Journal of Numerical Cognition
jnc.psychopen.eu | 2363-8761

Research Reports

# Cardinal and Ordinal Aspects of Finger-Counting Habits Predict Different Individual Differences in Embodied Numerosity

Kyle Morrissey*[a], Darcy Hallett[a]

[a] Department of Psychology, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada.

## Abstract

The hand with which one starts to count has been shown repeatedly to influence numerical performance. However, methods vary greatly in how researchers determine starting hand. As such, it is impossible to say whether starting hand reflects one construct that is being differently measured, or if these methods reflect different constructs. To investigate these possibilities, we employed a binary magnitude comparison task known to elicit spatial-numerical biases and embodied number magnitude effects, as well as both cardinal and ordinal assessments of starting hand. In addition to this, we further examined whether being made aware of one's finger-counting habits prior to the numerical task (through a finger-counting inventory) may alter performance during a spatial-numerical reaction-time task. Ordinal and cardinal starting hand classifications disagreed significantly in their classification of left vs. right-starters and predicted different aspects of numerical performance, which further interacted with procedure-order. The pattern of results suggest that 1) ordinal and cardinal aspects of finger-counting are dissociable and predict differing aspects of embodied numerosity, and 2) that assessing finger counting habits before performing a numerical task may affect performance on that task. Therefore, these methodological variations have important theoretical ramifications and need to be reported in greater detail in future work.

*Keywords:* magnitude comparison, finger counting, representational effects, embodied cognition, SNARC, order effects

Journal of Numerical Cognition, 2018, Vol. 4(3), 613–635, doi:10.5964/jnc.v4i3.138

Received: 2017-07-05. Accepted: 2018-05-17. Published (VoR): 2018-12-21.

*Corresponding author at: Psychology Department, University of Winnipeg, 515 Portage Ave, Winnipeg, MB R3B 2E9, Canada. E-mail: krm031@mun.ca



Finger-counting habits have become an important area of study for embodied numerosity. Finger counting is the most common form of bodily representation for numbers (Bender & Beller, 2012), which is used across cultures, sometimes without direct instruction (Butterworth, 1999; but see Crollen, Seron, & Noël, 2011b as this is a disputed point), and with the earliest likely documentation of finger counting dated as early as 27,000 years ago (Overmann, 2014). Finger representations combine the sense of touch, vision, verbal rehearsal and the motor system into a single activity (Moeller, Martignon, Wessolowski, Engel, & Nuerk, 2011), which reinforces the one-to-one correspondence that Arabic digits have with a learner's fingers (Alibali & DiRusso, 1999). Counting on ten fingers may also be helpful in internalizing the base ten counting system, and may be the reason we use a base ten counting system in the first place. Counting from thumb, to index finger, to middle finger and so on can reinforce that numbers occur in a particular order and that this order is meaningful. Learning to count on one's fingers may also help reinforce that no matter which number or finger is counted first, counting principles remain the same.

Furthermore, and of particular interest to this paper, people who start counting on their left hand (left-starters) differ from those who start counting on their right hand (right-starters) in both numerical performance (Fabbri, 2013; Fabbri & Guarini, 2016; Fischer, 2008; Morrissey, Liu, Kang, Hallett, & Wang, 2016; Newman & Soylu, 2014) and motor cortex activation evoked by single digit numbers (Tschentscher, Hauk, Fischer, & Pulvermüller, 2012). These findings support the general argument that fingers are linked to numerical cognition, but they also raise the question of why the hand on which one starts counting would make a difference. Perhaps this is a consequence of a left-to-right bias that associates smaller quantities with the left and larger values with the right (i.e., similar to the SNARC effect). Perhaps it is a consequence of beginning to count on the hand with which one is or is not, writing; in which case handedness would be an unknown moderator of any effect of starting hand. Most research on this topic either restricts their sample to right-handed participants (e.g., Morrissey et al., 2016; Newman & Soylu, 2014; and Tschentscher et al., 2012) or have samples of approximately 90% right-handed participants (e.g., Fabbri, 2013; Fabbri & Guarini, 2016; as well as Fischer, 2008), and so handedness remains largely unexamined, despite previous research indicating that handedness does impact participants' reported starting hand (Sato & Lalain, 2008).

Nevertheless, there are two reasons why it is difficult to explain the right-starter/left-starter difference. First, there are different methods to differentiate between left-starters and right-starters. For example, some studies have used a cardinal method, where participants are asked to show a set of numbers, one at a time, on their fingers and the hand that is used to show the numbers 5 or less is taken to be the starting hand (also called finger montring gestures, Crollen, Mahe, Collignon, & Seron, 2011a). Other studies have used an ordinal method, where participants are asked to begin counting from 1 to 10 on their fingers and the hand they start counting on is taken to be the starting hand. Second, recent research has demonstrated that these different methods yield related but different classifications of starting hand (Wasner, Moeller, Fischer, & Nuerk, 2014; Wasner, Moeller, Fischer, & Nuerk, 2015). This variability makes it difficult to understand who actually are left-starters and right-starters, and therefore why they would differ on numerical tasks.

The purpose of this study was to explicitly investigate whether different methods of assessing starting hand have differing relations with measures of numerical cognition. The objective is to ascertain if one of these methods better differentiates numerical ability, or if these different methods actually reflect different constructs. Our further goal was to discern what these results might mean theoretically for these previously observed differences between left- and right-starters.

## Fingers and Spatial-Numerical Reference Frames

One possible mechanism by which finger-counting may lead to embodiment of numeracy is through a SNARC-like spatial reference frame. Among populations that read from left to right, SNARC is characterized by faster association of smaller numbers with left hand space and larger numbers with right-hand space (Dehaene, Bossini, & Giraux, 1993). SNARC appears to partly be a function of reading direction for both numbers and for words, with individuals who come from cultures where reading occurs from right to left showing opposite patterns of SNARC to those who read from left to right (Shaki, Fischer, & Petrusic, 2009). However, SNARC is also impacted by experiencing left and right through one's body (Conson, Mazzarella, & Trojano, 2009; Patro, Nuerk, & Cress, 2015; Viarouge, Hubbard, & Dehaene, 2014). Viarouge et al. (2014) examined the SNARC effect under a variety of situations and proposed a dynamic hierarchical arrangement of reference frames to explain differences in SNARC as a function of experimental context. One noteworthy observation, at least for the current topic, was that participants showed no evidence of SNARC when their instructions emphasized which hands to use rather than which buttons they should press (Viarouge et al., 2014). In another example of how the left-right reference frame can interact with finger counting direction, Riello and Rusconi (2011) actually observed a robust SNARC effect when responses are limited to two fingers on the right hand in the prone posture or the left hand in the palm-up posture and a significantly reduced SNARC for the contrasting hand positions (i.e., when a response hand is held such that the thumb is to the left side and the little finger is on the right). However the interaction of these different reference frames may be complex, possibly involving individual differences, as Fischer (2008) reported that participants who typically begin counting on their left hand would demonstrate a stronger SNARC than those who begin counting on their right hand (but see Wasner et al., 2014, 2015).

## The Impact of Right- vs. Left-Starting Hand on Numerical Cognition

So far, research that has investigated individual differences between left-starters and right-starters has found several preliminary differences. Fabbri (2013) observed that right-starters, as assessed through Fischer's (2008) written questionnaire, showed greater evidence of a typical left-right SNARC effect in a parity task than did left-starters. These findings do not seem to match those reported in Fischer (2008). Fischer observed that left-starters had a significantly larger left-right SNARC association of magnitude, with left-starters associating large numbers more with right hand space, while right-starters did not demonstrate a statistically detectable SNARC effect. Fabbri (2013) suggests that a potential reason for the disparity between the two studies may be cross-cultural in nature, as both their study and Fischer's found that the stronger SNARC effect was associated with the most common starting hand.

Left-starters and right-starters have also been found to exhibit performance differences in a variety of numerical tasks aside from those meant to measure SNARC. In an addition study, Newman and Soylu (2014) found that child left-starters (aged 5-12) made more errors than right-starters, and adult left-starters showed a slower response time than right-starters. Morrissey and colleagues (Morrissey et al., 2016) observed that, when comparing number pairs where both numbers are typically counted on two hands, left-starters reliably showed a greater processing load. Taken together, it does appear that left-starters and right-starters are doing something different with regards to numbers; however, drawing clear mechanistic suggestions are difficult due to some procedural variability in these studies.

