC sequences from the right hand. Even though the proportion of right- and left-starters differed significantly depending on handedness, there was still a lot of unexplained variance, which could not be accounted for by reading direction (Polish speakers as other Western cultures read and write from left to right). This result is similar to other reports showing a relatively large prevalence of right-starters among Western cultures (*Di Luca et al., 2006*; *Wasner et al., 2015*).

Here, the method of investigation is essential. When just presenting the FC questionnaire of *Fischer (2008)*, the majority of participants (e.g., 54% in *Wasner et al., 2015*) reported starting with the left hand. However, in spontaneous counting, the vast majority (72% in *Wasner et al., 2015*) started with the right hand. In our study, about 57% started with the right hand. This is approximately in the middle between the 72% in spontaneous counting and the 46% in the questionnaire condition of *Wasner et al. (2015)* study. Two reasons might be responsible for that divergence: cultural and methodological differences. First, as shown by *Lindemann, Alipour & Fischer (2011)*, there are considerable differences between cultures in their FC routines even if these cultures have the same reading direction. Secondly, we first asked the participants to count spontaneously and then to report it in the questionnaire. It remains possible that some participants were influenced by the questionnaire and reported left-to-right counting although they did not spontaneously do so. These reasons merit further investigation in future cross-cultural and cross-methodologicatol studies.

Finally, this observation provides further evidence that the role of FC routines for directional SNAs might not be as strong as previously assumed (*Fischer, 2008*). Although the majority counted right-to-left, typical left-to-right SNAs have been demonstrated several times in Polish speakers (*Cipora & Nuerk, 2013*; *Cipora et al., 2016*).

Finger counting description

Nearly all participants declared starting counting with their thumb and using both hands while counting to 10. The revealed pattern of FC is consistent with previous findings on Western cultures (*Wasner et al., 2014*) and, at the same time, opposite to the

routines of Middle-Eastern (e.g., Iranians, who typically counted from the pinkie to thumb; see *Lindemann, Alipour & Fischer, 2011*), and Chinese individuals, who predominantly used only right hand while counting to ten, wherein numbers 1–5 were counted beginning from an index finger, and 6–10 by using unique symbolic gestures; see *Domahs et al., 2010*; *Morrissey et al., 2016*). Regarding the techniques used, in the current study, there was little variation—almost all out of 380 participants declared starting from the closed palm and extending consecutive fingers. Around three-quarters of them used this as the only strategy. This result is also consistent with previous data except with studies on Japanese people. In comparison with Europeans, Japanese participants typically started counting from the open palm and bent consecutive fingers (*Butterworth, 1999*). However, the vast majority of reports and descriptions in the literature were based on single measurements of FC routines. Their reliability and validity for numerical cognition studies largely depend on whether they are indeed stable over time.

Stability of finger counting routines

In the literature, to the best of our knowledge, there are no data on the intraindividual temporal stability of FC in adults. Previous studies have focused only on the stability of FC routines across development (*Sato & Lalain, 2008*; P. Räsänen & T. Koponen, 2010, unpublished data). Stability of the routines seems crucial for the justification of previous findings, especially those that constitute an empirical basis for far-reaching theories about the embodied foundations of numerical processing. Notably, *Fischer (2008)* suggested that SNAs are ontogenetically earlier than the acquisition of reading and FC habits are among the crucial factors that shape them. In this suggestion Fischer seems to implicitly assume that FC routines are stable over time too, because it is hard to imagine how unstable, unreliable and highly flexibly FC routines should form relatively stable SNAs (but see *Cipora, Patro & Nuerk, 2018* for an overview of situated influences on SNAs).

Since previous reports did not directly address neither declared nor actual stability of FC routines, we investigated this issues in our survey. The series of questions directly or indirectly concerned participants' declared stability of their FC routines. It appeared that the majority of participants viewed their FC technique as stable and half of them declared using their preferred hand for counting even when it is full. Moreover, those measures were congruent—the proportion of participants using the preferred hand in any circumstances was related to declared stability. Also, counting against one's typical routine turned out to be more natural and comfortable for those declaring no problems using one's non-preferred hand for FC. Nevertheless, all these data come from self-report, and as shown by *Lucidi & Thevenot (2014)*, such reports might not be accurate in the case of FC. Therefore, we used an additional means for testing temporal stability, testing the same participants for the second time.

