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Cross-Cultural and Intra-Cultural Differences in Finger-Counting Habits and Number Magnitude Processing: Embodied Numerosity in Canadian and Chinese University Students

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Abstract

Recent work in numerical cognition has shown-that number magnitude is not entirely abstract, and at least partly rooted in embodied and situated experiences, including finger-counting. The current study extends previous cross-cultural research to address within-culture individual differences in finger counting habits. Results indicated that Canadian participants demonstrated an additional cognitive load when comparing numbers that require more than one hand to represent, and this pattern of performance is further modulated by whether they typically start counting on their left hand or their right hand. Chinese students typically count on only one hand and so show no such effect, except for an increase in errors, similar to that seen in Canadians, for those whom self-identify as predominantly two-hand counters. Results suggest that the impact of finger counting habits extend beyond cultural experience and concord in predictable ways with differences in number magnitude processing for specific number-digits. We conclude that symbolic number magnitude processing is partially rooted in learned finger-counting habits, consistent with a motor simulation account of embodied numeracy and that argument is supported by both cross-cultural and within-culture differences in finger-counting habits.

Keywords: magnitude, Chinese, finger-counting, embodied cognition, individual differences

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The role of finger-counting in the acquisition of number concepts has continued to attract growing research interest over the past decade (Fischer, Kaufmann, & Domahs, 2012; Moeller et al., 2012; Roesch & Moeller, 2015). In 2010, Domahs, Moeller, Huber, Willmes, and Nuerk examined how culturally acquired finger-counting habits influenced mental representations of number magnitude in adults. Three groups of adults were chosen for the characteristics of their respective finger-counting systems: Chinese one-hand counters, German two-hand counters and deaf-German two-hand counters. The Chinese participants used a culturally unique finger-counting strategy. Numbers 1-5 are counted on the right hand in a way that would be familiar to those in North America and most of Europe; however numbers 6-10 are counted using symbolic sign gestures continued on the same hand (see Figure 1). German deaf and hearing participants counted on two hands in non-symbolic ways, and they showed reliable evidence of increased reaction times when comparing number pairs where at least one number would have been counted using two hands. Chinese participants, who count on only one hand, did not show this increased reaction time. Domahs et al. (2012) referred to this as a five-break effect, and it was one of the first indications of how cross-cultural differences in finger-counting habits may influence basic numerical processing.

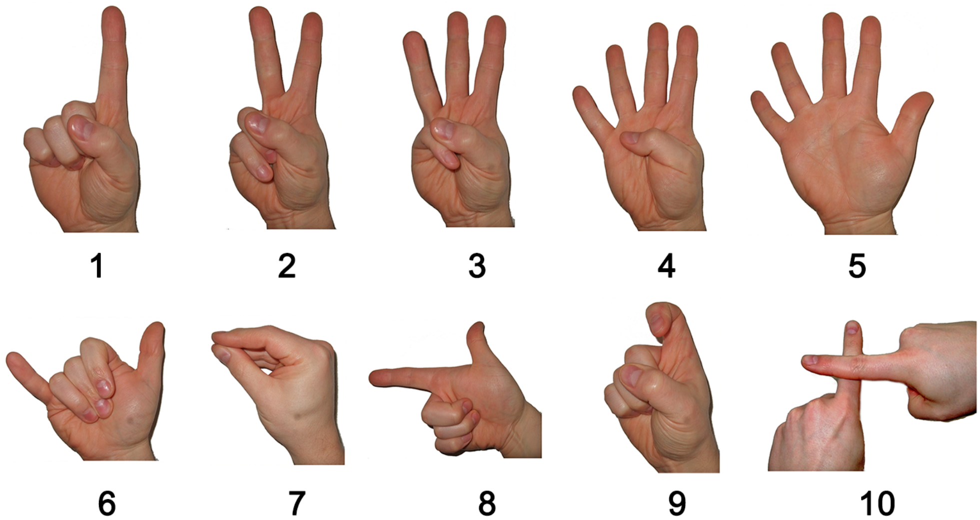

Figure 1. Chinese finger-counting system.

In order to further understand these differences, we sought to replicate and expand the work by Domahs et al. (2010) focusing on individual differences within cultures in addition to cross-national differences. Although almost all North Americans count on two hands, there are some who start counting on their left hand and some who start counting on their right hand. At the same time, while many Chinese count on one hand, there are some who count on two hands. This study investigates whether these differences in finger-counting habits within cultures, as well as those between cultures, are related to performance in a numerical processing task.

We will first discuss how finger-counting habits are important to early acquisition of number concepts. We will then address the current evidence for the continued role of finger-counting habits in the cognitive processes of adults, followed by a summary of the current literature on how structural aspects of finger-counting habits may influence adult cognition. Finally, we will discuss the rationale for conducting this study with Canadian and Chinese university students.

Finger-Counting and Children's Math Performance

Some research has suggested that the spatial awareness of one's fingers, known as finger gnosis, is an important associate of early math performance (Noël, 2005), as well as adult math performance (Penner-Wilger, Waring, & Newton, 2014), and may indicate a common representational format for mathematics and finger gnosis (Anderson & Penner-Wilger, 2013; Penner-Wilger & Anderson, 2013). Finger gnosia for 5-7 year olds has been found to predict math performance a year later, and may be a better predictor than IQ, reading ability, or other performance indicators (Fayol, Barrouillet, & Marinthe, 1998; Marinthe, Fayol, & Barrouillet, 2001; Noël, 2005).

Some evidence suggests an important function of finger-counting in children is to bypass working memory limits by transiently representing number digits (Alibali & DiRusso, 1999; Berteletti & Booth, 2015; Costa et al., 2011; Matsuo et al., 2003; Reeve & Humberstone, 2011). Alibali and DiRusso observed that 4-year-olds were better able to keep track of their counting and made fewer errors coordinating a number of items with the appropriate number word when encouraged to use finger-number gestures during a number task. Costa et al. (2011) also suggest that poorer finger gnosia may be associated with a difficulty in transiently representing symbolic number magnitudes, and that this persists when conrolling for global intelligence and working memory performance.