## Problems in Assessing Left-Starters and Right-Starters

As it turns out, there is more than one way to question someone about their finger counting habits. For example, cardinal finger-number gestures include finger numeral configurations which may be used to represent an individual number symbolically, similarly to written numerals, such as when showing a number to another person (Di Luca, Lefevre, & Pesenti, 2010). Studies that assess starting hand in this cardinal fashion (e.g., Crollen et al., 2011a; Morrissey et al., 2016; Wasner et al., 2015) asked participants to show a selection of numbers (one number at a time) on their fingers, and starting hand was determined by which hand was used to represent numbers between 1 and 5. On the other hand, ordinal finger counting habits refer to the order in which fingers would be used to count a number sequence. Studies that assessed starting hand in this spontaneous/ordinal way (e.g., Sato & Lalain, 2008) asked participants to count from 1 to 10 on their fingers, without further instructions regarding how or with which hands/fingers to count, and then noted with which hand they started. A third method, used by Fischer (2008) and Tschentscher et al. (2012), used a written finger counting assessment where participants assigned numbers to particular fingers on a picture of two hands. This latter method appears to have more in common with the ordinal/spontaneous inventories used in the literature than with the cardinal/finger-montring inventories, however it is sufficiently distinct to warrant being described as its own category. It is also common for studies in this literature to lack specific details as to how participants were questioned about their finger counting habits (see Di Luca & Pesenti, 2008). Often, researchers only mention that finger counting habits are assessed as spontaneous (see Newman & Soylu, 2014, Experiment 2; Zago & Badets, 2016), as part of an information survey (see Newman & Soylu, 2014, Experiment 1), or would simply refer to the typical finger counting strategy of the region (see Di Luca, Granà, Semenza, Seron, & Pesenti, 2006). This lack of detail would be less concerning if we could be confident that determining starting hand was a relatively straightforward procedure.

While cardinal and ordinal gestures are related, they are not always the same. Wasner and colleagues (Wasner et al., 2014; Wasner et al., 2015) explicitly compared different methods of assessing finger counting habits. They found that ordinal and cardinal assessments of finger-counting habits only indicate the same starting hand 62% of the time (Wasner et al., 2015). This team also found that the relative proportion of participants that start counting on the right hand or left hand was heavily influenced by whether finger counting habits are questioned spontaneously or with visual/proprioceptive cues (Wasner et al., 2014). When asked to finger count spontaneously, the majority of adults were right-starters, but when asked to place their hands in front of their eyes before being asked to count, there were more left-starters. When they were given pictures of hands and asked to label each finger with a number (the method highest in visual and proprioceptive cues, and the third method mentioned above used by Fischer, 2008 and Tschentscher et al., 2012), the majority were left-starters. The likely reason for these differences in left or right-starting across inventories is that cardinal finger-number gestures are treated in a symbolic fashion, similar to written numerals, while ordinal/written inventories likely tap into culturally acquired left-right associations (Shaki, Petrusic, & Leth-Steensen, 2012). Therefore any study that finds, or does not find, differences between participants who start counting on the right or the left hand will likely be confounded by how those finger counting habits were assessed.

In addition to these differences in assessment, there is also some variability across studies about when the assessment is given. Some experimenters questioned participants about their counting habits prior to the main task (Domahs et al., 2012; Fabbri, 2013; Fischer, 2008; Sato & Lalain, 2008; Tschentscher et al., 2012), while other researchers report questioning participants about counting habits at the end of the study (Di Luca & Pesenti, 2008; Di Luca et al., 2010; Riello & Rusconi, 2011). In the case of some studies, the timing of finger counting questions was not mentioned explicitly (Domahs et al., 2010; Fabbri & Guarini, 2016). This is problematic, as drawing participants' attention to their fingers has been shown to alter numerical task performance. Viarouge et al. (2014, Experiment 1) have experimentally demonstrated that the effect of SNARC is eliminated when instructions specify participants right and left hands, while instructions that instead referenced right and left-buttons resulted in a typical SNARC. Given that questioning someone about their finger counting habits is both potentially drawing attention to a hand-based reference-frame, and a hand-based reference frame that is semantically and developmentally linked to numbers, it is prudent and reasonable to check whether self-reporting of finger counting habits in turn influence the tasks used to assess their role in cognition.

## Current Study Rationale and Objectives

The current study is a combination of a retrospective study using data from Morrissey et al. (2016) and new data collected explicitly for the purpose of this study. In Morrissey et al. (2016), a cardinal finger-counting inventory was used to determine starting hand, and demonstrated that Canadian left- and right-starters differed in how they responded to number comparisons that were represented on two hands (e.g., 6 vs. 8 and 7 vs. 9). However, during a pilot study embedded in data collection for Morrissey et al. (2016), 32 participants received assessments of both ordinal and cardinal finger counting habits, yielding some disagreement between these two inventories. This disagreement prompted this follow-up investigation. Although Wasner and her colleagues (Wasner et al., 2014, 2015) have already demonstrated that cardinal and ordinal finger counting inventories can lead to different classifications, they did not test how these different classifications relate to individual performance differences. Without comparing how cardinal and ordinal classifications each predict individual differences on different aspects of numerical cognition, we do not know if these two different methods represent two different constructs, or if one of these is just a better measure of starting hand than the other.

For this reason, the present study separately evaluates the effect of starting hand differences, using both the ordinal and cardinal classifications, on two separate numerical cognition phenomena. The first of these was the embodiment of SNARC-like response compatibility effects. The second was the differences in response time for certain number comparisons whose numbers are represented on two hands, as reported by Morrissey et al. (2016). The objective was to examine these two embodied numerical phenomena that are known to exhibit right/left-starter differences and ascertain whether cardinal and ordinal classifications of right/left-starters would support different interpretations of the impact of starting hand. The same paradigm was used as in Morrissey et al. (2016), in order to ensure procedural consistency. This paradigm has been shown to demonstrate cross-cultural differences in cognitive load that are consistent with specific structural features of five distinct forms of cardinal finger-counting habits, reported in four different countries, including whether finger-counting gestures require one hand, two hands, or symbolic finger-configurations (Domahs et al., 2010; Morrissey et al., 2016), or gestural motions (Domahs et al., 2012), as well as cognitive load differences between cardinal left-starters and right-starters among Canadians. This task also can be recoded in order to serve as a measure of SNARC-like response compatibility effects, which are very similar to the categorical SNARC effect described in other number magnitude comparison paradigms (Wood, Willmes, Nuerk, & Fischer, 2008).

The main difference between this sort of SNARC-like response compatibility effect and a more typical categorical SNARC task is in the explicitness of space in participants' decision-making process. A typical SNARC magnitude comparison test present number-digit stimuli in the center of the screen, and participants rate these items as smaller, or larger, than some reference value, typically 5. Therefore, relatively faster responses for larger number-digits with the right hand, and vice versa, are argued to be a function of an implicit spatial association of number digits (Dehaene et al., 1993). In the case of SNARC-like congruity effects, like the current paradigm, there was an added explicit spatial dimension, as the target number-digit is either on the right or left-hand side of the screen. Therefore, the aforementioned implicit spatial attributes of number-digit stimuli may be either congruent or incongruent with the explicit spatial attributes of the presented number-digits, resulting in faster SNARC-congruent and slower incongruent responses. However, by randomly counterbalancing whether the larger number is on the left or right, as was done in this study, the spatial effect of stimuli placement is independent of which trials are SNARC congruent or incongruent. Therefore, the SNARC effect can be calculated independent of explicit spatial characteristics. This type of paradigm has been published several times in the literature as either a measure of SNARC (Fischer, 2003), or a measure of SNARC-like congruity effects (Domahs et al., 2010; Morrissey et al., 2016).