The majority of the participants' FC behavior in our study, indeed, appeared stable when tested 2 months following the first session. Interestingly, stability was related to the starting-hand in the first measurement. Individuals who started with the right hand in the first measurement were more stable than individuals, who started with the left hand.

As pointed out above, it is possible that some who reported starting from the left hand in questionnaires were in fact right starters—this could explain the divergence between the findings about FC starting habits in the current and in *Wasner et al. (2014)* study.

It is worth to emphasize that the procedure of our study was not identical to the visual perception condition in *Wasner et al. (2014)*. In the Wasner et al.'s visual perception condition, the participants were instructed to hold their hands in front of them and then to count, while in the current study, participants, before getting the questionnaires, were orally instructed to have their hands free and to keep their arms down. Thus, they were not holding the hands in front of them, and they did not see them.

It is conceivable that the visual perception of fingers lined up from left-to-right—like in the visual perception condition in the study by *Wasner et al. (2014)*—could affect at least some participants that they are more likely to count from left-to-right. The data seem to support this interpretation: in the Wasner et al.'s visual perception condition, 54% of the participants started FC with their left hand, and in our sample, it was only 43% ($chi_1^2 = 7.81$, $p = 0.005$). However, cross-cultural differences cannot be theoretically excluded, although, there is no theoretical reason (such as a different reading/writing direction) to predict such a difference between Polish and German participants.

Our procedure also differs from the spontaneous FC condition in *Wasner et al. (2014)* study, in which the experimenter observed how the participants are counting. Thus, there was no left-to-right presentation of hands anywhere in this condition. In the current study, the participants did not have a visual perception of their hands in front of them while counting, but they did have such a perception when reporting how they counted on the paper. This might have influenced their reports if they did not remember well, how they counted or decided to report a different counting direction when they had the schematic presentation of their hands in front of them. The results again support this suggestion. In the Wasner et al.'s spontaneous condition 28% of participants started FC with the left hand, while in the current study 43% did so ($chi_1^2 = 5.17$, $p = 0.023$). This significant difference suggests that the schematic presentation of the hands in the report also influenced performance.

All these subtle differences raise the question, how to best assess FC in a way that the type of assessment does not influence the reports of the habits too much. In this study, we conducted a group study, because we wished to investigate large-scale numbers of participants. By our instruction, we wanted to reduce the influence of visual perception during the counting process. In the report, we used the standard way of reporting counting preferences. Given our results, it can be critically discussed whether the depiction of hands and fingers should be different to assess FC preferences in a group study. We suggest that there is no simple solution to this issue. If, for instance, one would put the hands vertically, subjects might be tempted to name the fingers from top-to-bottom, because this is the standard way of numerical lists and tables in our reading culture. Additionally, they have to perform a mental rotation, in which the left and right hand should not be mixed up. Therefore, having the hands in vertical schema might not be optimal either. Furthermore, any types of a verbal list might bias participants to report congruent to the order of the list.

The report of FC preferences is at least in some participants induced by the way it is assessed. In our view, this certainly merits further investigation. Not only the "true" FC preferences (if they exist) should be uncovered by the best possible assessment, but beyond that this raises the question about embodied cognition, that is, how the perception and sensation change our cognition and memory about usual numerical counting habits.

Finger counting use—exploratory analysis

When it comes to FC, apart from how, it is important to determine when it is actually used and to provide quantitative estimates. In the case of our subjects, FC is used most often to list elements (e.g., counting the number of guests at the party) and to present one's arguments or plans to others. In these two aspects more than 40% of participants declared that they use FC often or very often. FC is also quite commonly used for calendar calculations (e.g., determining what day of the week is the deadline for submitting conference abstracts) and communicating quantity. These cases correspond with typical examples mentioned in the literature (*Butterworth, 1999*). In our study, the least prevalent use of FC use was for multiplication—77% of participants declared to never use it mdash; which is congruent with everyday observations indicating that currently such a calculating method is used very rarely despite its wide popularity in past decades (*Ifrah, 1981*; *Butterworth, 1999*). Relatively low on the FC use list were simple arithmetical operations. These results show that the use of fingers in adults rather serves as a means to reduce working memory load and to support both cardinal and ordinal aspects of processing numerical information (e.g., enumerating objects).