It is important to observe that finger-counting habits are not only a useful tool in the development of numeracy, but that they may also shape the way that number information is understood and processed in the brain. There is also the suggestion that the sub-base-five structure of children's finger-counting habits may influence how they interpret numerical information, and in particular that some of these influences may continue to shape this interpretation well into adulthood. In the next section, the role of finger-counting habits in adults will be addressed.

Finger-Counting in Adults

The embodied literature has demonstrated a common mental representation format for fingers and numbers in adults. Studies of Gerstmann's syndrome - characterized by left/right confusion, lack of awareness of one's fingers and math difficulties - have hinted at a possible developmental relationship between awareness of one's fingers, lateral aspects of spatial awareness, as well as numeracy (PeBenito, Fisch, & Fisch, 1988; Spellacy & Peter, 1978). For example, Imbo, Vandierendonck, and Fias (2011), have demonstrated that using a device to passively move participant's hands resulted in interference during counting tasks, but not during other types of numerical tasks where memory retrieval is encouraged as a strategy. Andres, Ostry, Nicol, and Paus (2008) observed that participants would widen their grip size more in order to grasp blocks with a larger number digit printed on them. Rusconi, Walsh, and Butterworth (2005) further supported the notion of an overlap in the representation of numbers and hands. Rusconi et al. observed that the application of repetitive transcranial magnetic stimulation (rTMS) to participant's left angular gyrus resulted in temporary Gerstmann-like symptoms. Participants had difficulty making coordinated finger movements as well as difficulty making number magnitude judgments. Rusconi et al. hypothesized that the left angular gyrus is involved in representing spatial aspects of the mental number line, which become linked with finger gnosis through early experiences of finger-counting. The latter point may offer a neurological basis for a functional overlap between mental representations of one's hands and of numbers.

Cognition and Structural Aspects of Finger-Counting Habits

Despite this growing evidence for neurocognitive overlap between finger-counting and number representation, the data do not *necessarily* require a functional role for finger-counting in number manipulation. However, there are some indications for a functional role of individual differences in structure of finger-counting habits among adults. Fischer (2008) observed differences in spatial associations of magnitude between individuals whom start counting on their right versus their left hand, with left starters showing a stronger SNARC association of small quantities with left-hand space and larger quantities with right-hand space. There has also been evidence that both children and adults who typically begin counting on their left hand will make more errors on an addition task than those who typically begin counting on their right hand (Newman & Soylu, 2014). Newman and Soylu actually found these differences were even clearer in adults, with left-starters showing slower task performance as well as lower working memory scores. Finally, Domahs and his colleagues (Domahs et al., 2012) followed up their 2010 study with a group of deaf Korean participants who were fluent in Korean Sign Language (KSL). Finger-counting KSL is different from most systems in the sense that both finger configuration and palm orientation are features of counting-signs (palm-forward vs. palm facing away). Experimenters observed additional processing differences for users of KSL, and not for German or Chinese participants, in response to Arabic digits which coincided with finger number gestures requiring a change in palm orientation, leading researchers to conclude that reaction times were partially a function of the complexity of corresponding finger-counting gestures (Domahs et al., 2012).

In summary, we suggest finger-counting habits are more than just a precursor mathematical ability. While these processes serve a more active conscious role in children learning counting rules and carrying out basic calculations, in adults it appears that the brain continues to activate motor processing associated with finger-counting whenever faced with single digit numbers. Exactly what operations activate these processes, under what circumstances and to what degree, needs to be characterized with greater precision.

The Present Study

The present study attempted simultaneously to replicate the cross-national work by Domahs et al. (2010, 2012) while extending the current model of embodied numerical cognition to include the addition of intra-national individual differences in finger-counting habits for both Canadian and Chinese participants. One of the drawbacks of cross-cultural comparisons is a lack of relevant research on international differences to put any observations in context (Bender & Beller, 2012). Most research investigates differences between right-hand counting starters and left-hand counting starters (Fischer, 2008), deaf sign-language (Iversen et al., 2006), cross-cultural differences in finger-counting (Domahs et al., 2010), or a combination of the latter two (Domahs et al., 2012). It is also difficult to make causal inferences. For instance, the main difference between Chinese participants and other groups observed in the literature thus far has been the absence of an observed effect of finger-counting habits among those Chinese participants. This result could plausibly have been due to the Chinese education system emphasizing the use of an abacus in first grade in order to aid in single digit number calculations and to facilitate faster computation speeds (Zhou & Peverly, 2005). As a result, we ask whether children, raised in a Chinese culture, show sub-base five effects if they were taught to count on both hands. Therefore we took steps to sample right and left-starters among Canadians, as well as Chinese participants who use finger-counting systems other than the one-hand counting system detailed in Domahs et al. (2010, 2012). The two-hand subset of Chinese participants also offer the opportunity to more accurately rule out additional performance differences between Chinese and Canadian participants which are likely not a result of finger-counting habits.

We aimed to extend previous work through: i) a replication of cross-national differences in numerical performance which coincide with structural characteristics of finger-counting habits and which would not be predicted by a strictly abstract representation of numbers; ii) intra-national comparisons of SNARC-like effects and other laterality biases, with left-starters anticipated to demonstrate a greater SNARC-like impact on their performance; and finally, iii) comparisons of individuals taught to count on two hands versus a single hand both cross-nationally and intra-nationally, anticipating that single-digit numbers which would each be typically represented on two hands would pose a greater processing demand-cost on both Canadian and Chinese two-hand counters.