A number of investigations have demonstrated ordinal starting-hand as a moderator of SNARC (Fabbri, 2013; Fischer, 2008), as well as other SNARC-like effects (Fabbri & Guarini, 2016). Further, as drawing participants' attention to their hands has been shown to reduce the impact of SNARC (Viarouge et al., 2014), the timing of administration of either finger counting inventory may also serve to moderate subsequent SNARC-congruity effects. Therefore, this task afforded an opportunity to – for the first time – evaluate both cardinal and ordinal finger-counting habits as moderators of multiple published effects simultaneously within the same number task.

Furthermore, by counterbalancing the order of task administration, there was an additional opportunity to test Viarouge et al.'s (2014) suggestion that activating a hand-based frame of reference may moderate the impact of SNARC. This is of particular interest here, as manipulations of hand orientation have also been shown to moderate SNARC effects in line with the counting direction of the hand used to respond (Riello & Rusconi, 2011), and therefore activating a finger-based frame of reference through practicing finger-counting habits prior to the computer test may have a different impact on left starters as opposed to right-starters, given that finger-based reference frames may also differ for these individuals.

## Summary of Study Objectives

The primary objective of this investigation was to examine two separate numerical phenomena known to exhibit right/left-starter differences and ascertain whether cardinal and ordinal classifications of finger-counting habits would lead to different conclusions about the impact of starting hand. A secondary objective within this is to further examine whether being made aware of one's finger-counting habits prior to the numerical task (through a finger-counting inventory) may alter performance during a spatial-numerical reaction-time task in ways consistent with prior investigations that have suggested that this is indeed possible when left/right hands are emphasized instead of left/right buttons (Viarouge et al., 2014), or when palm orientation is altered by experimenters (Riello & Rusconi, 2011). Satisfying these objectives should 1) make it clearer as to whether cardinal/ordinal finger-counting habits are supplying different information, as well as 2) provide an indication as to whether or not greater methodological reporting requirements would be a prudent recommendation.

# Method

## Participants

The data used in this study were a combination of two different datasets, with all participants having participated in an identical number comparison task. Dataset one consisted of 98 participants specifically recruited for this investigation who all received both cardinal and ordinal finger counting inventories, although two participants were later excluded after committing more than 25% errors. Dataset two consists of published and unpublished data for 135 participants tested during Morrissey et al. (2016). Of those participants in dataset two, 34 had received both cardinal and ordinal finger-counting habit inventories as part of a pilot investigation for the current investigation, despite only cardinal finger counting habits having been analysed in that publication.

Overall, there were 96 participants included in Dataset one and 135 participants in Dataset two, with an average accuracy of 95.2% (*SD* = 3.09). See Table 1 for a detailed breakdown of participants. Included participants were an average of 20.93 years of age (*SD* = 4.33). All participants included are right–handed. Participant recruiting took place from October of 2012 through March of 2017. Participants were recruited through voluntary subject pools in exchange for course credit. Regardless of dataset, all participants provided informed consent prior to their participation, and all procedures were approved by the participating university's research ethics board.

## Stimuli

The stimuli and procedure for both datasets were the same as that used Morrissey et al. (2016), which was a replication of Domahs et al. (2010). Number-digit stimuli consisted of a series of number pairs which were all separated by a numerical distance of two. The number digit pairs ranged from 1 vs. 3, to 18 vs. 20. Stimuli presentation was counter-balanced such that the smaller digit of each pair would appear on the left-hand side five times and on the right-hand side five times, within each of the two experimental study blocks. Participants were always instructed that when the correct answer was to their right, to press the response key on the right, and when the correct answer was to their left, to press the response key on their left. This was done to ensure that all responses were Simon-congruent and so any observed SNARC-congruity effects were not confounded by participants simply choosing the larger number faster with the right-hand because it was on the right-hand side (Simon, 1969). Each of the blocks would include experimental trials and practice trials. Half of participants began Block 1 with the instruction to select the larger number in the pair, and the rest of participants were instructed to choose the smaller number in the pair. At Block 2 instructions reversed from Block 1. Seventy-two of these number pairs were practice trials, split into two instruction conditions of 36 trials each preceding Block 1 and Block 2 respectively, which is standard for this task (Domahs et al., 2010; Morrissey et al., 2016). Practice trials were accompanied by their own set of written instructions and provided participants with accuracy feedback. Block 1 and 2 also contained 180 experimental trials each. Practice trials were not included in data analysis. Each number comparison was only visible for two 2,000 ms, and so each practice block could take at maximum about 72 seconds. In total, each participant was exposed to 432 randomly presented number pairs, with 360 experimental trials. These 360 experimental trials were composed of 5 repetitions of 72 unique combinations constructed by 18 stimuli (the 18 different number pairs) by 2 response sides (larger number being on the left or the right) by 2 conditions (asked to pick the smaller or larger number).

## Apparatus

A single numerical task was used for all participants. All number pairs were Arabic Digits in black Arial 60pt font, and presented on a white screen, using E-prime 2.0 on either a 15” or 18” lab computer monitor (Schneider, Eschman, & Zuccolotto, 2002). Number pairs appeared on the same horizontal line, centred and separated by seven spaces. Each trial would consist of a white screen lasting 500ms, then 200ms with a centred fixation cross, followed by the number pair. Participants were instructed to provide their answer using two keyboard keys marked off with a coloured sticker. The keys marked off were in the position of the “f” and “j” key of a QWERTY keyboard. A response from the participant would begin the next trial, while participants would move on to the next stimulus pair after 2,000 ms with no response.

## Finger Counting Inventories

In Dataset one, participants were given both a cardinal and an ordinal finger-counting inventory to determine whether they were left-starters or right-starters. In Dataset two, 101 participants only received the cardinal inventory while 34 received a cardinal and an ordinal finger-counting inventory. The cardinal finger-counting inventory included a brief questionnaire about counting habits, where participants were asked to respond to different numbers from 1-10 by demonstrating the relevant number gesture. Participants were instructed to provide number gestures as quickly as possible and with the gesture that feels most natural. The hand used for each number gesture was recorded on a sheet picturing a variety of hands using different counting gestures. Right- and left-starters were classified by which hand was used to represent one through five. The ordinal finger-counting habits inventory instead asked participants to count from 1-10 on their fingers as they would normally, and their starting hand was recorded.

## Procedure

Each participant in the study answered demographic questions about ethnicity, first language, gender, language spoken in primary school, and nationality. Participants who went to school outside of Canada or who used a first language other than English or French were excluded, as previous work has shown that different cultures may impact patterns of numerical performance (Domahs et al., 2010; Morrissey et al., 2016). In Dataset one, finger-counting inventories were counter-balanced, such that participants would be in one of four conditions: 1) ordinal inventory, then number comparison task, then cardinal inventory, 2) number comparison task, then ordinal inventory, then cardinal inventory, 3) cardinal inventory, then number comparison task, then ordinal inventory, and 4) number comparison task, then cardinal inventory, then ordinal inventory. In Dataset two, the cardinal finger counting inventory was given either before the numerical task (like Condition 3, except without the ordinal inventory at the end) or after the task (like Condition 4, except without the ordinal inventory at the end). Therefore, while some participants in Dataset two received only one inventory, there is no possibility of order effects changing their responses compared to Dataset one participants in Conditions 3 and 4. Almost all of the 34 participants in Dataset two who were given the ordinal inventory were in Condition 4. To make the distribution of conditions even for the ordinal inventory, Dataset one almost exclusively consisted of Conditions 1 thru 3. The end result, collapsed across Dataset, is an *N* of 29, 35, 35, and 33 for Conditions 1 thru 4, respectively. It should also be noted that while some participants received only the cardinal inventory, there were no participants who received only the ordinal inventory. See Table 1 for a summary of the number of participants per condition.

Participants were coded as being in the before-task or after-task condition; depending on if either the cardinal or ordinal finger counting inventory was given prior to the number comparison task. It has been shown recently in the literature that situated factors and experimental procedure can impact self-reported finger-counting habits (Wasner, Moeller, Fischer, & Nuerk, 2014). Therefore, these procedure-order conditions were used to examine the possibility that either finger counting inventory may interact with the numerical task itself.