Differences between various subgroups, for example, individuals who use their fingers for simple arithmetical operations vs. participants who do not do it, should be subject to further research. The observed gender difference (females declaring more often using FC and males declaring more frequent finger montring), also desires further investigation. The comparison between participants who declared to be stable vs. unstable in FC habits seems justified, since the results of our study indicate that self-report measures are indeed fairly accurate. The question of how the particular groups differ regarding various number processing-related features deserves more attention in future research. Such research should address, in our opinion, not only the mutual relationship between the stability of FC habits and SNA, but also its relation to math skills and approximate number system measures.

CONCLUSION

Many publications emphasize the following claims about FC: it is widespread across the vast majority of cultures since prehistoric times (*Göbel, Shaki & Fischer, 2011*; *Overmann, 2014*); it played an important role in the development of Western mathematics (*Ifrah, 1981*); it is extremely important in the acquisition of numerical competences (*Piaget, 1942*; *Gelman & Gallistel, 1986*; *Jordan et al., 2008*); it affects adult numerical processing directly (*Domahs et al., 2010*; *Klein et al., 2011*; *Previtali, Rinaldi & Girelli, 2011*); and finally, it is a splendid manifestation of the embodiment of mathematics

(*Fischer & Brugger, 2011*; *Fischer, 2012*), as shown, for example, by the finding that simple mental calculations are realized through off-line simulation of finger movements (*Andres, Seron & Olivier, 2007*).

While the benefits and influences of FC have been often and controversially discussed (*Moeller et al., 2012*), we do not know so much about the attributes of FC. Here, we show that default FC habits are relatively stable in the majority of participants (to the best of our knowledge for the first time in a test–retest design). Moreover, most participants report that they are, nevertheless, relatively flexible in changing their FC habits when necessary (e.g., when holding an object) and that actual finger use is still widespread in healthy adults for a variety of activities. We conclude that these findings underline the practical significance of FC throughout the life-span.

ACKNOWLEDGEMENTS

We would like to thank Aleksandra Machniak for contributing to data collection, Magdalena Senderecka for very helpful comments regarding the analyses of handedness data, and Julianne Skinner for proofreading the manuscript. We are also grateful to the reviewers: Oliver Lindemann and the Anonymous Reviewer 2 for their valuable remarks.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

Mateusz Hohol is supported by the research grant 2015/19/B/HS1/03310 funded by the National Science Centre, Poland and the START scholarship funded by the Foundation for Polish Science (FNP). Kinga Wołoszyn is supported by the grant 2017/25/N/HS6/01052 funded by the National Science Centre, Poland. Krzysztof Cipora and Hans-Christoph Nuerk are supported by a grant from the Deutche Forschungsgemeinschaft (German Research Foundation) to Hans-Christoph Nuerk (NU 265/3-1). Krzysztof Cipora and Hans-Christoph Nuerk are further supported by the LEAD Graduate School & Research Network (GSC1028), which is funded within the framework of the Excellence Initiative of the German federal and state governments. There was no additional external funding received for this study. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Grant Disclosures

The following grant information was disclosed by the authors:
National Science Centre, Poland: 2015/19/B/HS1/03310; 2017/25/N/HS6/01052.
Foundation for Polish Science (FNP).
Deutche Forschungsgemeinschaft (German Research Foundation): NU 265/3-1.
LEAD Graduate School & Research Network: GSC1028.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Mateusz Hohol conceived and designed the experiments, performed the experiments, contributed reagents/materials/analysis tools, authored or reviewed drafts of the paper, approved the final draft, he substantially contributed to the interpretation of data.
- Kinga Wołoszyn performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft, she substantially contributed to the interpretation of data.
- Hans-Christoph Nuerk contributed reagents/materials/analysis tools, authored or reviewed drafts of the paper, approved the final draft, he substantially contributed to the interpretation of data.
- Krzysztof Cipora conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft, he substantially contributed to the interpretation of data.