Methods

Participants

There are a total of 69 students from Trent University, 77 students from Memorial University of Newfoundland, and 103 students from Northeast Normal University who participated in this study. All participants included are right–handed. Participant recruiting took place from October of 2012 through March of 2015. The intent was to recruit as many participants as practically possible. Canadian participants were enrolled either at Trent University, in Peterborough, Ontario or Memorial University in St. John's, Newfoundland. Participants in Canada were recruited through their respective SONA and PREP voluntary subject pools in exchange for course credit. Chinese participants were enrolled at Northeast Normal University, a comprehensive university in China with a variety of course offerings comparable to what would be available to students at Canadian universities of similar size. The recruiting procedure at Northeast Normal is somewhat different since there is no research participation pool available. Posters were displayed throughout campus in order to advertise the experiment, and participants were offered a compensation of 10 yuan (about $1.66 Canadian) in return for their participation. All other procedures within Canada and China were kept the same and all ethical guidelines/experimental procedures followed the requirements of the Trent Research Ethics Board senate policy on ethics. All research staff needed to be familiar with these ethical requirements and were required to sign an ethics agreement to that effect.

There were ten Chinese participants in the original sample who were members of ethnic and language minority groups, and who likely attended a different school system than the majority Mandarin, Han Chinese participants. A sub-group of three participants self-identified Wei as their ethnicity and language (possibly referring to the Hakka Chinese dialect), and were all two-hand counters, making up three of the 15 participants in that group. However, there were no notable differences in performance from the main sample, or other Chinese two-hand counters and so they remained included.

Stimuli

The stimuli and procedure used were designed to replicate those used in Domahs et al. (2010). Stimuli consisted of a series of number pairs which were all separated by a numerical distance of two. Trials were organized into two blocks, each with practice trials and experimental trials. Half of participants began Block 1 with the instruction to select the larger number in the pair, and the rest were instructed to choose the smaller number in the pair. At Block 2 instructions reversed from Block 1. Half of trials, interspersed within each block, were presented with number pairs with the smaller digit on the left, while half were presented with the smaller digit on the right. The pairs ranged from 1 vs. 3, to 18 vs. 20. 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. Block 1 and 2 also contained 180 experimental trials each. Practice trials were included in order to replicate the method of Domahs et al. (2010) and because they allowed for an opportunity for participants to learn the rules of the task, and seek clarification if unclear about changes in instructions. Data from practice trials were not included in data analysis. Each number comparison was only visible for two seconds, and so each practice block could take at maximum about 72 seconds. In total, each participant was exposed to 432 randomly presented number pairs.

Apparatus

All number pairs were Arabic Digits in black Arial 60pt font, and presented on a white screen, using E-prime 2.0 on a lab computer (Schneider, Eshman, & Zuccolotto, 2002). The lab in China used a 15" computer screen running at 1366x768 resolution. The Trent and Memorial university labs used a 15" and 18" computer screen respectively, running at the same resolution as the Chinese lab. 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 green sticker. The keys marked off were in the position of the "f" and "j" key of a QWERTY keyboard. Each number pair appeared on screen for a maximum of two seconds unless a response was received (Domahs et al., 2010).

Procedure

All documentation seen by participants was subject to back translation. Back translation is a common cross-cultural research practice whereby documents are translated into a different language, and then translated back into the first language again by a different translator (Brislin, 1970). The process repeats until both translators arrive at a version of the text that is equivalent in both languages. This practice ensures that both groups receive the same information, despite the fact that the documentation is in different languages. Note that participants in both nations responded to Arabic number-digits during the number magnitude task itself.

Each participant in the study answered demographic questions about ethnicity, first language, gender, language spoken in primary school, and nationality. This was followed by 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. Experimenters recorded the hand used for each number gesture on a sheet picturing a variety of hands using different counting gestures. Right and left counting starters were classified by which hand was used to represent one through five. If there was any disagreement across numbers, participants were asked to clarify their dominant strategy. One and two-hand counting styles were classified by similar means. It is worth noting that three of the 15 Chinese two-hand counters reported one-hand gestures for numbers from 1-10, but were then clarified to be predominantly two-hand counters. Demographics questions were counter-balanced so that for half of participants, this part of the procedure took place prior to the number comparison portion of the task, while the other half were not asked about demographics or finger-counting habits until the end of the study. These two different conditions are referred to respectively as the before-task and after-task conditions. 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 we used the before-task and after-task conditions to rule out the possibility that procedural aspects of this kind of research influence the strategies used by participants while making number magnitude judgments.

Data Analysis

All participants are right-handed. Given the cross-cultural focus of this study, only English-speaking Canadian participants who counted on both hands and Mandarin speaking Chinese participants, who reported a coherent finger-counting strategy, were included in data analysis. This reduced the Canadian sample by 11 participants (all were recent international students), and the Chinese sample by 9 participants (all students reporting an ad hoc mixture of finger-counting systems which could not be readily classified). Additionally, participants with a mean error-rate more than 3 standard deviations above average were excluded. Two Canadian participants and four Chinese participants were excluded for making excessive errors. These exclusions resulted in a final sample of 91 Chinese participants and 133 Canadian participants. Only correct answers for participants were considered in analyses of reaction time data. All reaction time data is log-transformed, and scores 2.5 standard deviations or further from a participant's individual mean were excluded in the same manner as Domahs et al., 2012. The latter exclusions resulted in a loss of 6.22% of all remaining reaction-time data.

Prior to conducting statistical analyses, it was observed that there were no right-handed Chinese participants who started counting on their left hand. This stands in contrast to the Canadian sample, where 21, or approximately 15%, of right-handed participants began counting on their left hand. There were, however, 15 Chinese participants,

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or about 16%, who reported primarily counting on both hands, as opposed to one hand. These two minority strategies were treated as distinct finger-counting styles.

