EMBODIED NUMERACY: EXPLICATING THE ONGOING RELATIONSHIP BETWEEN FINGER COUNTING AND NUMERACY IN ADULTS

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Abstract

Finger counting is a very clear example of embodied cognition, as finger-number gestures form an external symbolic representation of numbers, while simultaneously existing as a culturally acquired motor behaviour, and even a type of communicative tool. Finger counting habits typically assist in the acquisition of early number concepts and in the development of arithmetic competence. Recent research now also shows that finger-related processes are longitudinally linked to numerical performance and continue to share overlap in their neural underpinnings well into adulthood. This work suggests that the mental representation of number magnitude is not entirely abstract, and is at least partly rooted in embodied experiences and situational demands, including those posed by culturally-acquired finger counting habits.

This dissertation is an investigation of individual differences in the cross-cultural, intra-cultural, and contextual effects of finger counting on mathematical cognition. These investigations each converge on the idea that finger counting habits do influence cognitive processes related to numeracy. The starting hand, or hand typically used to start counting, appears to be a particularly important correlate of numerical performance among Canadians. However, the effects of finger counting processes on adults' cognition do appear to vary as a function of participants' typical culturally-acquired finger counting habits, as well as through experimental context.

The ultimate goal of this program of research is to examine how individual differences in finger counting habits and early cultural experience may be used in order to construct more detailed models of embodied numeracy, which will improve our understanding of the scope of embodied numeracy.

Keywords: magnitude comparison, Chinese, Canadian, finger counting, representational effects, decade break, five break, embodied cognition, cross-culture, within-culture, methodology, SNARC

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Co-authorship Statement

I, Kyle Morrissey, am the principle author for all six chapters of this dissertation. This dissertation was completed under the supervision of Dr. Darcy Hallett of the Research Centre for the Development of Mathematical Cognition, Department of Psychology, Memorial University of Newfoundland. I am responsible for theoretical conception, research questions, methodology, data analysis, and interpretation of all manuscripts contained in this dissertation. My supervisor, Dr. Hallett, is listed as coauthor for all manuscript chapters; inclusive of Chapters Two through Five. I also collaborated with a number of colleagues from the education department at Northeast Normal University in China, as well as with several undergraduate honours students from the psychology department at Memorial University. Dr. Kang is listed as third author on Chapter Three and fourth author on Chapter Four, alongside Ming Han who is listed as fifth author on Chapter Four. Dr. Kang has been a collaborator of mine for about 6 years, and has been responsible for overseeing any institutional approval, research staff, and data collection necessary for research that took place at Northeast Normal University, China. Dr. Kang also supervised any back-translation necessary for consent forms or other documentation used in China. Back-translation is a procedure by which a document is translated repeatedly between two languages until both translators fully agree that the content is equivalent. Ming Han supervised data collection and adherence to experimental procedures in China for Chapter Four. Finally, Rutanya Wynes was an honours student working on Study Three, detailed in Chapter Four. Rutanya assisted with approximately half of the data collection that occurred in Memorial University for Chapter Four, as well as assisting with the testing of research equipment.

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Chapter One: Introduction to Embodied Numerical Cognition

Embodied and situated cognition can mean many things. Situated cognition usually frames thought as derived from action on, and interaction with, the world surrounding the thinker. Embodied cognition, or the way in which cognition is situated specifically in bodily action and experiences, is often used synchronously with situated cognition, of which the former is an aspect. In order to be embodied, cognition must also be situated, but cognition can be situated without necessarily being embodied. For example, people do not simply think about objects' objective qualities but also about how one would interact with such an object. By this logic, chairs are not only objects with a particular shape and number of legs, but also as something that is sat upon (Anderson, 2003). Phrases like 'grasping an idea' also communicate an abstract idea through bodily metaphor. In 2004, Margaret Wilson attempted to disentangle the various claims of embodied cognition into a few specific assertions. These include that: 1) cognition is situated, and therefore requires an interaction with the world through perceiving and acting upon it; 2) cognition is time-pressured and so thinkers must be able to construct models of their environment that generally succeed despite the constraints of the proximate environment; 3) people engage in off-loading cognitive work to the environment, such as through writing, computers, the internet, objects, fingers, etc.; 4) the environment is part of cognition, and may be more important at times for determining the shape of cognitions than the mind that generates those cognitions; 5) cognition is for action and the mechanisms of cognition must be understood through how they generate situation-appropriate behaviour; and, 6) off-line cognition is body-based, such that even when day dreaming, our cognitions are shaped and limited by information processing mechanisms that evolved to guide behaviour.

The current dissertation will focus mainly on how numerical cognition is situated, and how it is body-based. However the other concepts outlined above do often overlap with, or inform, these ideas. For instance, when counting two sets of objects, you may use your fingers to retain the first count, while completing the second count verbally. This is a form of off-loading cognition to the environment, except it is also an example of how cognition is body-based. That is to say, in this context, cognition has become embodied such that a part of the body is also a part of the environment. This information can then be decoded, retrieved, and reintegrated into general cognition, either through visual or somatosensory modalities. The context and choice of modality can also have consequences on the nature of thought and how people understand the world around them.

Finger counting is a very clear example of embodied cognition, as finger-number gestures form an external symbolic representation of numbers, while simultaneously existing as a culturally acquired motor behaviour, and even a type of communicative tool (Butterworth, 1999). Finger counting habits typically assist in the acquisition of early number concepts, in the development of arithmetic competence, and continue to share overlap in their neural underpinnings into adulthood. The role of finger counting in cognition and the acquisition and use of number concepts has grown in research interest over the past decade, suggesting that number magnitude is at least partly rooted in embodied experiences (Fischer, Kaufmann, & Domahs, 2012; Moeller, Fischer, Link, Wasner, Huber, Cress, & Nuerk, 2012; Morrissey, Liu, Kang, Hallett, & Wang, 2016).

This dissertation is an investigation of the effect of finger counting on mathematical cognition. While subsequent chapters will describe these studies, the purpose of this chapter is to preface this research by examining the finger counting literature across cultures and across development. The role of likely evolutionary constraints on numerical cognition will also be discussed. The ultimate goal of this research program is to examine how individual differences in finger counting habits and early cultural experience may be used in order to construct more detailed models of embodied numeracy, which will improve our understanding of the scope of embodied numeracy.

Finger Gnosis and the Development of Numeracy

While the majority of this chapter will address how cross-cultural and individual differences in learned finger counting habits impact numerical cognitions, it is important to address the contribution of finger gnosis to embodied numeracy, as this may play a role in why finger counting should matter for numbers in the first place. Finger gnosia is defined as one's ability to discriminate their fingers efficiently through the sense of touch (Noel, 2005). A great deal of embodied numeracy literature has either followed directly or indirectly from investigations of the clustering of symptoms relating to Gerstmann's syndrome, which is characterized by the co-occurrence of left/right confusion, difficulty discriminating one's fingers (finger agnosia), and the development of learning disabilities in the area of mathematics (Rusconi, Walsh and Butterworth, 2005). The co-occurrence of these symptoms led researchers to investigate whether shared mental representations between finger gnosis and mathematics may underlie these symptoms.

Noel (2005) is an often cited example of how finger gnosis is tested. Experimenters had first graders place their hands palm-down and out of view. Researchers would then lightly touch a finger and ask the child to identify which finger had been touched. Each finger was tested twice, adding up to 10 randomly organized trials. This was followed by a set of trials where two fingers were touched successively, requiring the child to correctly identify which two fingers were touched, and in what order. The composite finger gnosis score was based on the success with which children identified the finger(s) that had been touched. Finger gnosis predicted between 13% and 23% of the variability in numerical accuracy scores, but was not associated with other competencies like reading in that investigation.

Finger gnosis ability in grade 1 longitudinally predicts math ability in grade 2 (Fayol, Barrouillet & Marinthe, 1998; Noel, 2005). Finger gnosis also predicts mathematical ability for up to 3 years in this age group (Marinthe, Fayol & Barrouillet, 2001), with other investigations suggesting that finger gnosis actually becomes a better predictor for older children's math ability (Newman, 2016). Finger gnosis abilities increase with age and are associated with the use of fingers to aid calculation among 5-7 year olds (Reeve & Humbersone, 2011). Finger gnosis training has also been examined in connection with subitizing ability, which is the ability to rapidly decode numerosity of small quantities without the need for counting or estimating the quantity. Finger gnosis training has been shown to improve both subitizing and finger-gnosis scores (Gracia-Bafalluy & Noel, 2008), but this last result has been criticized as a possible example of regression to the mean (Fischer, 2010). More recent work has extended the role of finger gnosis as a predictor of mathematical ability to adults as well (Penner-Wilger, Waring, & Newton, 2014). This research linking the touch sensitivity of fingers to mathematical performance supports the notion that at least parts of mathematical cognition are embodied.

Developmental and Phylogenetic Models of Embodied Numeracy

Currently, there are two main theoretical views describing why numeracy should be embodied: the functionalist (Butterworth, 1999) and the reuse views (Penner-Wilger & Anderson, 2013; Dehaene & Cohen, 2007). The functionalist view suggests that fingers become functionally linked to number representations through development as finger counting is heavily used in early arithmetic, as well as when learning number concepts and counting rules (Butterworth, 1999). In contrast, the reuse view argues that brain regions underlying finger gnosis have been repurposed in order to subserve new functions, and now contribute to number representations, as well as to their original functions (Penner-Wilger & Anderson; Anderson, 2007). Therefore, the functional view is a developmental model of embodied numeracy and the reuse view is a phylogenetic model of embodied numeracy.

The neural reuse view.