Human Ethics

The following information was supplied relating to ethical approvals (i.e., approving body and any reference numbers):

The study was conducted in accordance with ethical guidelines for human studies of the Institute of Psychology, Jagiellonian University, Cracow, Poland. The design of the study was approved by the Local Ethics Committee of the Copernicus Center for Interdisciplinary Studies (Jagiellonian University Kraków, Poland; decision issued on 30th September 2015; 2/2015).

Data Availability

The following information was supplied regarding data availability:

Cipora, Krzysztof, Mateusz Hohol, Kinga Wołoszyn, and Hans-Christoph Nuerk. 2018. "Finger Counting—Temporal Stability." OSF. September 14. DOI 10.17605/OSF.IO/RQHFK.

REFERENCES

Andres M, Di Luca S, Pesenti M. 2008. Finger counting: the missing tool? *Behavioral and Brain Sciences* **31(6)**:642–643 DOI 10.1017/S0140525X08005578.

Andres M, Seron X, Olivier E. 2007. Contribution of hand motor circuits to counting. *Journal of Cognitive Neuroscience* **19(4)**:563–576 DOI 10.1162/jocn.2007.19.4.563.

Arning L, Ocklenburg S, Schulz S, Ness V, Gerding WM, Hengstler JG, Falkenstein M, Epplen JT, Güntürkün O, Beste C. 2015. Handedness and the X chromosome: The role of androgen receptor CAG-repeat length. *Scientific Reports* **5(1)**:8325 DOI 10.1038/srep08325.

Banks WP, Fujii M, Kayra-Stuart F. 1976. Semantic congruity effects in comparative judgments of magnitudes of digits. *Journal of Experimental Psychology: Human Perception and Performance* **2(3)**:435–447 DOI 10.1037//0096-1523.2.3.435.

Barsalou LW. 1999. Perceptual symbol systems. *Behavioral and Brain Sciences* **22(4)**:577–660 DOI 10.1017/S0140525X99002149.

Barsalou LW. 2008. Grounded cognition. *Annual Review of Psychology* **59(1)**:617–645 DOI 10.1146/annurev.psych.59.103006.093639.

Beller S, Bender A. 2011. Explicating numerical information: when and how fingers support (or hinder) number comprehension and handling. *Frontiers in Psychology* **2**:214 DOI 10.3389/fpsyg.2011.00214.

Bender A, Beller S. 2011. Fingers as a tool for counting? Naturally fixed or culturally flexible? *Frontiers in Psychology* **2**:256 DOI 10.3389/fpsyg.2011.00256.

Beratis IN, Rabavilas A, Nanou ED, Hountala C, Maganioti AE, Capsalis CN, Papadimitriou GN, Papageorgiou C. 2009. Effect of initiation-inhibition and handedness on the patterns of the P50 event-related potential component: a low resolution electromagnetic tomography study. *Behavioral and Brain Functions* **5(1)**:51 DOI 10.1186/1744-9081-5-51.

Borghi AM, Barca L, Binkofski F, Tummolini L. 2018. Varieties of abstract concepts: development, use and representation in the brain. *Philosophical Transactions of the Royal Society B: Biological Sciences* **373(1752)**:20170121 DOI 10.1098/rstb.2017.0121.

Butterworth B. 1999. *The Mathematical Brain*. Oxford: Macmillan.

Butterworth B. 2005. The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry* **46(1)**:3–18 DOI 10.1111/j.1469-7610.2004.00374.x.

Chinello A, Cattani V, Bonfiglioli C, Dehaene S, Piazza M. 2013. Objects, numbers, fingers, space: clustering of ventral and dorsal functions in young children and adults. *Developmental Science* **16(3)**:377–393 DOI 10.1111/desc.12028.

Cipora K, Patro K, Nuerk H-C. 2018. Situated influences on spatial-numerical associations. In: Hubbard T, ed. *Spatial Biases in Perception and Cognition*. Cambridge: Cambridge University Press, 41–59.