Log-residualized reaction-time scores were largely replicated from Domahs et al. (2010) and performed in much the same way. Participant reaction-time data were averaged from 360 observations into 18 comparison scores per participant, with stimuli numbered by the lowest number in each comparison (i.e., three for both the pair 3 vs. 5 and 5 vs. 3). A logarithm was taken of each of these scores for each participant. People tend to take longer time when making judgments about larger numbers (e.g., 20) than with smaller numbers (e.g., 1) (Göbel et al., 2011). Past research has supported a logarithmic mental number line as the strongest model for how magnitude influences number processing time (Dehaene, 2003). 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. A 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 any given number pair. These fit lines were subtracted from the logarithm of the averaged reaction time scores for each participant, and the resulting difference scores standardized with a mean of 0 and a standard deviation of 1. This operation was performed in order to properly replicate the analysis used by Domahs et al. (2010), as well as Domahs et al. (2012), and in order to remove any effects of number magnitude. These standardized residual scores should also allow Chinese and Canadian participants to be equitably and transparently compared to each other and to previous research despite any individual or group differences in reaction time.

In an attempt to partially validate the residualized reaction-time transformation from Domahs et al. (2010), we conducted a parallel set of analyses using error-proportions. Errors are expected to produce similar results to residualised reaction-time scores, although the low average error-rate in this task is expected to render these analyses significantly less powerful. Error proportions are also anticipated to underestimate differences between groups as, given the binary-choice nature of this research design, a participant would be expected to get a correct answer around 50% of the time even when responses are driven by an incorrect impulse. Additionally, given the low baseline error-rate in this task, and over-representation of participants whom made no errors in certain comparisons, there was a significant positive skew in the data. Although other studies using these types of data have used a simple arcsine transformation for error proportions (Domahs et al., 2010; Riello & Rusconi, 2011), these transformations actually increase positive skew in error proportions that are close to floor, rendering subsequent analyses excessively liberal. Therefore, all mean error-rate data was normalized using an arcsine square root transformation $y = \mathrm{asin}(\mathrm{sqrt}(x))$ prior to data analysis, which better reduced skew and rendered subsequent analyses more conservative. All Cohen's *d* effect sizes and descriptive statistics are reported using untransformed error scores in order to aid in interpretability, except where residualized RT scores are used.

Finally, a series of preliminary analyses were conducted to investigate whether asking participants about their finger-counting habits either before or after the study task (i.e. the before-task condition vs. the after-task condition) made a difference to reaction times or error rates. For Canadian participants, a chi-square analysis first tested whether the proportion of participants who reported being a left-starter versus a right-starter differed between the before-task and after-task conditions. There was a marginal but non-significant difference between the before- and after-task procedures, $\chi^2(1, N = 136) = 3.009$, $p = .083$, $\phi = .149$, with left-starters being 2.30 times more common in the after-task condition (10.29% vs. 20.89%). For Chinese participants, there were no right-handed participants that reported counting first on their left hand in either condition or either counting group. To test for differences in errors and RT, a pair of Between-Within 18 x 2 x 4 ANOVA were conducted, with the 18 different number comparisons as a within-subjects factor, as well as before/after-task and counting group as between-subjects variables. Standardized residual RT scores and transformed error scores for each number pair comparison were the dependent variables. Despite the marginal frequency differences in those reporting themselves to be left- or right-starts among Canadians, there was no meaningful multivariate or univariate main effect of, or interaction with, before/after-task procedure and either participants' residualized RT or error scores. For this reason, the before-task/after-task condition was not included in any further analyses.

Results

Concordance of Errors and Reaction-Times

Given that we wanted to use both errors and reaction time to indicate differences in numerical processing, our first analysis explored how these two measures were related to each other. We started by examining participants' mean reaction time against participants' mean error rate using a series of correlation analyses. Similar to Domahs et al. (2012), there was no reliable speed-accuracy trade off among any of the respective counting groups, with all *ps* > .05 and *rs* < .150. We then examined the pattern of error rates across number comparisons and counting group and compared it to the pattern of residualized RT (see Figures 2 and 4). Both of these measures demonstrate a similar pattern and have structural features that are expected for this study. For example, both error proportions and residual RT demonstrate the "ten-break" effect – a dramatic drop for comparisons where one number is a one-digit number the other is a two-digit number (e.g., 8 vs. 10 and 9 vs. 11). Across the whole range of number comparisons, within each of the four finger-counting counting groups, the average error rate per comparison is strongly correlated with each counting group's average standardized residual RT scores per comparison pair, with Pearson's correlations all between $r(16) = .624$ and $r(16) = .780$. In other words, although there is little relation between error rate and reaction time at the individual level, there is a strong positive association between error rate and reaction time across the different number comparisons. Taken together, these analyses indicate that standardized residual RT scores and error scores are likely measuring similar constructs.

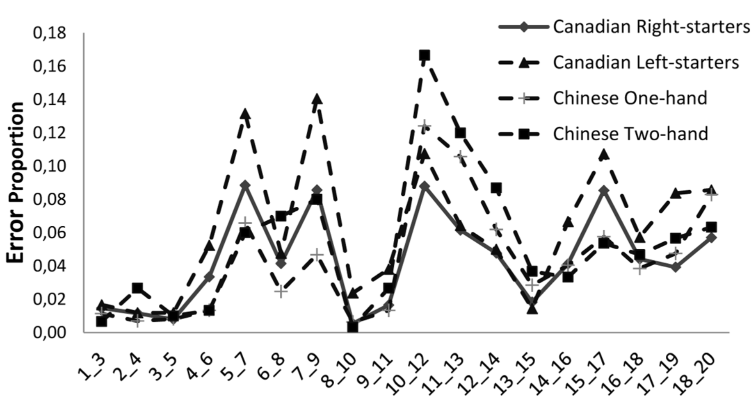

Figure 2. Error proportions across different comparisons.