Table 1

*Frequency of Participants in Each Procedure-Order Condition Across Dataset One and Dataset Two*

| | Dataset one | | | | Dataset two | |
|---|---|---|---|---|---|---|
| **Inventory / Starting hand** | **Cond. 1** | **Cond. 2** | **Cond. 3** | **Cond. 4** | **Cond. 3** | **Cond. 4** |
| **Cardinal** | | | | | | |
| Right-starter | 20 | 30 | 26 | 1 | 61 | 55 |
| Left-starter | 9 | 5 | 5 | 0 | 7 | 12 |
| **Ordinal** | | | | | | |
| Right-starter | 16 | 21 | 24 | 1 | 2 | 21 |
| Left-starter | 13 | 14 | 7 | 0 | 0 | 11 |

# Results

## Preliminary Analyses

A preliminary chi-squared analysis was conducted to test for frequency differences between cardinal left- and right-starters between the two datasets. There was no significant difference in proportion of left- and right-starters between those in Dataset one (77 right-starters vs. 19 left-starters), and the additional 135 participants from Dataset two (116 right-starters vs. 19 left-starters), $\chi^2(1, n = 231) = 1.334$, $p = .248$, $\phi = .076$. Further, as participants are to be examined as a function of whether they were questioned about their finger-counting habits before/after the numerical task, and because it was possible that participants with different finger-counting habits could be unequally represented across condition, we evaluated whether starting hand was independent of finger-counting inventory timing. Status as a cardinal left or right-starter did not vary as a function of inventory timing, $\chi^2(1, n = 231) < 0.0005$, $p = .984$, $\phi < .002$, nor did status as an ordinal left or right starter, $\chi^2(1, n = 130) = 0.291$, $p = .590$, $\phi = .047$.

Because this study has more people who were classified on the cardinal inventory than were classified on the ordinal inventory, it could be argued that this study has more power to detect an effect with cardinal starting hand than with ordinal starting hand. As it turns out, the statistical power for comparing left-starters and right-starters is actually quite similar for cardinal and ordinal classifications, despite there being more cardinal data. Using a moderate effect size, $d = 0.5$, the power for detecting an effect for starting hand in our study using the cardinal inventory is .80, while the power to do the same for the ordinal inventory is .77. The reason the power is comparable is because the ordinal inventory yields a much more balanced split between left- and right-starters (see Table 1). This compensates for the smaller number of participants that were given the ordinal inventory, and the end effect is there is similar power to detect a difference between starting hand for either inventory.

The proportion of left-starters and right-starters were examined as a function type of finger counting inventory. Because the off-diagonal frequencies were low (see Table 2), an exact binomial test was used instead of a McNemar test. This test indicated that the ordinal finger counting inventory was significantly more likely to identify a left-starter than a cardinal inventory, $p < .0005$, $\phi = .59$. This disagreement appears to be almost entirely due to ordinal left-starters, with which the cardinal inventory agreed only about 49% of the time, whereas the cardinal inventory agreed with the classification of ordinal right-starters about 98% of the time. The total disagreement between these inventories was ~18.5% of participants. While this represents a significant total disagreement between inventories, it is significantly less than the disagreement reported by Wasner and colleagues (Wasner et al., 2015). Wasner et al. (2015) tested 68 adults with cardinal and ordinal inventories, and reported 42 cases of starting hand agreement, and 26 cases of starting hand disagreement. After imputing Wasner et al.'s (2015) agreement/disagreement data alongside the current dataset into a chi-square test of independence, it was observed that disagreement between cardinal and ordinal starting hand in this sample departed significantly from theirs, $\chi^2(1, n = 198) = 9.248$, $p = .002$, $\phi = -.216$. There was, however, a very similar rate of ordinal left-starters to that reported in another larger sample, $n = 458$, with 34.6% ordinal left-starters here and 28% reported by Wasner et al. (2014).

Table 2

*Relative Disagreement of the Cardinal and Ordinal Inventories in Identifying Left-Starters Versus Right-Starters*

| Starter hand | Ordinal Right-starter | Ordinal Left-starter |
|---|---|---|
| Cardinal Right-starter | 83 | 22 |
| Cardinal Left-starter | 2 | 23 |

## Do Ordinal and Cardinal Finger-Counting Habits Predict Similar SNARC-Like Effects?

These analyses tested whether type of finger-counting inventory, as well as whether they were given this inventory before or after the reaction time task, affected participants' SNARC-like performance. Median reaction time scores were utilized in all analyses, as medians are more robust to violations of normality that are typical of reaction-time data. Reaction time scores follow a positively-skewed distribution, due to participants' inability to achieve a negative reaction time score. This is particularly important in a task like this where significant differences in errors and mean reaction time are expected between different items, independent of any variables of interest.

A SNARC-like effect was defined as reacting more quickly to SNARC congruent responses, (e.g., choosing the larger number of a pair with the right hand or choosing the smaller digit with the left hand) than to SNARC incongruent responses, (e.g., choosing the larger digit with the left hand or choosing the smaller digit with the right hand). SNARC-like performance effects were treated as categorical, similar to Wood et al. (2008, Table 1). Data analysis for either the current paradigm or a typical categorical SNARC is essentially the same, when both rely on magnitude comparison rather than parity. There were a few methodological differences from a traditional categorical SNARC, as that is usually a result of a comparison of a series of centrally-presented small individual quantities from 1-9, or 1-10, with some fixed standard, such as 5. The current task utilizes a variable standard, and number pairs ranging from 1 vs. 3 to 18 vs. 20. Therefore, to ensure comparability between these data and previous studies like Fischer (2008), as well as to ensure any observed effects are not limited to particular number-ranges, any SNARC-like effects with single-digit numbers (i.e., number pairs up to 7 vs. 9) were also compared to effects with double-digit numbers (i.e., from 8 vs. 10 to 18 vs. 20).

Errors have already been shown in Morrissey et al. (2016) to follow a SNARC-like pattern in the current test, with more mistakes made for SNARC-incongruent responses than SNARC-congruent responses. Errors are also not committed randomly for different number pairs, with smaller numbers and comparisons of 1 and 2 digit numbers (e.g., 8 vs. 10) tending to demonstrate fewer errors. Because of this, data was collapsed in two steps in order to ensure that participants were being equitably compared across the same conditions and number pairs. In the first step, correct median SNARC-congruent reaction times and correct SNARC-incongruent reaction times were calculated for each number comparison (within each participant). These reaction-time scores were then regressed on their SNARC-congruency, which yielded a non-standardized regression slope for each number pair, for each participant, indicating how much faster their responses were when SNARC-congruent versus when SNARC-incongruent.

Two separate 2 (Finger counting timing) x 2 (Starting hand) x 2 (single-digit vs. other number pairs) between/within ANOVAs were conducted on these SNARC-like advantage scores, with finger counting timing and starting hand as between-subject factors and single-digit vs. other number pairs as a within-subject factor. One ANOVA used the cardinal finger-counting inventory in order to differentiate right vs. left-starters, while the second ANOVA used the ordinal inventory for this purpose. The within-subject factor splits up the analyses into number pairs with single-digit numbers, as compared to all other number pairs. The ANOVA with the cardinal inventory used both Datasets while the ANOVA with the ordinal inventory included only those participants who received the ordinal finger counting inventory.