Cipora K, Hohol M, Nuerk H-C, Willmes K, Brożek B, Kucharzyk B, Nęcka E. 2016. Professional mathematicians differ from controls in their spatial-numerical associations. *Psychological Research* **80(4)**:710–726 DOI 10.1007/s00426-015-0677-6.

Cipora K, Patro K, Nuerk H-C. 2015. Are spatial-numerical associations a cornerstone for arithmetic learning? The lack of genuine correlations suggests no. *Mind, Brain, and Education* **9(4)**:190–206 DOI 10.1111/mbe.12093.

Cipora K, Nuerk H-C. 2013. Is the SNARC effect related to the level of mathematics? No systematic relationship observed despite more power, more repetitions, and more direct assessment of arithmetic skill. *Quarterly Journal of Experimental Psychology* **66(10)**:1974–1991 DOI 10.1080/17470218.2013.772215.

Clark A. 1998. *Being There: Putting Brain, Body, and World Together Again*. Cambridge: The MIT Press.

Crollen V, Noël M-P. 2015. The role of fingers in the development of counting and arithmetic skills. *Acta Psychologica* **156**:37–44 DOI 10.1016/j.actpsy.2015.01.007.

Dackermann T, Fischer U, Nuerk H-C, Cress U, Moeller K. 2017. Applying embodied cognition: from useful interventions and their theoretical underpinnings to practical applications. *ZDM* **49(4)**:545–557 DOI 10.1007/s11858-017-0850-z.

Dehaene S. 2011. *The Number Sense*. Oxford: Oxford University Press.

Di Luca S, Granà A, Semenza C, Seron X, Pesenti M. 2006. Finger–digit compatibility in Arabic numeral processing. *Quarterly Journal of Experimental Psychology* **59(9)**:1648–1663 DOI 10.1080/17470210500256839.

Di Luca S, Pesenti M. 2008. Masked priming effect with canonical finger numeral configurations. *Experimental Brain Research* **185(1)**:27–39 DOI 10.1007/s00221-007-1132-8.

Di Luca S, Pesenti M. 2010. Absence of low-level visual difference between canonical and noncanonical finger-numeral configurations. *Experimental Psychology* **57(3)**:202–207 DOI 10.1027/1618-3169/a000025.

Domahs F, Klein E, Moeller K, Nuerk H-C, Yoon B-C, Willmes K. 2012. Multimodal semantic quantity representations: further evidence from Korean sign language. *Frontiers in Psychology* **2**:389 DOI 10.3389/fpsyg.2011.00389.

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 DOI 10.1016/j.cortex.2007.08.001.

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.

Dupont-Boime J, Thevenot C. 2017. High working memory capacity favours the use of finger counting in six-year-old children. *Journal of Cognitive Psychology* **30(1)**:35–42 DOI 10.1080/20445911.2017.1396990.

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

Fabbri M, Guarini A. 2016. Finger counting habit and spatial–numerical association in children and adults. *Consciousness and Cognition* **40**:45–53 DOI 10.1016/j.concog.2015.12.012.

Fabbri M, Natale V. 2015. Finger counting and (2D:4D) digit ratio in spatial-numerical association. *Perception* **45(1–2)**:136–155 DOI 10.1177/0301006615594913.

Fayol M, Barrouillet P, Marinthe C. 1998. Predicting arithmetical achievement from neuro-psychological performance: a longitudinal study. *Cognition* **68(2)**:B63–B70 DOI 10.1016/S0010-0277(98)00046-8.

Fischer MH. 2008. Finger counting habits modulate spatial-numerical associations. *Cortex* **44(4)**:386–392 DOI 10.1016/j.cortex.2007.08.004.

Fischer MH. 2012. A hierarchical view of grounded, embodied, and situated numerical cognition. *Cognitive Processing* **13(S1)**:161–164 DOI 10.1007/s10339-012-0477-5.

Fischer MH. 2018. Why numbers are embodied concepts. *Frontiers in Psychology* **8**:2347 DOI 10.3389/fpsyg.2017.02347.