Within the neural reuse perspective, there are two related models: The redeployment hypothesis and the neuronal recycling hypothesis. The redeployment of embodied numeracy is a specific application of the Massive Redeployment Hypothesis of brain evolution (Penner-Wilger & Anderson, 2013). The Massive Redeployment Hypothesis posits that a particular cognitive competency will be made up of numerous cognitive working units, each of which executes a very low-level cognitive operation, which are combined and exapted to form larger networks. According to this model, new cognitive working units evolve relatively infrequently, while older working units are repurposed for new uses relatively more often. Also, redeployment does not require that cognitive working units be constrained by intuitive domain boundaries, only that they serve the same low-level computational function whenever recruited. This has been compared to software reuse, where a particular defined function may be reused to support a common purpose within software packages that otherwise look very dissimilar. The Neuronal Recycling Hypothesis, in contrast, makes extremely similar predictions, but is specifically intended to describe cognitive competencies like math and written language that are seemingly phylogenetically too recent to have been subjected to very much selective pressure (Dehaene & Cohen, 2007). In this model, cultural constructions take advantage of pre-existing cognitive biases (similar to working units), in order to create new cognitive competencies. In Neuronal Recycling, this process is analogous to an ecological niche, where new cognitive competencies become housed in parts of the brain where the neural climate is favourable. This is not the same as the functional hypothesis of embodied cognition, as that model describes fingers and numbers as being linked through associative learning, while neuronal recycling instead would predict that a common neural circuit is necessary for the function of both competencies (Dehaene & Cohen, 2007). So an important way to differentiate reuse from functionalism is that the overlap between fingers and numeracy in the brain is necessarily serving a constructive purpose for adults in the reuse models. This is because the repurposed neural networks are serving a common function for each of the competencies in which they have been recruited, while in the functionalist account their activation is an incidental consequence of two competencies having been learned together.

For the purposes of modelling embodied cognition, the redeployment and neuronal recycling hypotheses are largely equivalent in their predictions. Both predict that overlap between fingers and numeracy should occur in similar ways in the brain, and both are consistent with the prediction that these overlaps should impose cognitive costs as a function of interference between older and newer cognitive competencies. The only real difference for current purposes are that redeployment explains the overlap between numeracy and fingers as being a result of selective pressure over a phylogenetic time scale, while neuronal recycling suggests that numeracy has overlapping representation with fingers as a result of a shorter-term opportunistic process. One exception to the above is that neuronal recycling does seem somewhat more amenable to alternate combinations of cognitive working units between cultures than would be the case for the redeployment view. It is also likely that both are true to some extent, as a redeployment processes would have played a role in the types of cognitive working units available for a recycling process to exploit.

One example of a cognitive bias, or working unit, that has been implicated in neural reuse is the ideomotor mechanism. This concept, originally coined by James (1890), refers to how the mental representation of the anticipated consequence of an action plays a role in generating that action (Greenwald, 1970). For instance, imagining another person in pain may elicit a physical recoiling that is reminiscent of experiencing that same pain. Researchers have suggested that this ideomotor mechanism has been repurposed in order to make sense of abstract culturally invented concepts through the motor system (Badets, Koch, & Philipp, 2016). This is especially relevant for embodied cognition, as it is often argued that the mechanism by which embodiment impacts cognitive performance assumes some sort of motor simulation of actions that are semantically linked with the concept being studied. This review focuses mainly on how judgments of symbolic number quantities appear to produce motor simulation of one's learned finger counting habits.

The functionalist view.

The functionalist view of embodied numeracy instead focuses on how fingers and numbers become linked through experience, with that embodiment taking on specific characteristics of that experience (Butterworth, 1999). The functionalist account would not predict that embodiment of numeracy serves a consistently helpful purpose in adult cognition. Consistent with what would be necessary for a functionalist account of widespread embodied numeracy: 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); and with the earliest likely documentation of finger counting as recent as

27,000 years ago (Overmann, 2014). Fingers create an external representation of numbers that incorporates 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. 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 help reinforce that no matter which number or finger is counted first, counting principles remain the same (Morrissey, 2013). However, this is a somewhat Eurocentric view of finger counting systems. Finger counting habits can, and do, vary more widely across cultures than is currently represented in the literature, (Bender & Beller, 2012); however, this will be discussed in more detail in a later section. Also, Crollen, Seron, and Noël (2011b) argue in a review that while finger counting is a useful tool in the development of numeracy, it may not be a necessary one, as blind children have been observed showing typical numerical competence, aside from reduced working memory performance, despite lacking systematic use of finger counting (Crollen et al., 2011a).

The functionalist view is also consistent with findings in the literature which have observed cross-cultural differences in finger counting as a predictor of embodiment of number magnitude (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Domahs et al., 2012; Morrissey, Liu, Kang, Hallett, & Wang, 2016). Domahs et al. (2012) actually observed a relationship between numerical comparison time and the complexity of corresponding finger-number gestures, while Morrissey et al. (2016) observed consistent performance differences between those who begin counting on their left or right hand. This does suggest that embodiment of number is at least somewhat malleable to experience, and that this experience does have specific consequences for the embodiment of number. For example, passive movements of participants' hands appears to compromise performance to a greater extent during a task that requires a counting strategy to solve arithmetic problems, than when participants are asked to employ an arithmetic recall strategy (Imbo, Vandierendonck, and Fias, 2011; but see Soylu & Newman, 2016). Similar observations have been made in tests of addition, subtraction, and multiplication, where sequential finger tapping selectively interferes with all but multiplication, while foot tapping causes non-specific interference (Michaux, Masson, Pesenti, & Andres, 2013). Observations by Berteletti and Booth (2015) are consistent with these findings, having previously shown that finger-motor areas of the brain are activated more strongly for subtraction problems than multiplication problems. One of the consistent features of these investigations is that embodied interference is connected with finger use, and is more readily detected in research designs when counting is either implied through comparing small quantities, or required by testing characteristics, which would implicate early finger counting as a possible mechanism for the embodiment of numbers.

It is argued by Crollen et al. (2011b) that finger counting is not a necessary step in the development of numeracy, that finger counting is rarely used in systematic ways when it is not modeled, and that arithmetic competence is achieved without acquiring systematic finger counting habits. If true, this would have consequences for the reuse theories of embodied cognition. Crollen et al. (2011b) also cite research showing that children acquired verbal-number labels prior to learning how to use fingers to count (Nicoladis, Pika & Marentette, 2010). However, in another paper, Crollen et al. (2011a) argue that, while not necessary, finger counting habits are likely a beneficial tool when used well, and that their results are not mutually exclusive with redeployment. In fact, Crollen et al. (2011a) suggest that neuroimaging work with blind participants, who have not been instructed in finger counting, would be an excellent test of the redeployment hypothesis. If finger gnosis-linked brain regions, such as the left angular gyrus (Rusconi, Walsh, & Butterworth, 2005), show activation for these individuals during tests of numeracy, it would be supportive of redeployment.

Some other evidence suggests that rather than being critical to development, finger counting in children serves to bypass working memory limits by transiently representing number digits (Alibali and DiRusso, 1999; Berteletti & Booth, 2015; Matsuo et al., 2003; Costa et al., 2011; Reeve & Humberstone, 2011). For instance, Matsuo et al. (2003) observed that participants performed similarly when counting strokes in Japanese characters when asked to either use their fingers or hold their hands still. However, in the movement disallowed condition, participants showed greater activation of several brain regions. This result suggests that finger counting reduces the degree of neural activation necessary to perform the task. Alibali and DiRusso (1999) also observed that 4-year-olds who were encouraged to finger-count were better able to track their counting and made fewer errors coordinating a number of items with the appropriate number word. Costa et al. (2011) have since proposed that poor finger gnosia, rather than being a core deficit in numeracy, may instead be associated with a difficulty in transiently representing symbolic number magnitudes, and that this is unrelated to global intelligence or global working memory performance. If the latter were the case, then this may explain other observations suggesting an association between numerical performance and finger gnosis. This would be consistent with working memory span, rather than actual calculation ability, being one of the few differences between blind and sighted children in Crollen et al. (2011a). This can also be reconciled with Berteletti and Booth's (2015) observation that superior performance on subtraction questions was associated with less finger-related brain activation, as this may indicate a decreasing need for supplementing working memory as subtraction facts are automatized.

However, there are inconsistencies with the functional hypothesis of embodied numeracy. For instance, it is not clear why the functionalist view predicts a necessary relationship between finger gnosis and mathematics ability, contrary to what Penner-Wilger and Anderson (2013) suggest. If finger gnosis is not a crucial part of numeracy, then one would expect that it could be substituted with a verbal strategy or something else. Such a possible alternative cognition for numeracy has been described in Crollen et al. (2011a) with blind children. However Crollen et al. (2011a) make a case against finger counting but not finger gnosis as a necessary feature of numeracy. The blind children in the latter study actually had non-significantly better finger gnosis than the sighted children. Instead of finger gnosis being substituted with something else during development, it has been shown that finger gnosis ability predicts mathematics fluency in both children (Costa et al., 2011; Fayol, Barrouillet, & Marinthe, 1998; Marinthe, Fayol, & Barrouillet, 2001; Noel, 2005; Reeve & Humberstone, 2011; Wasner, Nuerk, Martignon, Roesch, & Moeller, 2016; Penner-Wilger & Anderson, 2013), and adults (Penner-Wilger, Waring, & Newton, 2014). At least one additional study has also suggested that finger gnosis becomes more important -rather than less- for calculation through development (Newman, 2016). It has also been observed that children with Spina Bifida experience a high rate of mathematics difficulties, which has been attributed to diminished functional use of their fingers (Barnes, Smith-Chant, & Landry, 2005). This literature seems to imply that the loss of sight is more easily compensated for in mathematics learning than poor finger gnosis. This is a difficult thought to reconcile with a purely functionalist account of embodied numeracy.