For the ANOVA using the cardinal inventory, one participant, a right-starter in the before-test condition, was excluded due to a disproportionate number of errors for a particular number pair, leading to an empty cell. As expected, there was a robust overall effect of SNARC-like response compatibility effects, as shown by the intercept, (21.037ms), $F(1, 226) = 27.963$, $p < .0005$, $\eta_p^2 = .110$, and this was not significantly moderated by whether single-digit numbers, (27.122 ms), or other number pairs (14.952 ms) were included, $F(1, 226) = 3.122$, $p = .079$, $\eta_p^2 = .014$. The within-subject factor did not interact with starting hand, $F(1, 226) = 0.529$, $p = .468$, $\eta_p^2 = .002$, nor with inventory timing, $F(1, 226) = 0.061$, $p = .805$, $\eta_p^2 < .0005$. There was also no evidence of a three way interaction among these factors, $F(1, 226) = 0.710$, $p = .400$, $\eta_p^2 = .003$. The results for the two between-subjects factors are shown in Figure 1. Consistent with predictions based on Viarouge et al. (2014), participants who had been given a finger counting inventory prior to the magnitude comparison task showed less evidence of SNARC-like response compatibility effects than those who had not, (before test: 8.414 ms, after test: 33.659 ms), $F(1, 226) = 10.067$, $p = .002$, $\eta_p^2 = .043$. Inconsistent with Fischer (2008), there was no difference in SNARC between cardinal left-starters and right-starters, (left: 24.529 ms, right: 17.545 ms), $F(1, 226) = 0.771$, $p = .381$, $\eta_p^2 = .003$. However, there was an interaction of the timing of the finger counting inventory with starting hand, $F(1, 226) = 5.185$, $p = .024$, $\eta_p^2 = .022$. Bonferroni-corrected post-hoc comparisons indicated that the interaction was driven by a significant difference between left-starters in the before-test (2.848 ms) and after-test (46.210 ms) conditions, $d = 0.89$, as well as a difference between before-test right-starters (13.981 ms) and after-test left-starters, $d = 0.65$. Left-starters in the after-test condition also exhibited stronger SNARC-like effects than right-starters in the after-test condition (21.109 ms), $d = 0.55$, however this was not statistically significant. All other pairwise comparisons, consisting of before-test vs. after-test right-starters, $d = 0.16$, before-test right-starters vs. before-test left-starters, $d = 0.25$, and after-test right-starters vs. before-test left-starters, $d = 0.48$, were non-significant after the Bonferroni correction.

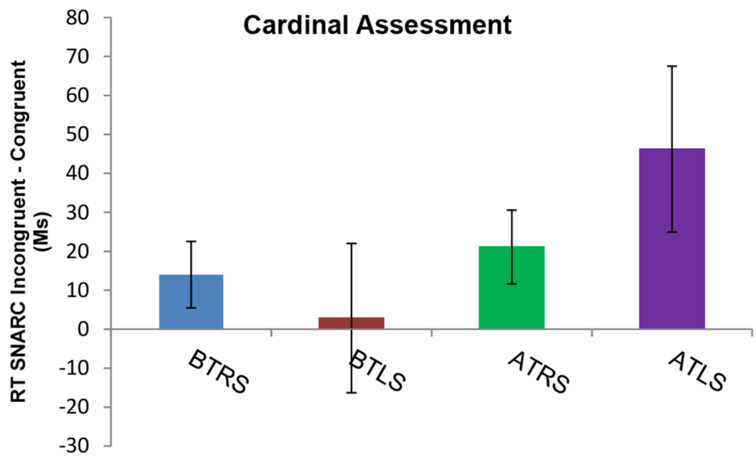


*Figure 1.* Average reaction-time difference between SNARC-congruent and SNARC-incongruent trials. Error bars are 95% confidence intervals. BTRS indicates before-test right-starters ($n$ = 106). BTLS indicates before-test left-starters ($n$ = 21). ATRS indicates after-test right-starters ($n$ = 86). ATLS indicates after-test left-starters ($n$ = 17).

The same repeated measures ANOVA model was tested again using the reported ordinal starting hand of these participants. As predicted, there was a large SNARC-like response compatibility effects (21.558 ms), as indicated by the intercept, $F(1, 126) = 31.248$, $p < .0005$, $\eta_p^2 = .199$, and this was not significantly moderated by whether single-digit numbers, (27.003 ms), or other number pairs (13.571 ms) were included, $F(1, 126) = 2.805$, $p = .096$, $\eta_p^2 = .022$. The within-subject factor did not interact with starting hand, $F(1, 126) = 0.879$, $p = .350$, $\eta_p^2 = .007$, nor with inventory timing, $F(1, 126) = 1.516$, $p = .221$, $\eta_p^2 = .012$. There was also no evidence of a three way interaction among these factors, $F(1, 126) = 0.02$, $p = .889$, $\eta_p^2 < .0005$. The results for the two between-subjects factors in this analysis are shown in Figure 2. As in the previous analysis using the cardinal inventory, and consistent with Viarouge et al. (2014), there was a reduction of SNARC if the finger counting inventory had been given prior to the number comparison task (12.542 ms) compared to after the task (30.574 ms), $F(1, 126) = 5.465$, $p = .021$, $\eta_p^2 = .042$. Ordinal left-starters also showed a non-significantly greater impact of SNARC-congruency of their responses (left: 27.929 ms, right: 15.186 ms), $F(1, 126) = 2.730$, $p = .101$, $\eta_p^2 = .021$, consistent with the findings of Fischer (2008). but this difference interacted with whether the inventory was given before or after the number comparison task, $F(1, 126) = 5.298$, $p = .023$, $\eta_p^2 = .04$. Bonferroni-corrected post-hoc comparisons indicated that the interaction was driven by a significant difference between left-starters in the before-test (10.037 ms) and after-test (45.822 ms) conditions, $d = 0.78$, a difference between before-test right-starters (15.047 ms) and after-test left-starters, $d = 0.69$, as well as a difference between after-test right-starters (15.325 ms) and after-test left-starters, $d = 0.63$. All other pairwise comparisons, consisting of before-test vs. after-test right-starters, $d = 0.007$, before-test right-starters vs. before-test left-starters, $d = .15$, and after-test right-starters vs. before-test left-starters, $d = 0.14$, were non-significant after the Bonferroni correction.

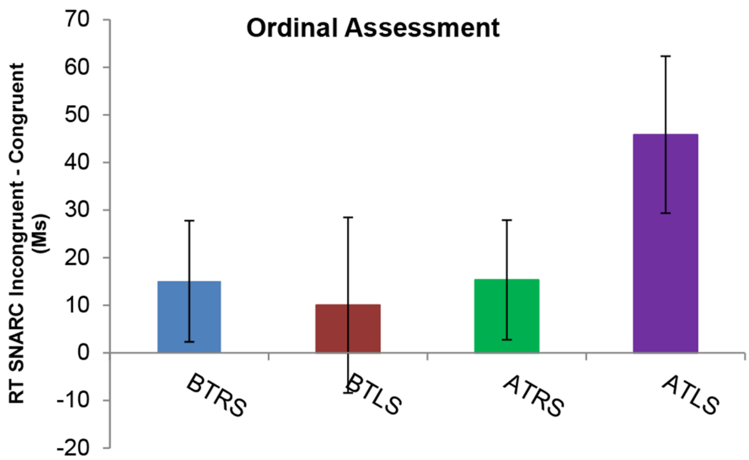


*Figure 2.* Average reaction-time difference between SNARC-congruent and SNARC-incongruent trials. Error bars are 95% confidence intervals. BTRS indicates before-test right-starters (*n* = 42). BTLS indicates before-test left-starters (*n* = 20). ATRS indicates after-test right-starters (*n* = 43). ATLS indicates after-test left-starters (*n* = 25).

On the surface, both the analysis involving the cardinal inventory and the analysis involving the ordinal inventory demonstrated similar patterns of results. SNARC-like response compatibility effects were observed, but differences between after-test left-starters exhibited these effects more strongly than other conditions. Assessed after the numerical task, left-starters showed a stronger SNARC-like response than right-starters for both the cardinal and ordinal classifications, although this difference was not statistically significant for after-test right and left-starters when using the cardinal classification. Given the extent to which these two classifications overlap, and given also the fact this overlap is not evenly distributed (i.e., out of the 130 participants who were coded on both, 2 were cardinal left-starters and ordinal right starters, while 22 demonstrated the opposite pattern), it is difficult to test whether the ordinal classification determined a reliably larger effect size for right and left-starters in the after-test condition using standard statistical methods. After collapsing SNARC-like difference scores evenly across all number-digit pairs, we used a bootstrapping procedure. With this procedure, it was possible to create a confidence interval around the difference between the effect found in the ordinal analysis and the effect found in the cardinal analysis. Resampling was done with 10 000 iterations while sampling with replacement. The resampling was set so that each sample were proportionally drawn from the 130 participants who had both classifications and the 101 participants who only had the cardinal classification. The 95% confidence interval generated by the procedure in milliseconds was [-1.73, 14.86]. This interval does include zero, so the effect for the ordinal classifications could not be said to be significantly larger than the effect for cardinal classifications.