Fischer MH, 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 DOI 10.3389/fpsyg.2011.00260.

Fischer MH, Shaki S. 2018. Number concepts: abstract and embodied. *Philosophical Transactions of the Royal Society B: Biological Sciences* **373(1752)**:20170125 DOI 10.1098/rstb.2017.0125.

Fischer U, Suggate SP, Schmirl J, Stoeger H. 2017. Counting on fine motor skills: links between preschool finger dexterity and numerical skills. *Developmental Science* **21(4)**:e12623 DOI 10.1111/desc.12623.

Fodor JA. 1975. *The Language of Thought*. Cambridge: Harvard University Press.

Gadermann MA, Guhn M, Zumbo BD. 2012. Estimating ordinal reliability for Likert-type and ordinal item response data: a conceptual, empirical, and practical guide. *Practical Assessment, Research & Evaluation* **17**:1–13.

Gelman R, Gallistel C. 1986. *The Child's Understanding of Number*. Cambridge: Harvard University Press.

Göbel SM, Shaki S, Fischer MH. 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.

Groen GJ, Parkman JM. 1972. A chronometric analysis of simple addition. *Psychological Review* **79(4)**:329–343 DOI 10.1037/h0032950.

Ifrah G. 1981. *The Universal History of Numbers: From Prehistory to the Invention of the Computer*. London: The Harvill Press.

Jackendoff R. 2002. *Foundations of Language: Brain, Meaning, Grammar, Evolution*. Oxford: Oxford University Press.

Jordan NC, Kaplan D, Ramineni C, Locuniak MN. 2008. Development of number combination skill in the early school years: when do fingers help? *Developmental Science* **11(5)**:662–668 DOI 10.1111/j.1467-7687.2008.00715.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**:197 DOI 10.3389/fpsyg.2011.00197.

Lahita RG. 1988. Systemic lupus erythematosus: learning disability in the male offspring of female patients and relationship to laterality. *Psychoneuroendocrinology* **13(5)**:385–396 DOI 10.1016/0306-4530(88)90045-5.

Lakoff G, Núñez RE. 2000. *Where Mathematics Comes From*. New York: Basic Books.

Landy D, Allen C, Zednik C. 2014. A perceptual account of symbolic reasoning. *Frontiers in Psychology* **5**:275 DOI 10.3389/fpsyg.2014.00275.

Lindemann O, Alipour A, Fischer MH. 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.

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* **46(4)**:1079–1087 DOI 10.3758/s13428-014-0447-1.

Moeller K, Fischer U, Link T, Wasner M, Huber S, Cress U, Nuerk H-C. 2012. Learning and development of embodied numerosity. *Cognitive Processing* **13(S1)**:271–274 DOI 10.1007/s10339-012-0457-9.

Morrissey KR, Liu M, Kang J, Hallett D, Wang Q. 2016. Cross-cultural and intra-cultural differences in finger-counting habits and number magnitude processing: embodied numerosity in Canadian and Chinese university students. *Journal of Numerical Cognition* **2(1)**:1–19 DOI 10.5964/jnc.v2i1.14.

Newman SD. 2016. Does finger sense predict addition performance? *Cognitive Processing* **17(2)**:139–146 DOI 10.1007/s10339-016-0756-7.

Newman SD, Soylu F. 2014. The impact of finger counting habits on arithmetic in adults and children. *Psychological Research* **78(4)**:549–556 DOI 10.1007/s00426-013-0505-9.

Noël M-P. 2005. Finger gnosia: a predictor of numerical abilities in children? *Child Neuropsychology* **11(5)**:413–430 DOI 10.1080/09297040590951550.

Nuerk H-C, Patro K, Cress U, Schild U, Friedrich CK, Göbel SM. 2015. How space-number associations may be created in preliterate children: six distinct mechanisms. *Frontiers in Psychology* **6**:215 DOI 10.3389/fpsyg.2015.00215.

Oldfield RC. 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* **9(1)**:97–113 DOI 10.1016/0028-3932(71)90067-4.