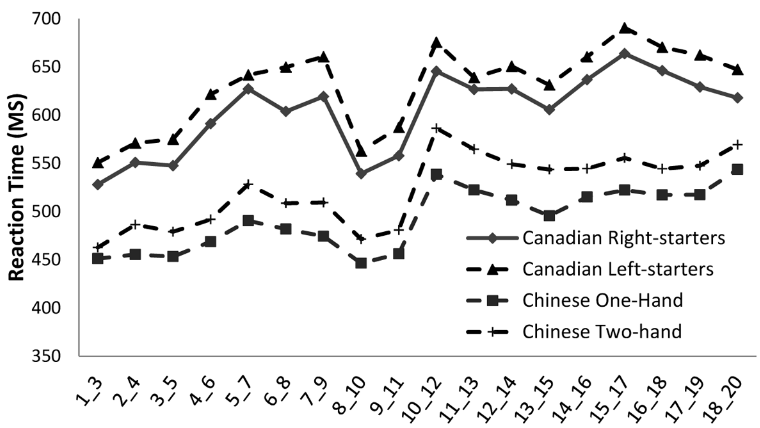

Figure 3. Raw reaction-time scores across comparisons.

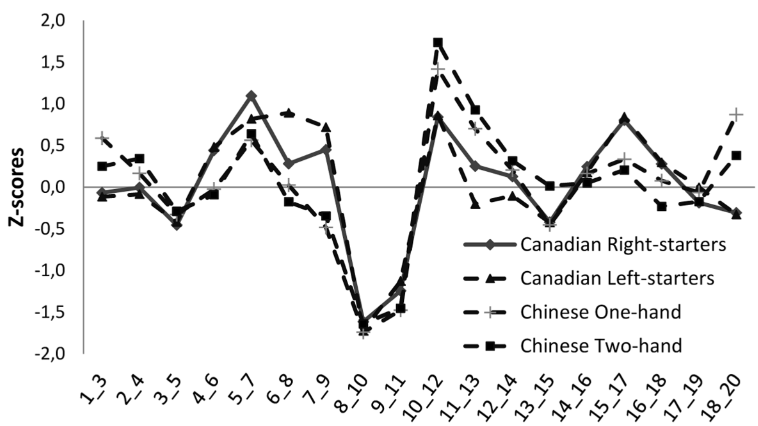

Figure 4. Standardized residual reaction-time scores across comparisons.

General Differences Between Counting Groups

A series of one way ANOVAs were used to examine average group differences in mistakes, non-residualized reaction time, and log-fit slope. A one way ANOVA did not find any evidence of a reliable difference in the slope of the log fit line for either country or any of the counting groups, $F(3, 223) = .65$, $p = .460$, $\eta^2_p = .012$, indicating that the log-fit function transformation was similar between groups (see Table 1). There were small but significant group differences in mean error rates, $F(3, 223) = .2.675$, $p = .047$, $\eta^2_p = .035$. Tukey's post-hoc tests found a significant difference in error rate between Canadian left-starters and Chinese one-hand counters, $d = .370$, $p = .047$. There was also a large and reliable difference in average reaction time that is modulated by counting group, $F(3, 223) = 38.646$, $p < .0005$, $\eta^2_p = .313$. See Table 1 for descriptive statistics and Figure 3 for differences across the number comparisons. Tukey's post-hoc tests found that Chinese one-hand counters were faster than either Canadian right-starters, $d = 1.363$, $p < .0005$, or Canadian left-starters, $d = 1.604$, $p < .0005$, but not Chinese two-hand counters. Chinese two-hand counters were also faster than Canadian right starters, $d = .841$, $p < .0005$, as well as Canadian left-starters, $d = 1.177$, $p < .0005$. Canadian right-starters and Canadian left-starters did not significantly differ from each other, indicating that this is a cross-national difference, rather than a difference necessarily modulated by counting style.

Further ANOVA testing for differences in error rates found that, although the above analyses demonstrate overall differences between the groups, these differences are not evenly distributed across the different number comparisons (see Figures 2 and 3). A pair of 18 x 4 between-within ANOVAs, with the 18 different number comparisons as the within factor and counting group as the between factor. Mauchly's test indicated violations of sphericity for both residual RT, $\chi^2(152) = 1305.699$, $p < .001$, as well as error scores, $\chi^2(152) = 471.934$, $p < .001$. Degrees of freedom have been corrected for both residual RT, $\varepsilon = .792$, and error scores, $\varepsilon = .818$. The ANOVA found a significant main effect of number comparison on residual RT, $F(13.47, 3002.95) = 93.657$, $p < .001$, $\eta^2_p = .296$, as well as on error proportions, $F(13.90, 3100.54) = 46.131$, $p < .001$, $\eta^2_p = .171$, with significant interactions between number comparison and counting group for both RT, $F(40.40, 3002.95) = 9.151$, $p < .001$, $\eta^2_p = .110$, and error proportions, $F(41.7, 3115.30) = 3.860$, $p < .001$, $\eta^2_p = .056$. Given that the effect of counting group is different for different number comparisons, the following analyses will test for specific effects expected by our hypotheses. First is an examination of SNARC-like effects in our sample. Then, specific number comparisons will be considered. In all subsequent analyses, residualized RT scores were used to control for both magnitude effects and overall group differences.

Table 1

Descriptive Statistics for the Four Finger-Counting Groups

Country	**Canada**		**China**	
Counting group	**Right starter (*n* = 112)**	**Left Starter (*n* = 21)**	**One hand (*n* = 79)**	**Two hand (*n* = 16)**
Age (*SD*)	20.96 (3.81)	19.29 (2.22)	21.32 (2.42)	20.20 (1.74)
RT (*SD*)	599.24 (94.89)	628.61 (104.40)	490.09 (51.70)	521.52 (69.17)
Error % (*SD*)	4.38 (2.56)	6.18 (3.78)	4.36 (3.08)	5.33 (3.11)
Log-fit equation[a]	=.064*ln(x) +6.24	=.066*ln(x) +6.28	=.059*ln(x) +6.06	=.066*ln(x) +6.10

Note. Reaction times are all measured in milliseconds.

[a]Log-fit lines calculate the log-transformed estimated RT using the average of any given comparison pair as x (e.g., 1 vs. 3 would be 2).