## Do Ordinal and Cardinal Finger-Counting Habits Predict Similar Number-Comparison Effects?

Like the previous section, cardinal and ordinal finger counting inventories were tested separately. Morrissey et al. (2016) found that left-starters exhibited an increased cognitive load when comparisons involved numbers that are represented on two hands (i.e., 6 vs. 8 and 7 vs. 9). This comparison is made after residualizing participants' data via a log-fit line calculated for each participant. This is done in this manner in order to control for effects of numeric magnitude, where responses for numerically larger number pairs tend to be slower than for numerically smaller number pairs (Göbel et al., 2011). Past research has also supported a logarithmic mental number line as the strongest model for how magnitude influences number processing time (Dehaene, 2003). In both analyses, median reaction time scores were used in place of log-transformed average reaction time scores used by Morrissey et al. (2016) and Domahs and colleagues (Domahs et al., 2010, 2012). This approach reduced data exclusions and rendered subsequent analyses more robust to violations of normality, just as it did for the analyses concerning the SNARC-like effects above. A median correct reaction time was taken for each of the 18 different number pairs per participant. A logarithmic line of best fit was calculated for each participant data set. For each fit line, a slope of $y = a*\ln(x)+b$ was computed, with x denoting the average of each pair of numbers. A larger slope denotes a relatively steeper increase in response for larger number pairs relative to response latency for smaller number pairs. It is important to rule out any possible magnitude effects on participant reaction-time performance, as doing so ensures that any systematic effects of particular numerosities are not due to these numbers simply being larger. These fit lines were subtracted from the median reaction time scores for each participant, at each comparison, and the resulting difference scores standardized with a mean of 0 and a standard deviation of 1.

We conducted a pair of independent samples t-tests, with Welch's corrected degrees of freedom, with cardinal and ordinal starting hand as the predictors and participants' log-fit slope as the dependent variable. Cardinal left-starters showed a slightly, but statistically significantly, steeper log-fit slope than right-starters, with 54.06 ms vs. 46.44 ms per log-digit magnitude increase respectively, $t(51.496) = 2.289$, $p = .026$, $d = 0.42$. Ordinal left-starters also had a marginally significant, but similar, difference in log fit slope, 53.70 ms vs. 46.52 ms per log-digit magnitude increase for right and left-starters respectively, $t(76.879) = 1.964$, $p = .053$, $d = 0.38$. A follow-up series of correlations of log-residualized response latency of all single-digit number comparisons found that the slope of the log-fit line predicted very little variance in either comparisons of 6 vs. 8, $r(229) = .115$, $p = .08$ or comparisons of 7 vs. 9, $r(229) = .058$, $p = .379$. Therefore this difference between right-starters and left-starters is very unlikely to explain individual differences for left-starters and right-starters' log-residualized scores for numbers typically counted on both hands, and instead likely constitutes a separate and independent difference between right-starters and left-starters that does not appear to have yet been characterized in the literature.

Using the cardinal inventory, a 2 (starting hand) x 2 (finger counting timing) between-subjects ANOVA was conducted on the mean log-residualized response latencies for comparisons of 6 vs. 8 and 7 vs. 9. These two comparisons were singled out in Morrissey et al. (2016) as both number-digits require two hands in order to count (see the 6 vs. 8 and 7 vs. 9 comparisons in Figure 3). There was a reliable effect of starting hand on log-residualized response latency, with larger latency scores for the 38 cardinal left-starters, $M = 0.67$, $SD = 0.80$, compared to 193 cardinal right-starters, $M = 0.32$, $SD = 0.61$, $F(1, 227) = 9.378$, $p = .002$, $\eta_p^2 = .040$, $d = 0.56$ (see the 6 vs 8 and 7 vs. 9 comparisons in Figure 4). However, there was no reliable effect of inventory timing, $F(1, 227) = 1.332$, $p = .250$, $\eta_p^2 = .006$, and no interaction, $F(1, 227) = 1.174$, $p = .280$, $\eta_p^2 = .0005$.

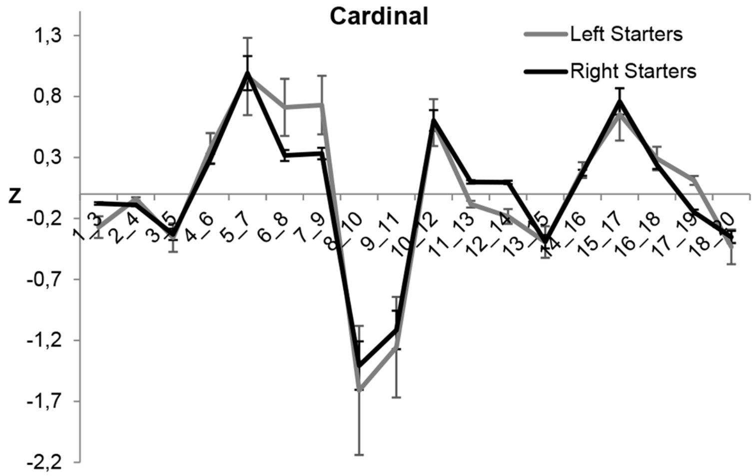


*Figure 3.* Standardized residual scores across the 18 comparisons, when right-starters and left-starters are classified via cardinal finger-counting habits. Error bars are 95% confidence intervals.

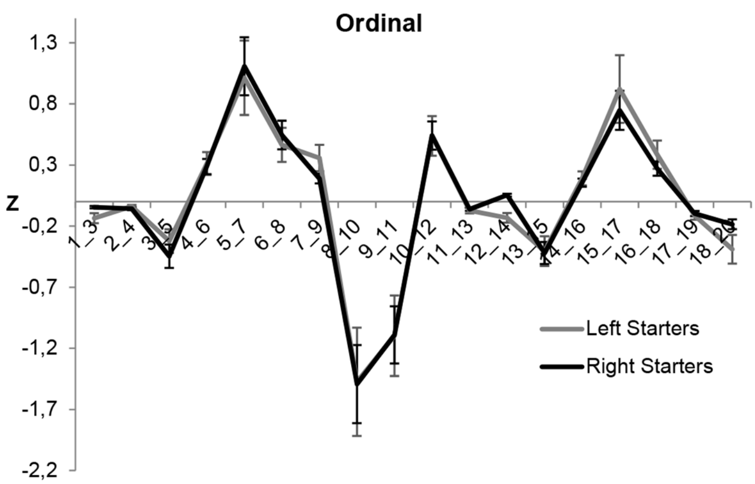


*Figure 4.* Standardized residual scores across the 18 comparisons, when right-starters and left-starters are classified via ordinal finger-counting habits. Error bars are 95% confidence intervals.

The above analyses were repeated using the ordinal starting hand classifications. Unlike cardinal starting hand, ordinal starting hand did not predict any mean differences in log-residualized response latency between the 45 left-starters, $M$ = 0.41, $SD$ = 0.66, and the 86 right-starters, $M$ = 0.37, $SD$ = 0.58, $F(1, 126) = 0.157$, $p = .693$, $\eta_p^2 = .001$, $d$ = 0.07 (see the 6 vs 8 and 7 vs. 9 comparisons in Figure 2). Like cardinal starting hand, there was no reliable effect of inventory timing, $F(1, 126) = 1.025$, $p = .313$, $\eta_p^2 =.008$, and no interaction, $F(1, 126) = 0.404$, $p = .526$, $\eta_p^2 = .003$.

As was case in the analyses of the SNARC-like response compatibility effects, it was necessary to directly compare whether ordinal classifications yielded different results than cardinal classifications. In this case, there was a significant effect of starting hand in the cardinal analyses but not one for the ordinal analyses. However, having one effect that is statistically significant and another one that is not does not necessarily mean that these two effects are different from each other. To test if the difference in these effects differed from zero, again a bootstrapping procedure was performed using the same parameters as above. The 95% confidence interval of the difference in the effect using the cardinal classifications and the effect using the ordinal classifications was [0.044, 0.592]. This confidence interval did not include zero, and so the effect found using the cardinal classifications was stronger than the effect found using the ordinal classifications.