A study by Andres, Ostry, Nicol, and Paus (2008) further complicates a functionalist associative learning account of embodied numeracy. In this study, participants were instructed to grasp and move one of three sizes of wooden blocks with a written Arabic digit printed on it. Participants would move the block one direction or another depending on if the digit was even or odd. These number digits included 1, 2, 8, and 9. When grasping a 60mm block, participants would open their hand wider at first when the numbers 8 or 9 were printed on the block, only to adjust their grip as their hand came closer to the block. While an interesting finding on its own, this is not an isolated observation. Namdar, Tzelgov, Algom, and Ganel (2014) have since made the same essential observation, except using coloured number digits, with the colour of the digit being what determined the direction to move the block. The latter study showed that grasp size was influenced by numerical magnitude even when numerical magnitude is irrelevant to the task. Other researchers have shown that words like “apple” will result in the formation a larger grasp of an object than words such as “grape”, presumably because apples are larger than grapes (Glover, Rosenbaum, Graham, & Dixon, 2004). Participants also grasp small neutral objects more quickly in association with small number digits, while also grasping larger objects more quickly in association with larger number digits (Lindemann, Abolafia, Girardi, & Bekkering, 2007). In yet another example, numerical magnitude influenced how effectively participants believe that they can grasp a neutral object (Badets, Andres, Di Luca, & Pesenti, 2007). Namdar et al. (2014) have also since replicated their own findings with spoken number digit stimuli, as well as with tones of short versus long durations (Namdar & Ganel, 2015). This literature poses the greatest objection to the purely functionalist account of embodied numeracy so far. It is clear that judgments of numerical magnitude influence other irrelevant forms of magnitude judgment in ways that imply that processing symbolic numerical quantity is being confused, if only momentarily, with motor planning. It is not clear at all how this series of observations could be made without something analogous to neural reuse playing a role in repurposing some brain areas previously used for finger motor movement to support a common aspect of magnitude judgment across several domains and situations.

The ongoing debate over the phylogenetic and developmental contribution of fingers to numeracy is important for understanding what forces are operating in the development of embodied numeracy, and how empirical observations are explained in the literature. As the role of learned finger counting habits is reviewed further, it should be understood that finger counting habits likely share considerable overlap with finger gnosis, as well as other competencies. Also, to date, there has not been any published research that may provide a framework by which to more fully disaggregate possible separate, but overlapping, roles of finger gnosis and finger counting. Therefore, research in this area should be evaluated critically, and with an awareness that the relationship between numeracy and finger counting is likely to manifest in complex ways across different study designs. One such example of how this complex interaction manifests is in the relation between different kinds of finger counting habits and mathematical cognition. The next section will review the current evidence and methods linking finger counting habits to numeracy.

Finger counting Habits as a Symbolic Representational Format

The Arabic number system has ten distinct digits, with a power base of ten. The numeric meaning of those digits is dictated by their shape and order when counting. In contrast, finger counting has an implied sub-base due to each person only having five fingers per hand. So while the meaning of a Canadian finger counting gesture is typically decoded as a function of the number of raised fingers, rather than the shape of the gesture, there is still a structural transition where three raised fingers may refer to either three or eight, depending on whether this gesture is combined with another full hand.

The potential cognitive consequences of these structural features of finger counting can be understood through Zhang and Norman's (1995) representational taxonomy. According to this taxonomy, the base-ten Arabic numeration system would be a 1x1D system, with each digit's meaning being computed along two dimensions. Namely, the shape of the individual digit connotes meaning, while its written placement relative to other digits also modulates that meaning. So the digit '1' simultaneously has a same meaning and a different meaning from when it is placed next to a zero, such as in '10'. The shape of a number digit connotes the quantity it refers to, while number of zeros attached to the right of the digit defines the power dimension. So while '1' is a single unit of one, the same digit in '10' represents a single unit of ten. Meanwhile, a typical Canadian finger counting system could be a (1x1)x1D numeration system or a 1D system depending on how it is used. A (1x1)x1D system would refer to there being a power dimension and a unit dimension, but with an implied sub-dimension as a function of meaning being decoded (in order) through both the number of fingers, and the number of full hands, which is further modified by an internal dimension designating whether one is counting in single units, by tens, by dozens, etc. Each translational step in decoding the meaning of a number, be it a cardinal finger-number gesture or an Arabic digit, requires cognitive processing time. Therefore, such translational steps should be evident in the cognitive workings necessary in order to decode meaning from a given number, and can therefore be used to test models of how people decode number symbols.

In a 2012 review, Bender and Beller discussed a multitude of structured finger counting systems with a variety of different cognitive implications, as examined with the aid of Zhang and

Norman's (1995) taxonomy. In some systems, individual units are represented on one hand and iterations of 5, 10, and 100 on the other hand. Others use postural or gestural cues to indicate a power or sub-base dimension. There are systems where users predominately count from thumb to little finger and others where users count from their little finger towards their thumb (Bender & Beller, 2012). There are systems, such as used in China, Korean Sign Language or American Sign Language, where users count exclusively on one hand (Domahs, Klein, Moeller, Nuerk, Yoon & Willmes, 2012). There are also systems, such as in India, where counting on the joints or knuckles is common. This is not even to speak of the array of body counting systems that have been used in a variety of cultures, nor of the extent of diversity within a particular system. Only a very few finger counting systems have been explored using cognitive methodologies. While the topic of the diversity of finger counting habits and their shared/non-shared structural features with spoken and written numeration systems could form a thesis in its own right, for current purposes, the important facts to draw from this are that diversity exists in these systems, that diversity likely has complex cognitive implications, and it is important that investigations not simply assume a particular finger counting system.

The idea that finger-number gestures can function as a unique and meaningful form of number representation in their own right has been supported in the literature. For example, Badets, Pesenti, and Oliver (2010) utilized a paradigm where participants would verbally answer a series of arithmetic problems. The onset of a participant's answer would trigger a photograph outcome while that participant gave their answer. It was observed that showing photos of canonical finger counting gestures to adult participants resulted in superior response time performance, relative to a set of vertical bars, but only when those gestures indicated a correct answer to the previously displayed question. The latter observation indicates that this was not simply due to pictures of hands, rather that pictures of hands were congruent with an automatic internal representation of that counting gesture that was generated by solving the arithmetic question. Di Luca and Pesenti (2008) observed that cardinal finger-number gestures were processed symbolically in two ways. First, participants were faster at identifying photos of finger configurations consistent with their own finger counting habits, and that when used as subliminal primes these gestures facilitated the correct identification of Arabic digits. In a later publication, Di Luca, Lefevre, and Pesenti (2010) observed that finger-number gesture primes that were congruent with a participant's own counting habits had a greater effect on performance than incongruent primes, but that the relative interference of a congruent finger-number gesture prime was a function of the numerical proximity of the represented numerosity to a target Arabic digit. Therefore a finger-number gesture for five would benefit performance for the identification of the number six or four more so than if the same gesture had acted as a prime for the identification of the numbers two or eight. Incongruent finger-number configurations had no influence on response latency unless they represented a quantity larger than the target. Another publication from this research group appears to rule out visual differences as a possible cause of the former results (Di Luca & Pesenti, 2010). These observations, taken together, suggest that visual presentations of congruent finger-number gestures are treated similarly to Arabic number digits while atypical gestures are treated as non-symbolic magnitudes.

Domahs, Krinzinger, and Willmes (2008) examined the sub-base five structure of childrens' finger counting and observed that first and second graders made a disproportionate number of split-five errors when evaluating simple and complex arithmetic problems. A split-five error constitutes an answer that differs by five from the correct result. For example, the error 5 x 5 = 20 or 30 occurred more frequently, than the error that 5 x 5 = 22 or 28. The proportion of these errors decreased over the testing periods, in problems with a result >10. Children in first and second grade typically made these errors by losing track of full hands being counted. By the end of the second grade most split five errors were a result of giving the correct multiplication answer to a simple addition problem. Domahs et al. (2008) suggests that this as a consequence of a shift in children's strategies from overt finger manipulation to memory retrieval. The implicit sub-base structure of finger counting habits has also been shown to persist among adults when response time measurements are taken in place of errors. Klein, Moeller, Willmes, Nuerk, and Domahs (2011) tested a group of medical students and demonstrated that there was a response time cost associated with arithmetic operations that crossed the base-10 power dimension (i.e., a standard effect of a carry operation), as well as a smaller response time cost for arithmetic operations that crossed a sub-base of five.

In another pair of investigations, Domahs et al. (2010; 2012) examined how cross-cultural differences in the sub-base structure of culturally acquired finger counting habits influenced mental representations of number magnitude in adults. Four groups of adults were chosen for the structural and sub-base characteristics of their respective finger counting systems: Chinese one-hand counters (international students in Germany), German two-hand counters, deaf-German two-hand counters, and deaf-Korean one-hand counters. In the Chinese finger counting system, numbers less than six are represented on a single hand in a one-to-one correspondence format; however numbers 6-10 are represented using symbolic sign gestures continued on the same hand. German deaf and hearing participants represent numbers less than ten in a one-to-one correspondence format, with a sub-base of five, in the same manner as most North American and European finger counting systems. Korean Sign Language (KSL) utilizes only one hand when representing quantities; however this system also requires hand movements for some gestures, and changes in palm-forward versus palm-inward orientations of the hand in order to communicate meaning. When asked to make binary magnitude judgments of Arabic digits, Germans demonstrated a reliable response-time cost for 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 response time. Domahs et al. (2010) referred to this as a five-break effect. Users of KSL also showed a slightly different five-break, however this increase in response latency co-occurred with number signs that required changes in palm orientation, rather than a change in number of hands.

The cross-cultural findings of Domahs et al. (2010) have since been replicated, as well as furthering them to include within-culture differences (Morrissey et al., 2016). The difference between Chinese international students and domestic German students were replicated in a sample of domestic Chinese university students and domestic Canadian university students. Canadian participants that used a finger counting system with a (1x1)x1D structure with a sub-base of five, exhibited both a response time cost and an error rate increase when making binary magnitude comparisons of number pairs where both digits would have been counted on two hands (i.e., 6 vs. 8 and 7 vs. 9). These comparisons were chosen due to them co-occurring with the greatest structural differences in finger counting between the respective finger counting systems. Chinese participants that exhibited a 1x1D finger counting system showed no such costs. However, a sub-group of Chinese participants that predominantly counted on both hands similarly to Canadians, with a (1x1)x1D finger counting structure, made a greater number of mistakes for these target number magnitude comparisons. Morrissey and colleagues (2015) also found that Canadians who started counting on their left hand (left-starters) had higher response times for these comparisons than Canadian participants that began counting on their right hand (right-starters).

These observations are consistent with a notion of a reciprocal relationship between Arabic digits and finger counting gestures. Zhang and Norman's (1995) predicted finger counting translation steps are clearly evident in the performance of both children and adults, even when these participants are asked to make judgments of Arabic digits. This is supportive of both the importance of finger counting in cognition as well as the notion of embodied cognition. Finger counting habits influence the way in which Arabic digits are decoded. Further, individual and cross-cultural differences in the structural features of finger counting habits correspond in predictable ways with binary magnitude comparison performance. The evidence presented also supports that finger counting habits themselves are decoded in a symbolic way rather than by simply counting. The only observation here that does not clearly fit into Zhang and Norman's taxonomy is the difference between right-starters and left-starters seen among Canadians, which will be expanded upon later.