SNARC-Like Effects

SNARC-like congruity effects in participants' error proportions and reaction time scores were assessed using a pair of 2 x 2 x 4 mixed ANOVAs. Instruction condition (choose smaller or choose larger) as well as right vs. left response side, were the within subjects factors, with the four finger-counting groups as a between-subjects factor. The ANOVA indicated that there was a main effect of instruction condition for both reaction time scores, $F(1, 223) = 97.055$, $p < .0005$, $\eta^2_p = .76$, as well as for errors, $F(1, 223) = 4.109$, $p = .044$, $\eta^2_p = .022$, with choosing the smaller number of a pair associated with slower reaction times and more errors. There was a marginal interaction of counting group and instruction condition for reaction times, $F(3, 223) = 2.681$, $p = .048$, $\eta^2_p = .056$, with Chinese participants showing a smaller RT gap in reaction time between instruction conditions, however the same was not true for error proportions, $F(3, 223) = .667$, $p = .573$. There was no main effect of left/right response side for RT, $F(1, 223) = 2.168$, $p = .128$, or for errors, $F(1, 223) = .616$, $p = .434$. There was also no interaction of group and left/right response side for RT, $F(3, 223) = .477$, $p = .699$, or for errors, $F(3, 223) = .677$, $p = .567$. However, there was a reliable SNARC-like interaction of instruction condition and response side for both reaction times, $F(1, 223) = 14.886$, $p < .0005$, $\eta^2_p = .058$, as well as for errors, $F(1, 223) = 7.663$, $p = .006$, $\eta^2_p = .039$, with left hand responses being faster and more accurate for choosing a smaller number and right hand responses being faster and more accurate for choosing a larger of a pair of numbers. The lack of a three-way interaction with counting group either with reaction times, $F(3, 223) = .049$, $p = .986$, or with error proportions, $F(1, 223) = 1.972$, $p = .119$, however, suggests that this SNARC effect was similar in magnitude across the different counting groups.

Ten-Break Comparisons

Given the nature of both our base 10 Arabic numerals and our finger-counting systems, we would expect a processing difference when comparing a number that is less than 10 with a number that is more than 10. A series of one-sample t-tests indicated that Canadian right-starters, $m = -1.429$, $p < .0005$, Canadian left-starters, $m = 1.425$, $p < .0005$, Chinese two-hand counters, $m = -1.530$, $p < .0005$, and Chinese one-hand counters, $m = -1.609$, $p < .0005$, all responded more quickly when comparing a single digit number and a two digit number. This effect was not reliably modulated by counting group. While these results may suggest that Chinese participants are more facilitated by these comparisons than Canadians, the absolute effect sizes are small and partially a function of how scores were residualized, with Chinese participants being less variable in their reaction-times. In terms of actual reaction-time scores, the facilitation for Chinese participants was negligibly smaller, at around 39 ms versus 42ms for Canadians when compared to each group's average reaction-time.

Two-Hand Comparisons

A pair of ANOVAs were conducted with the two performance variables (residual RT and error proportion) to test for differences between the four counting groups in participants' average scores from the comparisons where both single digit numbers are > 5 (e.g., 6 vs. 8 and 7 vs. 9). Follow-ups consisted of planned contrasts comparing Chinese one-hand counters with all other counting groups across each performance variable. This would be the most likely place to expect a difference in representational demand-related effects due to the activation of finger-counting habits since the traditional Chinese counting system uses entirely symbolic gestures for numbers in these number pairs. It was expected that Chinese one-hand counters would have fewer errors and a lower residual RT score than each of the other three groups.

The ANOVAs found that counting group modulated average residual RT, $F(3, 223) = 25.537$, $p < .0005$, $\eta^2_p = .260$, as well as average errors, $F(3, 223) = 8.336$, $p < .0005$, $\eta^2_p = .097$, when comparing single-digit numbers > 5 (see Table 2 for descriptive statistics). Consistent with expectations, the planned contrasts found Chinese one-hand counters had a significantly lower proportion of errors on these two comparisons than Canadian right-starters, $d = .545$, $p < .0005$, Canadian left-starters, $d = 1.164$, $p < .0005$, or Chinese two-hand counters, $d = .734$, $p = .013$. Contrast scores also revealed that Chinese one-hand counters had significantly smaller residual RT scores than Canadian right-starters, $d = .975$, $p < .0005$, as well as Canadian left-starters, $d = 1.782$, $p < .0005$, but not reliably less than Chinese two-hand counters, $p = .978$. Additionally, contrary to expectations, Tukey's post-hoc tests also indicated that Canadian left-starters had a reliably larger residual RT score than Canadian right-starters on these comparisons, $d = 0.702$, $p = .012$.

Table 2

Descriptive Statistics for Two-Hand Comparisons

	RT residuals	Errors (%)
Group	**Mean (*SD*)**	**Mean (*SD*)**
Chinese one-hand	-.23 (.55)	3.4 (4.4)
Chinese two-hand	-.28 (.61)	7.5 (8.7)
Canadian right-starter	.36 (.64)	6.4 (5.5)
Canadian left-starter	.81 (.52)	9.1 (6.7)

Note. The three Chinese two-hand counters, whom were classified as predominantly two-hand counters, rather than as exclusive two-hand counters, incurred 8.33% errors here, roughly average for that group.

Discussion

The study examined how numerical processing would differ between those with different finger-counting styles. As expected, there were significant cross-cultural differences in numerical performance, which were associated with numbers typically counted on two hands for Canadians, or symbolically on one hand for Chinese participants. In addition to this observation, we found that intra-national individual differences in finger-counting habits were associated with differences in numerical performance when comparing particular numbers that differ the most in how each finger-counting system would represent them. These performance differences do not appear to be a function of SNARC, nor of left/right response assignment, but rather appear to be a function of the cognitive demand posed by comparing particular number pairs. There are many implications for these findings on our theoretical understanding of how finger-counting may be tied to numerical processing.