# Discussion

The research reported here was prompted by recent work indicating that finger montring /cardinal finger-number associations may differ from spontaneous or ordinal finger-number gestures (Wasner et al., 2015), as well as work suggesting that activating hand-based frames of reference may impact the SNARC effect (Viarouge et al., 2014). It was therefore prudent to re-examine work linking numerical performance to individual differences in finger-counting habits with this knowledge in mind. This study used a combination of new and previously published data in order to examine two separate numerical phenomena known to exhibit right/left-starter differences and ascertain whether cardinal and ordinal classifications of finger-counting habits would lead to different conclusions about the impact of starting hand. A secondary objective was to examine whether being made aware of one's finger-counting habits prior to the numerical task (through a finger-counting inventory) may alter performance during a spatial-numerical reaction-time task, as prior investigations have suggested that this is indeed possible when left/right hands are emphasized instead of left/right buttons (Viarouge et al., 2014), or when palm orientation is altered by experimenters (Riello & Rusconi, 2011). This was accomplished by separately considering each of two numerical phenomena that could be detected within a single number-comparison task.

The first analysis examined how left- vs. right-starter would differ on a SNARC-like task. We also tested whether giving an inventory before the main task (which should draw participants' attention to their hands) lessens the SNARC-like response biases, similar to Viarouge et al. (2014). Several important conclusions can be drawn from this section. First, two recent literature findings were conceptually replicated (Fischer, 2008; Viarouge et al., 2014); however Fischer was only replicated under specific procedural circumstances. The increased impact of SNARC seen by Fischer for left-starters was only evident when finger counting habits were assessed after completing number magnitude comparisons. This effect was also somewhat stronger when using ordinal finger counting habits when compared to cardinal finger counting habits, although not significantly so. Therefore, these results do not suggest that ordinal/cardinal finger-counting habits make different predictions, or constitute different reference frames, regarding SNARC-like response associations. However, given that fact, and the significantly greater proportion of participants described as left-starters by the ordinal inventory, this inventory may have advantages for investigations of SNARC in terms of statistical power. It should also be noteworthy though, as described in Wasner et al. (2014), that the written finger counting assessment tool used in Fischer (2008) detects around twice as many left-starters as the ordinal finger counting inventory used in the current study. Therefore the fact that the left/right-starter difference was replicated at all may itself be surprising, given the demonstrated discordance between these inventories. However, in the future, the inventory used in Fischer (2008) should be compared to the ordinal finger counting inventory directly in order to establish which describes the underlying construct more effectively.

In addition, drawing attention to participants' hands appears to be a more persistent manipulation of SNARC-like response biases than may have been implied by Viarouge et al. (2014), which is consistent with their argument that hands constitute a separate spatial reference frame. Simply asking participants about their finger counting habits before the task, regardless of which inventory was used, reduced SNARC-like response compatibility effects. Further, this occurred despite finger counting inventories being in no way related to instructions given for the magnitude comparison task, in which participants were instructed to use the right and left keys identifiable with coloured stickers. This would suggest that it is in fact drawing attention to one's hands that is the basis of this effect rather than necessarily being a function of ordinal finger counting specifically. Interestingly, Fabbri (2013) questioned participants about their finger counting habits prior to a SNARC parity test, and found a larger impact of SNARC for right-starters, with no detectable SNARC for left-starters. This is similar to the pattern of results observed in the before-test condition above. This suggests that the mechanisms behind the embodiment of SNARC have been incompletely understood, with individual differences in finger counting habits also playing a role. For example, Riello and Rusconi (2011) observed that SNARC may be reduced when participants are asked to make binary number judgments in a numerical task with two fingers with either a left hand in a palm-down orientation, or a right hand in a palm-up orientation, suggesting that finger-counting direction within a particular hand may play a role in producing SNARC. SNARC was likewise preserved for the right hand in a palm-down orientation, or a left hand in the palm-up orientation. It was suggested that when response-hand orientation leads to a finger counting direction of right to left, from the thumb to the pinkie finger, that this finger-based reference frame conflicts with a more global left-right reference frame. Taken together, it may be that asking right-starters in the current study about their finger counting habits drew their attention to their right hand. They then would be asked to hold both hands palm down on a keyboard, which reinforced a left-right reference frame for the right hand. Meanwhile, a left-starter would have been reinforcing a hand-based reference frame for the left hand while their hands are in a palm-down orientation, which would reinforce a left-right reference frame. This account is consistent with the current observations.

There were, however, important differences between the current investigation and that of both Viarouge et al. (2014) and Fischer (2008). Both of these investigations utilized a parity task with a continuous SNARC, rather than a binary magnitude comparison task with a categorical SNARC. Past research has indicated larger effect sizes for investigations of SNARC using parity tasks rather than categorical magnitude classification tasks with a variable standard by which to judge magnitude, as was used here (Wood et al., 2008, Table 1). This is both a limitation and strength of the current study. These observations may generalize differently to parity tasks than what has been seen here. Requiring participants to make judgments about two number digits in each comparison may also evoke additional or different mental strategies than a parity task. However, it is useful to see that the basic findings of Viarouge et al. (2014) and Fischer (2008) do appear to generalize beyond just parity judgments.

The second analysis in this study examined individual differences in number representation effects, such as those investigated in Domahs et al. (2010, 2012), as well as Morrissey et al. (2016), where numbers typically counted on two hands demonstrate differences between left-and right starters in log-residualized response times. The results of these analyses suggest that, unlike analyses of SNARC-like effects, representation effects were not impacted by the timing of the finger-counting inventory. However, the findings regarding starting hand raise yet further questions as to what exactly is meant in the literature by a left-starter and a right-starter. Only the original cardinal inventory employed in Morrissey et al. (2016) differentiated left-starters and right-starters in terms of representational effects for single-digit numbers typically counted on two hands. This fits with the original model, as cardinal number gestures would diverge most for right- and left-starters at comparisons of 6 vs. 8 and 7 vs. 9, as that original study showed that differences at only these comparisons could differentiate right-starters and left-starters, as well two different Chinese finger counting systems.

Ordinal finger-counting habits did not differentiate right and left-starters on log-residualized reaction time scores, and this was not a function of differences in statistical power. This observation is also important in order to ensure that this finding can be replicated. The methods of Morrissey et al. (2016) do describe a finger counting inventory which is a cardinal finger-counting inventory, but the terms cardinal or finger montring were not used explicitly. It was also not clear at the time of that study that cardinal and ordinal finger counting habits would differ in such theoretically important ways. As a result, it is possible that an attempted replication of this finding would use ordinal finger counting habits, as a plurality of study designs appear to, and this observation would likely not have been replicated.

While research staff did not systematically record all aspects of bodily behaviour associated with producing finger counting gestures, it was also observed that cardinal gestures were not typically produced with participants looking at their hands, except for the production of number gestures for six through eight, which were not used in determining if participants were right or left-starters. Ordinal counting gestures were more often, but not universally, produced with a participant looking at their hands. Likewise, the highest rate of left-starters observed in the literature, appears to be for the written inventory used by Fischer (2008), with left and right-starters at approximate parity. This would also imply that there may be visual differences between the inventories that account for differences in participants' responses. It may be that differences between ordinal and cardinal left-starters may in fact simply be a reflection of ordinal (but possibly not cardinal) finger-counting habits and number comparisons measuring the same global left-right visual reference frame. However these ancillary behaviours during finger counting require further work in order to evaluate the degree to which they may explain additional inconsistencies in individual differences in numerical performance.

## Recommendations for Other Researchers

The findings discussed here raise several important points for research that involves finger counting habits and SNARC. The first point is methodological. It is very important that finger counting assessments be reported in greater detail, as different assessments result in different participants being classified as left or right-starters, as well as different overall rates in left and right-starters. While there was substantial discordance in starting hand for ordinal and cardinal finger counting habits, there are other inventories in use and so this does not capture the full range of how differences in finger counting inventories may alter the classification of right and left-starters. This suggests that methodological inconsistencies in the assessment of finger counting habits may be more pernicious in how they compromise the ability to replicate or directly compare research in this area. If studies are going to be reporting results for samples of ~30 participants, then the likelihood of one study group containing substantially more ordinal left-starters than another group is high. Combine this with unreported timing of finger-counting habits, or the emphasis of buttons versus hands in participant instructions (Viarouge et al., 2014), and it is not at all implausible that a researcher could obtain a mean between-group difference in SNARC due entirely to these confounding variables. In fact, these results could potentially provide an alternative explanation for the outcome differences between Fabbri (2013) and Fischer (2008), which have been previously attributed to a cross-cultural difference. Fabbri's (2013) results are consistent with the before-test condition above, with no statistically significant SNARC effect for left-starters, while Fischer observed a greater SNARC effect for left-starters relative to right-starters, which is consistent with the after-test condition of the current investigation. Fabbri tested finger counting habits prior to the SNARC task, while Fischer did not provide the necessary details in order to determine this aspect of their methods. If the results above are replicated by other researchers, it is likely that this sort of outcome has almost certainly happened several times in the literature already.