Neuroanatomical Basis of Embodied Numeracy

Recently, researchers have begun to identify neuroanatomical overlap between the representation of fingers and numbers. This has been cited as consistent with the redeployment theory of embodied numeracy (Penner-Wilger & Anderson, 2013). Zago et al. (2001) observed that retrieving simple arithmetic facts like "2 x 4" activated a left parietopremotor circuit in adults, and was more likely to represent past developmental experience with finger counting rather than overt or covert use of finger counting to solve the problems. Sato, Cattaneo, Rizzolatii, and Gallese (2007) provide further evidence that the link between fingers and numbers in the brain is not explainable by overt strategies. Participants were asked to perform simple parity judgments of single-digit numbers while the left hemisphere was stimulated using transcranial magnetic stimulation (TMS). Such stimulation lead to greater excitability in participants' right hands during the task, with particularly strong effects for judgments of numbers 1-4.

The left angular gyrus has been implicated in the intersection of finger gnosis and numeracy several times in the literature (Gerstmann, 1940; Rusconi et al., 2005; Roux, Boetto, Sacko, Chollet, & Trémoulet, 2003; Mayer et al., 1999). Roux et al. (2003) observed that preoperative stimulation of the angular gyrus resulted in finger agnosia and impaired number processing. Rusconi et al. (2005) observed that the application of repetitive transcranial magnetic stimulation (rTMS) to participant's left angular gyrus resulted in decreased neural activity at this location, as well as difficulty making coordinated finger movements and number magnitude judgments. The effects of rTMS at this site were qualitatively similar to Gerstmann's syndrome, discussed earlier in the context of finger gnosis. This similarity is important as other researchers have noted that damage at this site is associated with problems with both finger gnosis and arithmetic (Gerstmann, 1940; Mayer et al., 1999). In line with the aforementioned focus on the left angular gyrus, Soylu and Newman (2016) examined the influence of complex and simple finger tapping have on single-digit and two-digit addition, as a follow-up to Michaux et al. (2013). Using a single/dual-task addition paradigm, researchers observed that complex finger tapping appears to cause greater interference, and that single-digit addition is more affected than two-digit addition. Also, fMRI results are consistent with a greater activation of the left angular gyrus as a result of finger tapping during the single-digit task than during the two-digit dual task condition. This is consistent with earlier papers that seem to imply that finger gnosis plays a greater role in math fact retrieval than in active calculation. This is also consistent with other brain imaging work indicating that training in complex arithmetic may shift neural activation from the intraparietal sulcus to the left angular gyrus (Delazer et al., 2003; Ischebeck et al., 2006). This suggests that there is a neuroanatomical overlap between math-fact retrieval and coordinated finger movement, which may in turn implicate both finger counting and finger gnosis in adult number processing. This also suggests that the left angular gyrus is an important site for the intersection of these cognitive functions.

Tschentscher et al. (2012) extended some prior brain imaging findings linking finger counting and number representation to include individual differences. This study compared 15 participants who typically start counting on their right hand with 14 who typically start counting on their left hand. Starting hand was assessed using a written finger counting inventory outlined in Fischer (2008). Participants made parity judgments of Arabic number digit while an fMRI recorded associated brain activity. They observed that activation was greatest for number stimuli from 1-5 in the hemisphere that was contralateral to the participants' starting hand (Tschentscher et al., 2012), and so cerebral activation for numbers 1-5 varied as a result of whether participants reported counting first on their left or right hands. This observation is important here for two primary reasons: first, it clearly implicates finger counting habits rather than simply finger gnosis, and secondly, it indirectly implicates the role of Spatial Numerical Associations of Response Codes (SNARC) in embodied numeracy. The former point, while not often tackled directly in this literature, is an ever-present consideration. It is important to be mindful that connections between numbers and fingers are not automatically connections between numbers and finger counting habits. However Tschentcher et al. (2012) split participants into groups directly via individual differences in reported finger counting habits, and therefore finger counting habits are more clearly implicated in this result. Also, as will be addressed in greater detail later, finger counting habits play a role in the association of quantity with left and right-hand space as well (Fischer, 2008).

Spatial-Numerical Association of Response Codes

Spatial-numerical association of response codes (SNARC) is one of the longest studied phenomena in the field of numerical cognition. Originally described by Dehaene, Bossini, and Giraux (1993), the SNARC effect describes the tendency for larger magnitudes to be answered more quickly in right-hand space, and smaller magnitudes to be answered more quickly in left-hand space. However SNARC has since been extended to a number of related phenomena, and can include right and left hands instead of space, as well as a variety of forms of magnitude aside from just number digits. Wood, Willmes, Nuerk, and Fischer (2008) conducted a meta-analysis of the phenomenon. SNARC appears to be more easily detected when participants are instructed to make magnitude or parity judgments rather than when participants judge a number digit on some superficial characteristic such as colour or shape, as the former typically produce larger experimental effect sizes. SNARC also appears to be stronger in parity tasks, as well as in classifying magnitudes against some fixed standard or anchor, and weaker when making magnitude judgments against a variable standard. The latter type of procedure would be exemplified in Domahs et al. (2010; 2012) and Morrissey et al. (2016).

SNARC has been investigated as a function of numerous processes. Earliest models of the origination of SNARC were of adult reading habits (Berch, Foley, Hill, & Ryan, 1999; Dehaene et al.; Fischer, Mills, & Shaki, 2010; Hung, Hung, Tzeng, & Wu, 2008, Zebian, 2005). For instance, Hung et al. (2008) observed that Chinese readers show a typical left-right SNARC when making parity judgments of Arabic numerals, but an up-down SNARC when evaluating Chinese numerals. However, this account has since proved to be at least incomplete as other studies observed that SNARC exists in preliterate children (Opfer & Furlong, 2011; Opfer, Thompson, & Furlong, 2010; Patro, Fischer, Nuerk, & Cress,2016; Patro & Haman, 2012; Patro, Nuerk, & Cress, 2015; and see Nuerk et al., 2015 for a review). Recently, de Hevia et al. (2014) published observations of preferences for sequences of numerosities that ascend from left to right among 7-month-old infants. Other explanations have therefore been postulated for the origination of the SNARC effect, such as brain lateralization, monitoring/modeling adult behaviour (Nuerk et al., 2015), or even direct spatial learning through formal/informal finger counting instruction (Fischer & Brugger, 2011).

While this issue does not appear to be addressed yet in the literature, it is also possible that the determinant of SNARC and the origination of SNARC are not the same thing. It should not be taken for granted that the reference frames which contribute to a SNARC-like preference for left-right sequences in a 7-month-old are the same ones that contribute to SNARC in adults performing parity tasks with symbolic number digits. Certainly there is evidence that SNARC can be modified among adults by situational factors (Fischer et al., 2010) and Viarouge, Hubbard, and Dehaene (2014) have used such experimental manipulations of SNARC as evidence for multiple reference frames contributing to the phenomenon, which is a departure from trying to determine which particular reference frame actually causes SNARC. One of the largest bodies of evidence for multiple SNARC-like response codes has been the embodied literature, which has addressed the contribution of finger counting (Fabbri & Guarini, 2016; Fischer, 2008; Fischer & Brugger, 2011; Patro, Nuerk, & Cress, 2015), of finger length (Fabbri & Natale, 2015), interaction of finger counting and hand orientation (Riello & Rusconi, 2011), and even an interaction of hand orientation and whether task instructions emphasized hands or buttons (Viarouge et al., 2014).

There is also ongoing research into a similar type of spatial association called the linguistic markedness association of response codes (MARC), where participants demonstrate an association of a particular hand with even or odd number judgments, simultaneously with SNARC associations of number magnitude. The MARC effect also appears to be influenced by handedness, as this effect does not appear to be replicable among left-handed participants (Huber, Klein, Graf, Nuerk, Moeller, & Willmes, 2015), and may also be influenced by the peculiarities of the sub-base five structure of German deaf sign language (DGS) (Iversen, Nuerk, Jager, & Willmes, 2006). For German sign-language, counts for 1-5 would be the same as those for hearing Germans, while counts for 6-10 differ. A user of DGS would start counting on their thumb, with a full hand expressing the quantity five. However six would be represented by holding up the thumb of one's starting hand alongside full second hand. The main difference here is that rather than counting on one hand, and then continuing on a second hand, the second hand is only used to indicate, or not indicate, the quantity five. This can also be described as a sub-base-five decomposition, as the number six is represented as 5+1. For these participants, MARC-hand associations reverse when making parity judgements of digits 6-9 (Iverson et al., 2006). This has been attributed to the effect of the finger counting symbol system on internal representations of quantity (see Bender & Beller, 2012), as six would be an even number, but 5+1 are each odd numbers.

Fischer (2008) observed one of the first examples of an interaction between a more global SNARC reference frame with an embodied SNARC-like reference frame. Participants in this study who reported, in a written questionnaire, that they typically began counting on their left hand also showed a stronger impact of SNARC (Fischer, 2008). Another study found that early grade-school children who were left-starters also showed a leftward spatial bias relative to right-starters, when bisecting a line (Fabbri & Guarini, 2016). These investigations suggest that learned finger counting direction may interact with more general SNARC associations.

Finger counting direction is thought to affect left-right associations because the reference frame through which right and left is perceived is likely defined through egocentric bodily frames of reference operating in concert with a more global left-right association of quantity (Conson, Mazzarella, & Trojano, 2009; Patro, Nuerk, & Cress, 2015). Patro et al. (2015) observed that preschool children have a global preference for counting objects from left to right, but that there was also a tendency for counting direction to reverse (right to left) when the right hand was used. None of the children who started counting on their left hand counted objects from right to left, while about half of children who started counting on their right hand did so. The former results indicated a preference to begin counting objects on the same side of the body as the counting hand, which is secondary to a more global left-right preference. Conson et al. (2009) likewise observed, while using irrelevant numerical cues, that small numbers appeared to facilitate the identification of a line drawing of a left hand with fingers pointed up, but the line drawing of a right hand when the fingers were pointed down, with the reverse observed for large numbers. In other words, small numbers appeared to facilitate pictures of a left hand when held such as one would see their own hand when looking down, meanwhile these numbers would facilitate pictures of a right hand when the hand is oriented as if it belonged to someone else facing the participant. The former experimental procedure only showed hands centrally, and one at a time, and thus the association was with the hand that would be expected to be on the left, rather than with a visual setup where a hand was actually on the left-hand side.