Finger-Counting Simulation

Past research has suggested that embodied numeracy may stem from repeated pairings of particular numbers with particular fingers (Tschentscher, Hauk, Fischer, & Pulvermüller, 2012). Our results do not support a notion of direct finger-number associations as a basis for embodied numeracy. A direct finger-number association model should predict that visually comparing numbers typically counted on different hands would facilitate performance (e.g., 4 vs. 6). This is because although these numbers are still only separated by a numerical difference of two, their embodied aspects would be much further apart, as they would be represented in association with different hands. Instead, participants showed an increased cognitive load when making comparisons of numbers represented on two hands. These results are more consistent with a notion of motor simulation as the proximal cause of embodied numerosity (Gabbard, 2013). Rather than associating particular numbers with particular fingers, participants are instead subtly simulating finger-counting as a part of task performance. A mental simulation account would be consistent with past research by Domahs et al. (2012) which indicated that the complexity of finger number gestures may modulate the degree to which counting habits appear to influence cognition. This would also be consistent with a growing literature which suggests that finger-counting direction, as well as hand orientation may impact performance when matching number parity or magnitude with left/right space (Conson, Mazzarella, & Trojano, 2009; Iversen et al., 2006; Michaux, Masson, Pesenti, & Andres, 2013; Riello & Rusconi, 2011).

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Finger-Counting and Hebbian Learning

These observations may be analogous to what was described by Lev Vygotsky as private speech (Vygotsky, 1994). During early development, children tend to voice their own private thoughts out loud and gradually internalize these thoughts into automatic inner speech. It seems plausible that we are observing participants accessing an internalized finger-counting schema when recalling and comparing single digit numbers. Tschentscher et al. (2012) also mentioned that finger-counting habits may become tied into number processing via Hebbian learning mechanisms. In this context, Hebbian learning would refer to people repeatedly practicing one activity simultaneously with another to the point where the two become linked. Such mechanisms have been proposed to explain the developmental basis of mirror neurons, where people show activity in the same brain regions when they act purposefully or observe another person act purposefully (Del Giudice, Manera, & Keysers, 2009). Early in development, young children observe themselves carrying out a variety of actions, particularly with their hands, and so viewing these actions becomes linked with experiencing performing them (Del Giudice, Manera, & Keysers, 2009). As children practice on their fingers while they learn the rules of counting, it may be that the activity of finger-counting becomes tied in with their awareness of numbers and the mental number line, which results in related processes being activated when making judgments about numbers. This may not necessarily invoke the mirror neuron system itself, but does suggest a precedent for the idea that developmental associations may be able to support embodied simulations. A similar account has been described by Penner-Wilger and Anderson (2013) as an explanation for why finger gnosis would be functionally related to math performance.

Individual Differences for Two-Hand Comparisons

Despite greater structural congruence with a left-right mental number line in Canadian left-starters, when compared with Canadian right-starters, there were no absolute differences in SNARC observed in this study across groups. This may be related to the use of a binary comparison task, or even differences in how we classified left-starters and right starters. However, despite our predictions, SNARC effects did not help characterize individual differences on this magnitude comparison task. Also, a simple finger-number, or hand-number, association model would have predicted an effect of the fingers used in making a response, while a motor simulation model would link participants' reaction-time in linear fashion to the complexity of the simulated motor action, in line with Fitt's law (Solodkin, Hlustik, Chen, & Small, 2004). Comparisons of 4 vs. 6 and 5 vs. 7 would be somewhat different as this involves crossing a sub-base of five either by counting to another hand, or by switching from non-symbolic to symbolic counting gestures. Such a transition may explain increased response times and errors for both Canadian and Chinese participants, when comparing 5 vs. 7. Neither a strict finger-number association model, nor a strict motor simulation model, accounts for all the differences between these groups, although our results were more consistent with the simulation account. However, the difference between Canadian left-starters and right-starters when comparing 6 vs. 8 and 7 vs. 9 requires further examination.

It may be that right-handed participants, whom self-report being left-starters, may have more accessible and durable finger-counting habits than those whom default to begin counting on their dominant hand. Left-starters' counting direction is more consistent with a left-right mental number line (as well as SNARC-like associations) than with their own hand dominance. Right starters may begin counting on their right hands because their own right-dominance was more salient than maintaining congruence with the left-right mental number line in their finger-counting. This may also explain the lack of a residual RT five-break effect in Chinese two-hand counters, whom have likely grown up in a context where they learned about the one-hand counting system in addition to the two-hand system. Two-hand finger-counting habits would likely have been the least salient for the Chinese group of participants, as would be suggested by several participants in this group using a closed fist to represent the number five, or using a one hand gesture to sign six or seven, but resuming two hand counting for eight through ten.

Findings from Newman and Soylu (2014), do suggest at least one alternative explanation for our findings. Newman and Soylu observed poorer arithmetic computation speed and increased rates of errors among left-starters as compared to right starters. This was true of both adults and children. Newman and Soylu proposed that right-handed left-starters may have a more bilateral mental representation of small numbers, which increases processing times. Consistent with the former research, Canadian left-starters in this investigation were somewhat slower than right-starters, and made significantly more errors than right-starters; similarly, Chinese two-hand counters were both somewhat slower and made somewhat more errors than one-hand counters (see Table 1). Rather than contradicting finger-counting saliency, this may instead provide a mechanism for why finger-counting habits are more salient for some individuals versus others. However, this account leaves the question open as to the direction of the relationship. It remains to be seen whether left-starters finger-counting habits result in a more bilateral mental representation of small numbers, or whether children with a more bilateral representation would be more inclined to maintain a left-right finger-counting habit.

It is also noteworthy that while these individual differences among Canadians are pronounced in the pattern of participants' reaction-time data, that they are less evident in proportion of errors. Canadian right-starters compared 7 vs. 9 more easily than 5 vs. 7 when the measure was residualized reaction-time scores, but no such performance difference was evident in error proportions. Given how closely errors and residualized reaction-time scores corresponded overall, it is not clear why reaction times would differ so greatly between these comparisons, but not errors. It may be that while the task demands that lead to an error are extremely similar to those which cause a slowed reaction-time, they are not identical.