Overmann KA. 2014. Finger-counting in the Upper Palaeolithic. *Rock Art Research* **31**:63–80.

Patro K, Nuerk H-C, Cress U. 2016. Mental number line in the preliterate brain: the role of early directional experiences. *Child Development Perspectives* **10(3)**:172–177 DOI 10.1111/cdep.12179.

Patro K, Fischer U, Nuerk H-C, Cress U. 2016. How to rapidly construct a spatial-numerical representation in preliterate children (at least temporarily). *Developmental Science* **19(1)**:126–144 DOI 10.1111/desc.12296.

Penner-Wilger M, Anderson ML. 2013. The relation between finger gnosis and mathematical ability: why redeployment of neural circuits best explains the finding. *Frontiers in Psychology* **4**:877 DOI 10.3389/fpsyg.2013.00877.

Piaget J. 1942. *Child's Conception of Number*. London: Routledge.

Pika S, Nicoladis E, Marentette P. 2009. How to order a beer: cultural differences in the use of conventional gestures for numbers. *Journal of Cross-Cultural Psychology* **40**:70–80 DOI 10.1177/0022022108326197.

Previtali P, Rinaldi L, Girelli L. 2011. Nature or nurture in finger counting: a review on the determinants of the direction of number?finger mapping. *Frontiers in Psychology* **2** DOI 10.3389/fpsyg.2011.00363.

Reeve R, Humberstone J. 2011. Five- to 7-Year-Olds? finger gnosia and calculation abilities. *Frontiers in Psychology* **2**:359 DOI 10.3389/fpsyg.2011.00359.

Riello M, Rusconi E. 2011. Unimanual SNARC effect: hand matters. *Frontiers in Psychology* **2**:372 DOI 10.3389/fpsyg.2011.00372.

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)**:684–693 DOI 10.1162/jocn.2007.19.4.684.

Sato M, Lalain M. 2008. On the relationship between handedness and hand-digit mapping in finger counting. *Cortex* **44(4)**:393–399 DOI 10.1016/j.cortex.2007.08.005.

Shaki S, Fischer MH, Petrusic WM. 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.

Soylu F, Lester FK, Newman SD. 2018. You can count on your fingers: The role of fingers in early mathematical development. *Journal of Numerical Cognition* **4(1)**:107–135 DOI 10.5964/jnc.v4i1.85.

Tan Ü. 1991. Serum testosterone levels in male and female subjects with standard and anomalous dominance. *International Journal of Neuroscience* **58(3–4)**:211–214 DOI 10.3109/00207459108985436.

Tschentscher N, Hauk O, Fischer MH, 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.

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

Wasner M, Moeller K, Fischer MH, Nuerk H-C. 2015. Related but not the same: Ordinality, cardinality and 1-to-1 correspondence in finger-based numerical representations. *Journal of Cognitive Psychology* **27(4)**:426–441 DOI 10.1080/20445911.2014.964719.

Wasner M, Nuerk H-C, Martignon L, Roesch S, Moeller K. 2016. Finger gnosis predicts a unique but small part of variance in initial arithmetic performance. *Journal of Experimental Child Psychology* **146**:1–16 DOI 10.1016/j.jecp.2016.01.006.

Wiese H. 2004. *Numbers, Language, and the Human Mind*. Cambridge: Cambridge University Press.

Willems G, Feeters-Erenay MC, Depuydt-Bcrte R. 1980. L'intérêt de la discrimination digitale dans les troubles d'apprentissage. *La psychomotricite* **4**:135–140.

Wilson M. 2002. Six views of embodied cognition. *Psychonomic Bulletin & Review* **9(4)**:625–636 DOI 10.3758/BF03196322.

Wołoszyn K, Hohol M. 2017. Commentary: the poverty of embodied cognition. *Frontiers in Psychology* **8**:845 DOI 10.3389/fpsyg.2017.00845.

Zago L, Pesenti M, Mellet E, Crivello F, Mazoyer B, Tzourio Mazoyer N. 2001. Neural coorrelates of simple and complex mental calculation. *NeuroImage* **13(2)**:314–327 DOI 10.1006/nimg.2000.0697.