In line with prior findings, Di Luca, Grana, Semenza, Seron, and Pesenti (2006) investigated whether the fastest and most accurate number-key assignment of fingers was a left-right (SNARC congruent) assignment that corresponded with participants' learned mental number line, or an assignment that corresponded with typical Italian finger counting habits, which begins with the thumb of the right hand and completes with the little finger of the left hand. Researchers hypothesized that responses would be faster when finger-digit mapping corresponded with participant's finger counting habits. They found that even in altered posture conditions, the number-key assignment that was congruent with participant's own reported counting habits showed the best performance. This number-key mapping even out-performed the left-right key assignment.

Riello and Rusconi (2011) provided one of the stronger accounts for how the left-right SNARC reference frame can be altered as it is interpreted through an egocentric bodily perspective. They examined SNARC while limiting participants to respond with only one hand at a time, and with hand posture (prone vs. palm-up) varying between conditions. Riello and Rusconi (2011) observed that SNARC was reduced when a response hand is held such that the thumb is to the left side and the little finger is on the right. This orientation occurs when the left hand is palm-up and when the right hand is prone. This effect was observed both in response time data as well as proportion of errors. This showed an association of numbers with space (SNARC) which was modulated by finger counting habits, but also that this association could be changed by altering the posture of the hands, indicating that this relationship between hands and numerical associations is an ongoing aspect of numerical cognition. So, similar to Conson et al. (2009), SNARC is partly determined by finger position and where smaller numbers would be expected to be represented through finger counting rather than through a simple left-right reference frame.

Finally, a study by Viarouge et al. (2014) sought to characterize a hierarchical series of separate reference frames contributing to SNARC, including a global left-right reference frame, a bodily reference frame, and an object-centered reference frame. In a pair of experiments using multiple manipulations of instructions and response buttons, it was observed that emphasizing hands seems to decrease the strength of SNARC relative to instructions which emphasized left and right buttons, meanwhile emphasizing an object-oriented reference frame with a vertical orientation of buttons lead to an association of small numbers with the left hand and large numbers with the right hand.

The current literature investigating SNARC suggests that while the origination of the phenomenon is unclear, an egocentric bodily frame of reference appears to play a role. These results appear consistent with a global left-right reference frame that is being interpreted through a bodily frame of reference. So while, SNARC predicts an association of small quantities with left hand space and large quantities with right-hand space, the nature of how these associations are expressed are subject to bodily constraints. In the case of Conson et al. (2009), SNARC-like associations are modified by hands that would be expected to typically appear on the left hand side, rather than simply associating left hands with left hand space and right hands with right hand space. Similarly, Di Luca et al. (2006) and Riello and Rusconi (2011) found that left and right associations of quantity are modified by finger counting habits, such that typical finger counting direction can override a more typical SNARC, depending on how hands are oriented in space. Fischer (2008) and Patro et al. (2015) also suggest that individual differences in finger counting habits can impact SNARC-like associations, such that left-starters more consistently demonstrate the phenomenon than right-starters. Finally, Viarouge et al. (2012) suggest that these reference frames can all be active at the same time, and differences in instructions may emphasize one over the other at least temporarily. Taken together, this literature suggests that this left-right association is modified by both individual differences in finger counting habits, as well as instructions, and that investigating these situated and embodied influences on SNARC may further clarify the role that this phenomenon plays in numerical cognition.

What are Left-Starters and Right-Starters Really?

Studies in this literature vary considerably in how left- and right-starters are identified and often lack specific details as to how participants were questioned about their finger counting habits. This is problematic as conclusions have been drawn about the meaning of left/right-starter performance differences despite it not being clear which operational definition of left/right-starter is the most appropriate. This criticism is not speculative, as it has already been demonstrated in the literature that different methods of assessment disagree considerably in their classification of left/right-starters, with some inventories demonstrating much greater bias towards finding left or right-starters (Wasner et al., 2014). These differences between inventories may also be confounded with other constructs of interest in a given investigation, such as with reading direction in the case of written finger counting inventories (Fischer, 2008). It also remains unaddressed in the literature as to whether starting hand is even a stable construct or not. As a result, it is often unclear as to whether the same underlying phenomenon is actually being described from one investigation to another.

For instance, Cardinal and Ordinal finger counting habits are two of the most common types of finger counting that researchers attempt to describe. Cardinal finger counting habits – also described as Finger-montring gestures (Crollen et al., 2011a)– include finger numeral configurations which may be used to represent an individual number symbolically, such as when showing a number to another person. Ordinal finger counting habits –also described as spontaneous finger counting habits– refer to the order in which fingers would be used to count privately. While these gestures are related, they only indicate the same starting hand 62% of the time (Wasner et al., 2015). Another research group also found that cardinal and ordinal finger counting habits disagreed about a third of the time (Pika, Nicoladis, & Marentette, 2008). The relative proportion of participants that start counting on the right hand or left hand is also 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 surveyed by Wasner et al., (2014) were right-starters, but when visual and proprioceptive cues were present (i.e., when asked to put their hands in front of them or when presented with a picture of hands), the majority were left-starters.

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. For example, this concern is underscored by Morrissey et al. (2016) having administered a cardinal finger counting inventory with a counter-balanced inventory timing, while Newman and Soylu (2013) as well as Fabbri and Guarini (2016) assessed spontaneous finger counting, and both 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. In the light of Wasner et al. (2014), it is not clear if the left/right-starter distinctions described by those three different inventories are assessing the same underlying construct. So when Newman and Soylu (2013) observe that both adult and child left-starters perform worse on measures of arithmetic competence, it is not clear that these left-starters are the same left-starters as those from Fischer (2008), or the left-starters from Morrissey et al. (2016). Research needs to be conducted in order to evaluate the psychometric properties of these different inventories.

This problem is further compounded because other details about finger counting inventories are inconsistently reported, which may also impact how participants respond. Often, studies mention that finger counting habits are assessed as spontaneous with only some details as to how questions are asked (see Newman & Soylu, 2013, Experiment 2; Sato & Lalain, 2008; Wasner et al., 2015; Zago & Badets, 2016), as part of an information survey (see Newman & Soylu, Experiment 1), or would simply refer to the typical finger counting strategy of the region without assessing the counting habits of individuals in the study or clarifying how this normative finger counting pattern was established (Di Luca, Granà, Semenza, Seron, & Pesenti, 2006). Other studies utilized cardinal finger counting habits, assessed prior to a numerical task (see Domahs et al., 2010; Morrissey et al., 2016). There is also a subset of studies using a written finger counting inventory originating with Fischer (2008) (see Fabbri & Guarini, 2016; Tschentscher et al., 2012; Wasner et al., 2015). When this information is mentioned in other studies, experimenters would typically report questioning participants about their counting habits prior to the main task (Domahs et al., 2012; Fischer; Sato & Lalain, 2008; Tschentscher et al., 2012), or the timing of finger counting questions would not be mentioned explicitly (Domahs et al., 2010; Fabbri & Guarini, 2016) and even some that do mention timing leave it ambiguous as to whether finger counting assessment was on the same date as a numerical task (Fischer, 2008). However, some 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). Fischer (2008) and Tschentscher et al. (2012) are an exception here as they provided structured and replicable details for how participants were questioned about their finger counting habits.

Wasner, Moeller, Fischer, and Nuerk (2014; 2015) also included greater detail about how finger counting habits were questioned; however, these papers were explicitly about different ways of assessing finger counting habits.

The Purpose of the Current Dissertation

The literature reviewed thus far has demonstrated many interesting links between fingers and numbers. There are also several proposed theories that suggest plausible explanations as to why fingers may be related to numbers in the first place. However, there are a number of gaps in this literature. One of the most pressing gaps in this literature is the psychometric gap in which researchers try to assess finger counting habits, and starting hand in particular, while dissociating this result from other left-right associations. As mentioned above, Wasner et al. (2015) identified that visual cues can result in participants being more likely to self-identify as left-starters rather than right-starters. Fischer (2008) has also identified that left-starters exhibit a strong left-right association of quantity, known as SNARC. It is possible that the relationship between starting hand and SNARC is bidirectional, with left-starters performing as left-starters as a result of stronger left-right associations of quantity, either as a result of stable trait characteristics, or as a function of the way numerical information is communicated to participants during an investigation. It is also possible that self-reporting oneself as a left-starter by counting smaller quantities on the left hand may simply be an instance of SNARC in action, and not a fully separate phenomenon at all. The latter point, however, does conflict with a great diversity of research demonstrating a connection between fingers habits and mathematical competencies, as SNARC on its own does not appear to be related to mathematical competence (Cipora & Nuerk, 2013).

In this dissertation, I describe a series of four investigations that were conducted in order to further clarify the relationship between left-right space, and embodied numeracy. In Study One, right-handed participants were subjected to two types of finger counting inventories, either before a numerical magnitude comparison task or immediately following this task. Their classification as left or right-starters by these inventories were then compared against two numerical phenomena that have previously demonstrated differences between left-starters and right-starters. The goal of Study One was to evaluate whether these inventories were measuring the same underlying construct, as well as whether test characteristics may alter participants' performance or the usefulness of either inventory. Study Two describes a very similar investigation to Study One, except with the inclusion of left-handed participants. Study Two investigated the possibility that being a left or right-starter may be relevant to performance because students who do, or do not, count on their dominant hand may differ in some way relevant to their numerical performance. This is an understudied alternative to left-right associations as a function of SNARC. Study Three investigated whether calculation ability of adults is affected by simultaneous sequential finger movement, as well as whether any effect of sequential finger movement may differ between right and left-starters. Finally, Study Four used a divided visual field test in order to investigate whether the specialization in the function of the right and left hemisphere may itself be relevant to adults' performance of a numerical task that has shown right and left-starter differences in the past.