There has been a recent discussion in the literature about a lack of successful replication in psychological research (Open Science Collaboration, 2015). If unreported methodological inconsistencies can render the underlying embodied constructs discussed in this paper undetectable, then it is necessary to argue that they be reported in greater detail. This includes details about the inventory used, recording or controlling for participants looking at their hands during the inventory, as well as reporting the timing of the inventory within the procedure. Future research will also need to focus more on better operationalizing the concept of a left or right-starter.

## Evidence for Multiple Reference Frames

The second major point raised here is that of evidence for multiple independent finger-counting-based reference frames. Currently, this is the first study to demonstrate how inconsistencies in finger counting inventories can have consequences for the prediction of actual individual differences in numerical performance. If there were only one global left-right reference frame interacting with a hand-based reference frame, then these inventories should be predicting the same types of phenomena, but with varying degrees of success or clarity. This latter scenario appeared to be correct when describing SNARC-like response compatibility effects, with both ordinal and cardinal inventories predicting similar differences, with somewhat stronger effects detected with the ordinal inventory. However, what was particularly interesting about this analysis was not only that classifications of left and right-starters differed between the ordinal and cardinal inventories, but that this disagreement was almost entirely limited to the classification of ordinal left-starters. Despite this relative disagreement, both inventories predicted substantial individual differences with regard to SNARC-like response compatibility effects, while only the cardinal inventory found differences between right and left-starters when evaluating number representation effects. This fits with recent evidence suggesting that decoding ordinal and cardinal aspects of number symbols may be separable and each may predict unique variance in mathematical competence (Goffin & Ansari, 2016). That we have found a similar disassociation between cardinal and ordinal aspects of finger-counting is an interesting parallel finding. This leads us to suggest that while SNARC-like reference frames appear similar between ordinal and cardinal finger-counters, there may be dissociable representational properties underlying other left/right-starter differences in the literature.

## Conclusions

All in all, these results suggest that finger-based numerical representation may be more complex than originally thought. While we continue to find evidence that some participants respond more slowly than others when comparing numbers typically counted on two hands, it appears that only cardinal, and not ordinal, starting-hand is a useful predictor of this individual difference. While the use of a categorical SNARC-like task does soften our conclusions somewhat for spatial associations, these results do raise some concerns for interpreting other findings in the literature. Fortunately, the main recommendation that we make in order to avoid most of the issues raised here would be to simply transparently report timing and type of finger counting inventory in all studies using these variables. A possible side benefit for such improvements in reporting would be that differences between inventories, and between procedure-orders, may provide researchers with richer information as to what influences underlay certain aspects of numerical cognition, as we can see not only how certain manipulations impact performance, but how different types of participants may respond differently to these manipulations. This increased methodological exactness, and the further testing of the influence of finger counting habits, should help us to better understand what appears to be the increasingly complex connection between finger and numerical representations.

## Funding

The authors have no funding to report.

## Competing Interests

The authors have declared that no competing interests exist.

## Acknowledgments

The authors have no support to report.

## Data Availability

For this study, a dataset is freely available (see the Supplementary Materials section).

# Supplementary Materials

The following supplementary materials are available for the present paper via the OSF project page.

### Index of Supplementary Materials

Morrissey, K. (2018). *Cardinal and ordinal aspects of finger-counting habits predict different individual differences in embodied numerosity* [Supplementary materials]. https://osf.io/7mtkz/

# References

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

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

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

Conson, M., Mazzarella, E., & Trojano, L. (2009). Numbers are represented in egocentric space: Effects of numerical cues and spatial reference frames on hand laterality judgements. *Neuroscience Letters, 452*(2), 176-180. doi:10.1016/j.neulet.2009.01.043

Crollen, V., Mahe, R., Collignon, O., & Seron, X. (2011a). The role of vision in the development of finger-number interactions: Finger-counting and finger-montring in blind children. *Journal of Experimental Child Psychology, 109*, 525-539. doi:10.1016/j.jecp.2011.03.011

Crollen, V., Seron, X., & Noël, M.-P. (2011b). Is finger-counting necessary for the development of arithmetic abilities? *Frontiers in Psychology, 2*, Article 242. doi:10.3389/fpsyg.2011.00242

Dehaene, S. (2003). The neural basis of the Weber-Fechner law: A logarithmic mental number line. *Trends in Cognitive Sciences, 7*(4), 145-147. doi:10.1016/S1364-6613(03)00055-X

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

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*, 1648-1663. doi:10.1080/17470210500256839

Di Luca, S., Lefevre, N., & Pesenti, M. (2010). Place and summation coding for canonical and non-canonical finger numeral representations. *Cognition, 117*, 95-100. doi:10.1016/j.cognition.2010.06.008

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

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*, Article 389. doi:10.3389/fpsyg.2011.00389

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*, 251-266. doi:10.1016/j.cognition.2010.05.007

Fabbri, M. (2013). Finger counting habits and spatial-numerical association in horizontal and vertical orientations. *Journal of Cognition and Culture, 13*, 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

Fischer, M. H. (2003). Cognitive representation of negative numbers. *Psychological Science, 14*, 278-282. doi:10.1111/1467-9280.03435

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

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*, 543-565. doi:10.1177/0022022111406251

Goffin, C., & Ansari, D. (2016). Beyond magnitude: Judging ordinality of symbolic number is unrelated to magnitude comparison and independently relates to individual differences in arithmetic. *Cognition, 150*, 68-76. doi:10.1016/j.cognition.2016.01.018

Moeller, K., Martignon, L., Wessolowski, S., Engel, J., & Nuerk, H.-C. (2011). Effects of finger counting on numerical development – The opposing views of neurocognition and mathematics education. *Frontiers in Psychology, 2*, Article 328. doi:10.3389/fpsyg.2011.00328

Morrissey, K. R., 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*, 1-19. doi:10.5964/jnc.v2i1.14

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

Open Science Collaboration. (2015). Estimating the reproducibility of psychological science. *Science, 349*(6251), Article aac4716. doi:10.1126/science.aac4716

Overmann, K. A. (2014). Finger counting in the Upper Paleolithic. *Rock Art Research, 31*, 63-80.

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

Riello, M., & Rusconi, E. (2011). Unimanual SNARC effect: Hand matters. *Frontiers in Psychology, 2*, Article 372. doi:10.3389/fpsyg.2011.00372

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

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime: User's guide*. Pittsburgh, PA, USA: Psychology Software Incorporated.

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

Shaki, S., Petrusic, W. M., & Leth-Steensen, C. (2012). SNARC effects with numerical and non-numerical symbolic comparative judgments: Instructional and cultural dependencies. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 515-530. doi:10.1037/a0026729

Simon, J. R. (1969). Reactions towards the source of stimulation. *Journal of Experimental Psychology, 81*, 174-176. doi:10.1037/h0027448

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

Viarouge, A., Hubbard, E. M., & Dehaene, S. (2014). The organization of spatial reference frames involved in the SNARC effect. *Quarterly Journal of Experimental Psychology, 67*, 1484-1499. doi:10.1080/17470218.2014.897358

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

Wasner, M., Moeller, K., Fischer, M. H., & 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*, 426-441. doi:10.1080/20445911.2014.964719

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

Zago, L., & Badets, A. (2016). What is the role of manual preference in hand-digit mapping during finger counting? A study in a large sample of right-and left-handers. *Perception, 45*, 125-135. doi:10.1177/0301006615602628



PsychOpen GOLD is a publishing service by
Leibniz Institute for Psychology Information (ZPID),
Trier, Germany. www.leibniz-psychology.org