All three groups of two-hand counters were still performing similar numbers of errors on comparisons where both hands would be used to count each number in a pair (see Table 2). Given the simplicity of the task that participants were asked to perform, as well as a reliable SNARC-like association of magnitude and left-right space for participants' error frequencies, it seems likely that errors were influenced by momentary left/right confusion. This is supported by anecdotal accounts of many participants whom self-reported that the primary source of their errors was not confusion as to the target number, but rather accidentally moving the wrong hand. The former is potentially explanatory of our main observation of sub-base 5 errors, given that all three groups that counted on both hands experienced an increased rate of incorrect responding on these comparisons, which results from selecting a number on the right-hand side when the number on the left-hand side was the target (or vice versa). The Chinese one-hand counters, on the other hand, experienced an almost zero rate of errors on these comparisons. Similar to Chinese two-hand counters, all of whom were right-starters, Canadian right-starters also had much lower residualized RT scores than Canadian left-starters, but did not have reliably lower error-rates for these comparisons. Therefore, it may be that while Chinese two-hand counters, and Canadian right-starters to a lesser degree, were not slowing down as a result of activating finger-counting schema, that this activation still resulted in conflicting and competing signals from their hands, leading to more mistakes.

Limitations and Future Directions

At the time of this study, there were relatively few datasets addressing the impacts of cross-cultural differences in finger-counting habits (Bender & Beller, 2012; Domahs et al., 2010, 2012), or even individual differences in finger-counting habits (Fischer, 2008; Newman & Soylu, 2014; Nuerk, Iversen, & Willmes, 2004; Tschentscher et al., 2012). As such, these results should be interpreted conservatively and be subjected to further replication. The pattern of results seen in Chinese one-hand counters may be a result of finger-counting strategies simply not being implied at all rather than acting differently on participant performance. Despite this limitation, our findings are very much in line with the findings of Domahs et al., and replicate most of their main observations.

Another limitation is that preferred finger-counting habits cannot feasibly be randomly assigned. This makes establishing a causal relationship more difficult. There may be other unknown third variables which impact the results. All participants were right-handed, and it will therefore be informative to examine right vs. left-starter differences in a left-handed group of participants since a left-handed child may become a left-starter for different reasons than a right-handed child. Further complicating the assignment of finger-counting systems is the report from Dr. Kang and Dr. Liu that two-hand style finger-counting is generally used by children before transitioning to the one-hand finger-counting system. However, this limitation could explain the absence of greater differences between Chinese finger-counting groups.

There should be follow-up work to investigate the stability of participants' self- reported finger-counting habits. Finger-number associations in particular do not consistently correspond to spontaneous counting direction (Wasner, Moeller, Fischer, & Nuerk, 2014). The frequency of left and right-starters appear vary between different methods of questioning people about finger counting (Wasner, Moeller, Fischer, & Nuerk, 2014). It is not yet clear which of these motor codes would be the best predictor of individual performance differences. Given that this is a binary choice task; participants would be expected to get a correct response about 50% of the time, even when a response is driven by an incorrect impulse. Therefore our ability to discriminate individual differences in Chinese participants was less robust than in Canadian participants, whom were differentiated more so by response times. There should be additional research performed with Chinese participants, while employing a more difficult task. The so-called *distance effect* predicts that as numbers are separate by large magnitudes, they become easier to discriminate, and vice versa with numbers that are relatively close in size being more difficult to discriminate (Dehaene, Dupoux, & Mehler, 1990). Employing a task that either varied the numerical distance between number pairs, or used number pairs that were separated by a magnitude of 1 rather than 2, (e.g., 1 vs. 2, 1 vs. 3, etc.) may be more difficult and therefore more likely to incur response time differences among Chinese participants.

Conclusions and Implications

This study evaluated the role that culturally acquired finger-counting habits may play in the way in which adults represent and process number magnitude information. Participants included Canadians whom typically begin counting on their right hand (right-starters), Canadians whom typically begin counting on their left hand (left-starters), Chinese participants whom use a partially symbolic system where all single-digit numbers are counted on a single hand (one-hand counters), and Chinese right-starters (two-hand counters). The resulting findings provide additional support for the notion of embodied numeracy as a function of motor simulation, but also extend this to include individual differences among participants in the same country. The findings here which compare Canadians and Chinese participants, mirror those of Domahs et al. (2010), with break-five effects better accounted for by a finger-counting simulation model of number processing rather than a direct finger-number association model. Despite these similarities with other work, there are also some notable and theoretically important differences within each nationality. These differences may be explained by saliency of finger-counting habits and/or by more unilateral vs. more bilateral representations of numbers, but show a cross-cultural convergence of the effects of finger-counting habits where both Chinese and Canadian two-hand counters committed more errors than Chinese one-hand counters when comparing numbers that could be counted on two hands. An important theoretical observation is that the best discriminating set comparisons for differentiating counting groups, whether through errors or residualized RT scores, was 6 vs. 8 and 7 vs. 9 in every case. These comparisons are where structural differences in finger-counting habit systems are the greatest and which were predicted a priori via a motor simulation model of embodied numeracy to be the most important for differentiating group performance.

We conclude that finger-counting habits are not merely important for learning number rules in childhood, but remain as an important representational format for numbers in adulthood. The discovery that individual differences in finger-counting habits are associated in specific ways with numerical performance suggests that it is unlikely that the findings of previous work were a result of spurious associations, cultural differences, or simply task demands. While embodied representational formats seem to be related to overall task performance, these detriments seem to be more specifically localized to certain parts of the mental number line that correspond to the sub-base-5 system implicit in finger-counting representations. The relation between finger-counting and numerical cognition, however, is still not fully specified, so further research is warranted.

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Competing Interests

The authors have declared that no competing interests exist.

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