This is a manuscript-style dissertation, which means that each of these studies is presented as their own stand-alone chapter in a style that could be submitted to a journal for publication. In fact, Studies One (Morrissey & Hallet, *In Press*) and Three (Morrissey, Hallett, Wynes, Kang, & Han, 2018) have already been published. This also means that each chapter will have its own introduction, method, results, discussion and reference section, and there will be some repetition of content across these introductions. After these study chapters, the last chapter will provide a general discussion of the findings and how they further our understanding of the relations between finger counting habits and mathematical cognition.

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Chapter Two: Study One- Cardinal and Ordinal Aspects of Finger Counting Habits Predict Different Individual Differences in Embodied Numerosity

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Abstract

The hand with which one starts to count has been shown repeatedly to influence numerical performance. However, methods vary greatly in how they 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 response 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

Introduction

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 as recent as 27,000 years ago (Overmann, 2014). Fingers 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, 2013) and motor cortex activation evoked by single-digit numbers (Tschentscher, Hauk, Fischer, & Pullvermüller, 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, 2013; 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, 2011). 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 right side and the little finger is on the left). 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 (2013) 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 (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., 2011; 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, 2013, experiment 2; Zago & Badets, 2016), as part of an information survey (see Newman & Soylu, 2013, 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 (2014; 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 presents 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). 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 response 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.

Our ability to maintain comparable numbers of participants with different characteristics across conditions was limited, due to the inability to randomly assign finger counting habit variants. The latter was compensated for by recruiting as many participants as practically possible. 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) in the number comparison task. See Table 1.1 for a detailed breakdown of participants. Included participants were an average of 20.93 years of age (*SD* = 4.33). All participants included are self-report as 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 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, Eshman, & 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 1.1 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 1.1.

Frequency of participants in each procedure-order condition across Dataset One and Dataset Two

		Dataset one				Dataset two	
		Cond. 1	Cond. 2	Cond. 3	Cond. 4	Cond. 3	Cond. 4
Inventory							
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 1.1). 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 of type of finger counting inventory. Because the off-diagonal frequencies were low (see Table 1.2), 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 (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 entering 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, χ^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 1.2.

Relative disagreement of the cardinal and ordinal inventories in identifying left starters versus right-starters.

	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 response time task, affected participants' SNARC-like performance. Median response time scores were utilized in all analyses, as medians are more robust to violations of normality that are typical of response time data. Response time scores follow a positively-skewed distribution, due to participants' inability to achieve a negative response time score. This is particularly important in a task like this where significant differences in errors and mean response 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 response times and correct SNARC-incongruent response times were calculated for each number comparison (within each participant). These response 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, (21.037 ms), $F(1, 226) = 27.963$, $p < .0005$, $\eta_p^2 = .110$, 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, η_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, $F(1, 226) = 0.710$, $p = .400$, η_p^2 =.003. The results for the two between-subjects factors are shown in Figure 1.1. 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, $F(1, 226) = 5.185$, $p = .024$, η_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.

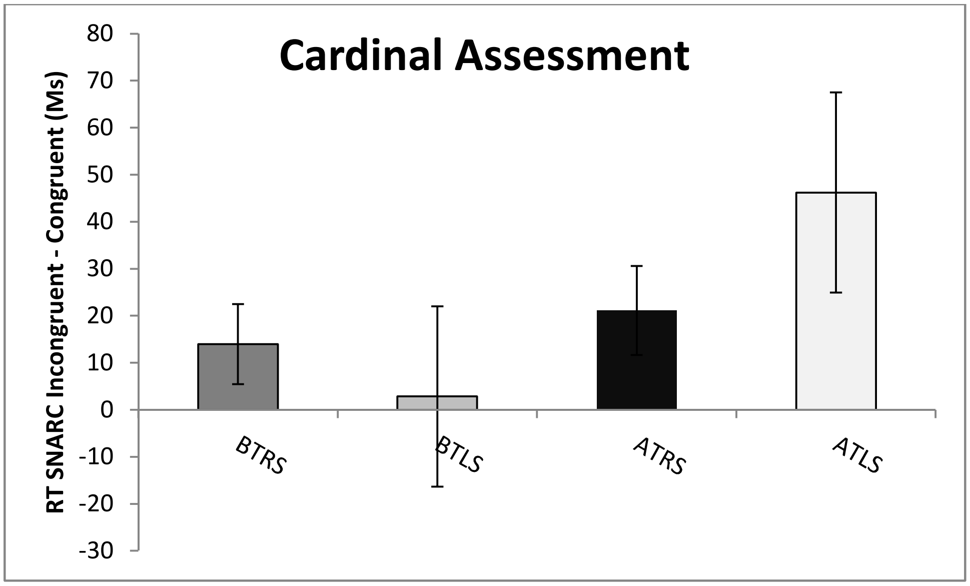

Figure 1.1. Median response time difference between SNARC-congruent and SNARC-incongruent trials. Error bars are 95% confidence intervals. BTRS indicates before-test right-starters (n = 106). BTLS indicates before-test left-starters (n = 21). ATRS indicates after-test right-starters (n = 86). ATLS indicates 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 1.2. 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.

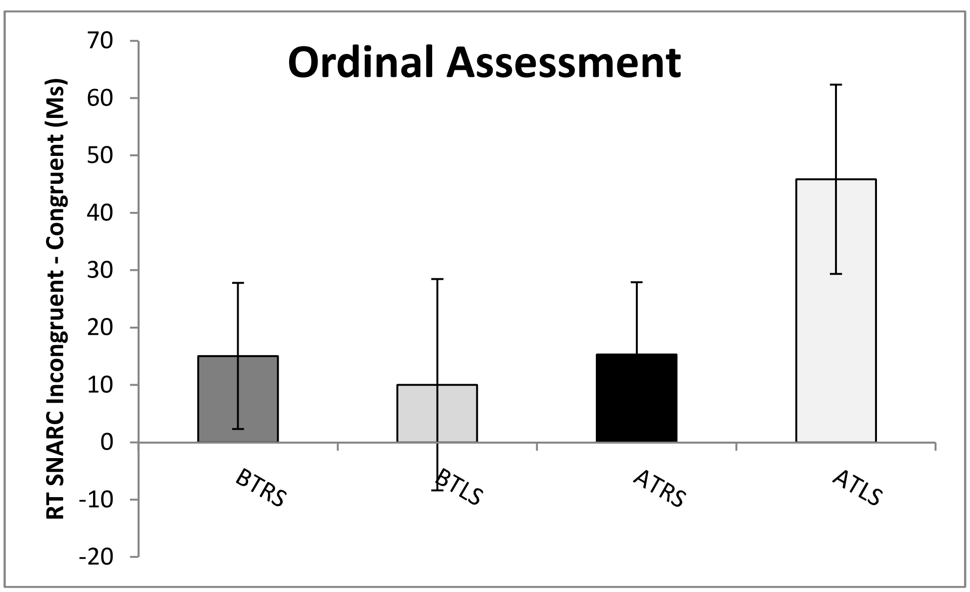

Figure 1.2. Median response time difference between SNARC-congruent and SNARC-incongruent trials. Error bars are 95% confidence intervals. BTRS indicates before-test right-

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 after-test left-starters exhibited these effects more strongly than other participants. 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 that 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 response time scores were used in place of log-transformed mean response time scores used by Morrissey et al. (2016) and Domahs and colleagues (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 response 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 response 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 response 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 54.06ms vs. 46.44ms 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, 53.70ms vs. 46.52ms 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 1.3). 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 1.4). However, there was no reliable effect of inventory timing, $F(1, 227) = 1.332$, $p = .250$, $\eta_p^2 = .006$, and no interaction, $F(1, 227) = 1.174$, $p = .280$, $\eta_p^2 = .0005$.

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 1.4). Like cardinal starting hand, there was no reliable effect of inventory timing, F(1, 126) = 1.025, $p = .313$, η_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.

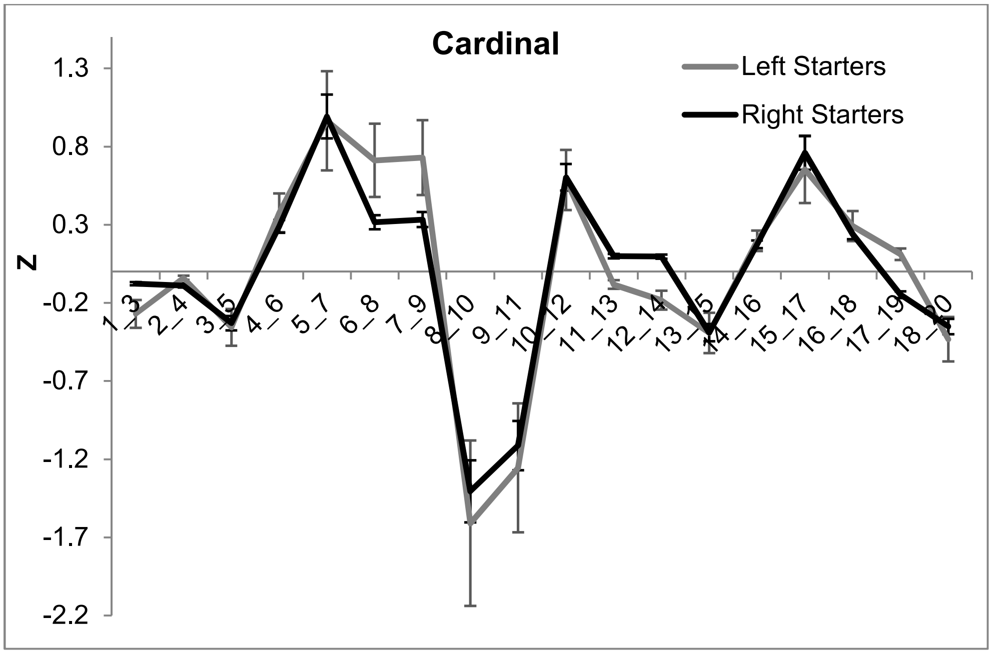

Figure 1.3. Standardized residual scores across the 18 comparisons, when right-starters and left-starters are classified via cardinal finger counting habits. Error bars are 95% confidence intervals.

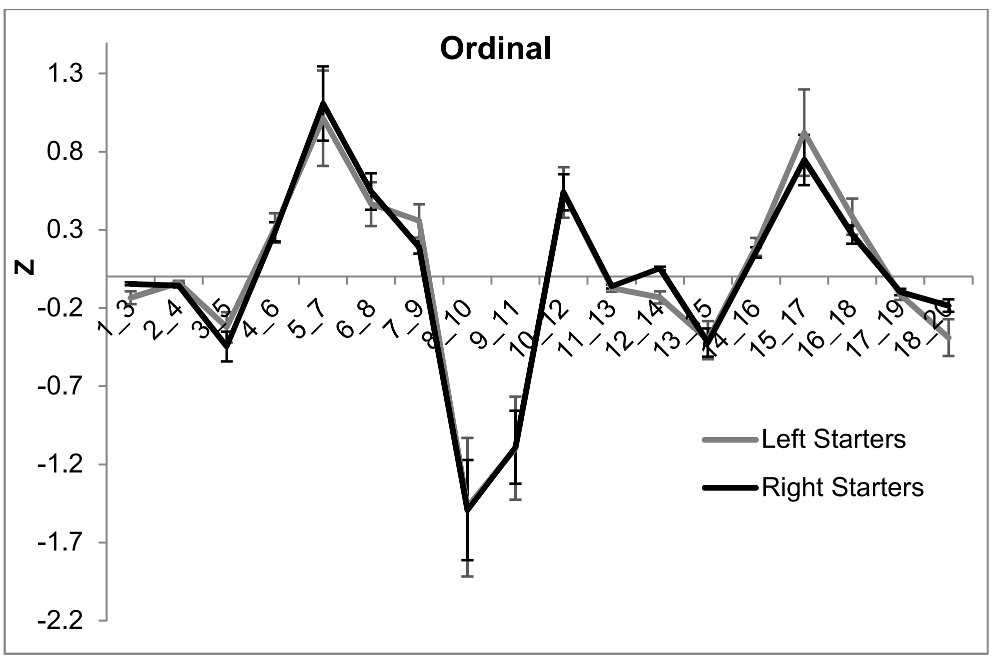

Figure 4. Standardized residual scores across the 18 comparisons, when right-starters and left-starters are classified via ordinal finger counting habits. Error bars are 95% confidence intervals.

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 response 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 (2013) tested finger counting habits prior to the SNARC task, while Fischer (2008) 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.

Data availability.

The data sets generated during and/or analysed during the current study are available in the Open Science Foundation repository, https://osf.io/7mtkz/.

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Chapter Three: Study Two- Handedness Does Not Modulate Embodied Numerical Cognition, Except When It Does: An Investigation of Cross-Cultural and Individual Differences in Finger counting Habits.

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Abstract

This investigation examined individual differences in both finger counting and handedness and their relationship to numerical cognition. Morrissey et al. (2016) observed reliable cross-national differences in a magnitude judgement task that corresponded to structural features of finger counting habits, as well as between Canadians who start counting on their right hand or their left hand. That investigation, however, was limited to right-handed individuals and, therefore, results may have been an incidental function of participants habitually counting or not counting on the hand used for writing. The present study tested both Chinese and Canadian left-handed participants in order to rule out this explanation. Results of the current investigation suggest that handedness may play a separate and distinct role independent of starting hand. We also investigated whether SNARC-like response compatibility effects differed for left- and right-starters. There were reliable SNARC-like effects for Canadian and Chinese right-handed participants, and no SNARC-like effects for either Canadian or Chinese left-handed participants. These individual differences in SNARC-like effects appear unrelated to finger counting direction, raising the possibility of multiple independent embodied numerical codes being used simultaneously, some of which may be culturally variable, while others may not.

Keywords: magnitude comparison, handedness, cross-cultural, finger counting, representational effects, embodied cognition, SNARC, order effects

Introduction

Finger counting habits are a growing area of embodied cognitive research. While not cross-culturally uniform in their structure (Bender & Beller, 2012), finger counting habits are used nearly universally, often without direct instruction (Butterworth, 1999), with the earliest documentation of finger counting at around 27,000 years ago (Overmann, 2014). Fingers offer a helpful tool for teaching children counting concepts (Alibali & DiRusso, 1999), and likely continue to play a role in the cognition of adults (Morrissey et al., 2016). However, while finger counting is a useful tool in the development of numeracy, it may not be a necessary one, as blind children have been observed showing typical numerical competence. However, there is some evidence that this may be associated with reduced working memory performance (Crollen et al., 2011a).

There have been several investigations to date that have identified that adults and children who start counting on their left hand (left-starters) demonstrate numerical performance differences from their right-starter peers (Fabbri, 2013; Fabbri & Guarini, 2016; Fischer, 2008; Morrissey et al., 2016; Newman & Soylu, 2013; see also Study Three), as well as differences in motor cortex activation evoked by single-digit numbers (Tschentscher, Hauk, Fischer, & Pullvermüller, 2012). While interesting in their own right, these investigations do raise questions as to why the hand used to start counting should matter in the first place. One possibility is that left-starters' finger counting habits are more consistent with a left-right association of quantity, similar to the SNARC effect (Newman & Soylu, 2013). Another possibility is that these differences are an indirect consequence of participants typically counting on different hand than the one that the use to write.

As with many cognitive studies that measure reaction time, most past researchers have restricted samples to right-handed participants (e.g., Morrissey et al., 2016; Newman & Soylu, 2013; and Tschentscher et al., 2012), and there has been very little work examining handedness as a potential moderator of finger counting habits (Sato & Lalain, 2008). The reason that many studies exclude left-handed participants is due to the concern that left-handers could exhibit different patterns of results, because of their handedness, that might be unrelated to the phenomenon in question. In the case of differences between left- and right-starters, however, differences due to handedness may be directly relevant, and may be used to test theories that attempt to explain why left- and right-starters differ.

The Current Study.

The current study investigated whether left- and right-starters differ when making binary magnitude comparisons of numbers typically counted with both hands, as an incidental consequence of relying on finger counting habits while writing. This was examined by comparing left- and right-handed individuals on a binary magnitude comparison task that has recently demonstrated differences between left- and right-starters (Morrissey et al., 2016). Morrissey et al. (2016) investigated the cognitive impacts of cross-cultural and individual differences in finger counting habits, in a replication and extension of Domahs et al. (2010). They observed that both culture and being either a left- or right-starter predict individual differences in number magnitude comparison performance. The traditional Chinese finger counting system employs only one hand and uses symbolic gestures meant to simulate the written Chinese numerals. Consistent with Domahs et al. (2010), Morrissey et al. (2016) found that this practice was related to simple number comparisons performance in predictable ways. Canadian participants were found to compare numbers more slowly and with more errors when those number pairs would have typically been counted using two hands. Also, right-handed Canadians who typically count first on their left hand responded more slowly to these number pairs than right-handed right-starters. Meanwhile, most Chinese participants who typically reported counting on only one hand answered these same number pairs relatively faster than other number pairs. Only a subset of Chinese participants who typically count on both hands made more errors on these number pairs. This provided support for the notion that individual finger counting habits themselves were being activated, despite not being mentioned or relevant for completing the task, and results were not due to cross-national differences. This study also opens the door for testing whether these results would be any different in a left-handed sample.

Using the findings on this task with right-handed individuals, data from left-handed participants were used to achieve two objectives in this study. The first objective was to test a potential criticism that results seen in Morrissey et al. (2016) were incidental consequences of individual differences in finger counting habits interacting with writing habits. In this model, Chinese participants did not show an increased response time for numbers between 6 and 9 because of superior number representations. The fact that Canadians did show slower responses for these numbers, with left-starters showing the slowest responses of all, would be an incidental result of some students habitually counting mainly a different hand than the one used to write. This would suggest that left-starters developed this counting habit from an increased reliance on finger counting while writing. If this hypothesis was true, then we would predict that the pattern would reverse for left-handed individuals, and instead it would be the right-starters who show an increased cognitive load relative to left-starters while comparing numbers typically counted on two hands.

The second objective of this investigation was to attempt a cross-cultural falsification of the multiple reference frame account of embodied SNARC, discussed in Study One. In that study, right-handed Canadian participants who reported typically counting on their left hand first demonstrated a stronger SNARC-like response compatibility effect than their right-starter peers, where left-hand responses were faster when selecting smaller number digits, while right-hand responses were faster when selecting larger number digits. The exception to this pattern was when participants had been questioned previously about their finger counting habits. In that condition, left-starters demonstrated no detectable SNARC effect, while right-starters performed much the same. This finding was consistent with previous work suggesting that drawing attention to participants' fingers may reduce the effect of SNARC (Viarouge et al., 2014). The multiple reference frame account was put forth as an explanation of how overlapping embodied and global reference frames may explain why being a left starter may predispose a stronger SNARC, except when attention is drawn to one's finger counting habits.

This account suggests that finger counting direction of each hand constitutes a reference frame and questioning participants about their finger counting habits resulted in this reference frame being more accessible in their conscious thoughts. Refer to Figure 2.1 for a visual reference of this model. The finger counting direction of the left hand is right→left while responding on a keyboard, while the finger counting direction of the right hand left→right. If it is indeed true that the changes in SNARC were due to an interaction of the finger counting direction of hands as they are positioned on a keyboard, and the saliency of certain finger counting habits, then left-handed participants should find the finger counting direction of their left hand more salient than right-handed participants, even without reminding them of this reference frame. As a result, both Canadian and Chinese left-handed participants should have a greater proportion of left-starters. Furthermore, both Canadian and Chinese left-handed participants should have a smaller SNARC-like effect compared to their right-handed peers, and perhaps even a reverse SNARC-like effect.

However, as mentioned above, Study One found that the SNARC-like results were affected by whether participants were reminded about their finger counting habits either before or after they completed the task. Therefore, reinforcing these finger counting habits for left-handed participants prior to the number task should qualify the overall differences in SNARC-like response compatibility effects hypothesized above. Three scenarios are posited: 1) Scenario one posits an additive model of reference frames. If the decrease in SNARC-like compatibility effects for right-handed left-starters seen in Study One were due to the reference frame for the dominant right hand being initially more available, but that being reminded of both hands increases the relative contribution of the reference frame of the non-dominant left hand, then reminding left-handed participants of their fingers should actually increase SNARC-like compatibility effects for left-handed right-starters (or decrease reverse-SNARC-like compatibility effects) since it would increase the relative contribution of the SNARC-congruent right hand reference frame; 2) Scenario two also posits an additive reference frame model; however, this scenario also suggests that there is a third left-right global SNARC reference frame that also contributes to participants' responses. In Scenario two, the differential effects due to handedness and starting hand would remain the same as in Scenario one, but a general left-right bias for a SNARC effect would also operate. This means that any groups posited to demonstrate a reversal of SNARC-like compatibility effects may instead demonstrate a reduced SNARC-like compatibility effect, while those posited to demonstrate typical SNARC-like compatibility effects would have an even stronger SNARC-like compatibility effect; 3) Scenario three posits that there is an interaction of handedness and finger counting salience. Participants who already start counting on their dominant hand are relatively less impacted by being questioned about their finger counting habits, as this reference frame was already relatively more available to consciousness. The main difference between Scenario two and Scenario three is that being primed for your dominant hand will not have an additive effect, so that any difference between being primed, versus not being primed, should happen only for left-handed right-starters and right-handed left-starters. The three respective reference frames described above can be seen in Figure 2.1.

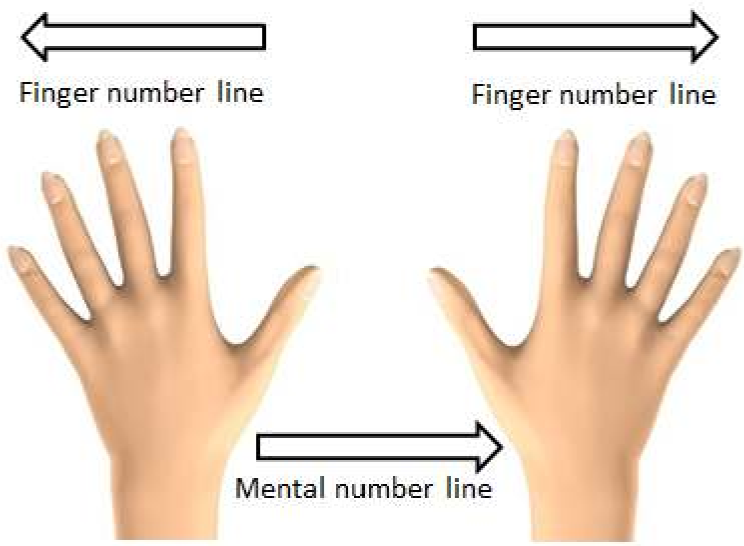

Figure 2.1. Proposed multiple reference frame model. This includes a left-right hand-based reference frame, a finger-based reference frame that is impacted by finger counting direction for individual hands, as well as a more global left-right association of magnitude and quantity such as the mental number line (MNL).

Scenario one therefore posits two reference frames, while Scenario two posits three reference frames, and Scenario three posits that participants' awareness of these reference frames is moderated by handedness. However, reminding Chinese participants of their fingers may not impact SNARC-like compatibility effects. The dominant finger counting strategy learned by this group involves counting on only one hand; thus, reminding them of their finger counting habits would not increase the saliency of finger counting direction for each hand, but rather simply for the single hand typically used to count (nearly always the dominant hand). Therefore, while handedness should have a similar aggregate impact for both Canadian and Chinese participants, the impact of priming finger counting habits may differ due to structural differences in the predominant finger counting strategies in each group. In other words, the effect of priming a finger counting habit likely will have a different impact, depending on what cultural finger counting system is actually being primed.

In order to 1) test for interactions of handedness and starting hand, and 2) better estimate error in participants' responses, data all right-handed Canadian and Chinese right-handed participants tested in Study One and Morrissey et al. (2016) had their data reused. Left-handed participants were recruited during data collection for Study one and Morrissey et al. (2016), but had not had their data examined previously. Given that left-handed individuals have consistently constituted only about 12.5% of those available to participate in both Canada and China during this investigation, and given that ordinal finger counting habits were recorded half-way through Canadian testing and after Chinese testing had already been completed, it is not possible to separately examine ordinal classifications of left- and right-starters. While it would be interesting to see if ordinal finger counting habits modulate these reference frames similarly to those of right-handed participants, Scenarios one, two, and three may still be supported or ruled-out for cardinal finger counting habits.

Method

Participants.

The data collected for this study consisted of 59 left-handed Canadians, and 20 left-handed Chinese participants that recruited during Study One and Morrissey et al. (2016). Left-handed participants were an mean age of 20.54 years old (*SD* = 2.956), and had a mean task accuracy of 95.11% (*SD* = 3.32). For certain comparisons, 231 right-handed Canadian participants were included from Study One, as well as 97 right-handed Chinese participants from Morrissey et al. (2016). Right-handed participants had a mean age of 21.01 years old (*SD* = 3.86), and a mean task accuracy of 95.21% (*SD* = 3.2). Participant recruiting took place from October 2012 through March 2017. 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 voluntary subject pools in exchange for course credit. Chinese participants were enrolled at Northeast Normal University, a comprehensive university in China. The recruiting procedure differed somewhat at Northeast Normal since there was 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 at the time) 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.

Stimuli.

The stimuli and procedure for this investigation were the same as 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 2,000 ms, and so each practice block could take a maximum of 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) X 2 response sides (larger number being on the left or the right) X 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, Eshman, & 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.

The cardinal finger counting inventory, included as Appendix B, 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 by the experimenter 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 simply participants to count from 1-10 on their fingers as they would normally, and their starting hand was recorded.

All finger counting inventories administered to right-handed Canadians were exactly as described in Study One. A total of 39 left-handed Canadians received both cardinal and ordinal inventories, while an additional 20 left-handed Canadians received only the cardinal inventory. Right and left-handed Chinese participants received a cardinal finger counting inventory, as data collection in China preceded the use of an ordinal finger counting inventory. While a limitation of the current investigation, it is not clear whether an ordinal finger counting inventory would have been useful with Chinese participants, as the structure of Chinese finger counting habits does not easily lend itself to ordinal finger counting habits. This was actually the original impetus for developing the cardinal finger counting inventory for Morrissey et al. (2016), as Chinese finger-counts are symbolic, and do not contain any ordinal structures beyond the quantities 1-5 (depending on the individual). A detailed participant breakdown is available in Table 2.1 and Table 2.2, however only cardinal finger counting habits will be considered in data analysis.

Table 2.1.

Frequency of cardinal left- and right-starters across handedness, country, and timing of assessment

			Right-starter	Left-starter
Country	Handedness	Finger counting inventory received		
Canada	Left-handed	Before-test	10	20
		After-test	11	18
	Right-handed	Before-test	107	21
		After-test	86	17
China	Left-handed	Before-test	4	5

	After-test	4	7
Right-handed	Before-test	56	0
	After-test	40	1

Table 2.2.

Frequency of ordinal left- and right-starters across handedness and timing of assessment

Country	Handedness	Finger counting inventory received	Right-starter	Left-starter
Canada	Left-handed	Before-test	8	12
		After-test	9	10
	Right-handed	Before-test	42	20
		After-test	43	25

Procedure.

Each participant in the study answered demographic questions about ethnicity, first language, gender, language spoken in primary school, and nationality. Due to the cross-cultural nature of the study, participants with a history of schooling outside of Canada or China, or who spoke languages other than English, French, or Chinese, were excluded, as previous work has shown that different cultures may impact patterns of numerical performance on this test (Domahs et al., 2010; 2012; Morrissey et al., 2016). Similarly, for data collection, 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, or after, 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 (e.g., Study One; Wasner, Moeller, Fischer, & Nuerk, 2014). Therefore, just as was the case in Study One, procedure-order conditions were used to examine the possibility that either finger counting inventory may interact with the numerical task itself.

Results

Objective 1: Handedness and Representational Effects.

Analysis of representational effects included only Canadian participants, as starting hand was the same as dominant hand for all but 9 Chinese participants. A median correct response time was taken for each of the 18 comparison scores per participant, with stimuli numbered by the average of comparison (i.e., 4 for both the pair 3 vs. 5 and 5 vs. 3). People tend to respond more slowly 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 effects of numeric magnitude on participants' response time performance, as doing so ensures that any systematic effects of particular numerosities are not due to these numbers simply being larger. 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 any given number pair. A larger slope denotes a relatively steeper increase in response for larger number pairs relative to response latency for smaller number pairs. These fit lines were subtracted from the median response time scores for each participant, at each comparison, and the resulting difference scores were also standardized with a mean of 0 and a standard deviation of 1, resulting in a metric that should be relatively free of overall effects of numeric magnitude.

Resulting standardized residual scores for number comparisons typically counted on both hands (i.e., 6 vs. 8 and 7 vs. 9) were then averaged. For Canadian participants, these data were analysed using a 2(handedness) x 2(starting hand) between-subject ANOVA in order to determine if handedness interacted with starting hand, which may indicate that the impact of starting hand was a function of whether or not it was someone's dominant hand. However, there was no interaction between handedness and starting hand in these data, $F(1, 286) = .227$, $p = .731$, $\eta_p^2 < .0005$. As in previous research, the overall difference between left-starters and right-starters remained statistically significant, $F(1, 286) = 8.371$, $p = .004$, $\eta_p^2 = .028$, $d = .34$, with right-starters responding relatively more quickly on these comparisons than left-starters. However, there was also a small mean difference between right-handed and left-handed participants, $F(1, 286) = 5.145$, $p = .024$, $\eta_p^2 = .018$, $d = .13$, with left-handed participants responding relatively more quickly on these comparisons then right-handed participants.

A Welch's corrected t-test was used, with a directional alpha of .05, in order to evaluate whether the right-handed representation difference had been replicated among left-handed Canadians. However, this analysis only had 80% statistical power for an effect size as large as $d = .68$, which is considerably larger than the expected small to moderate effect. However, the effect still approached statistical significance, $t\ (37.298) = 1.402$, $p = .0845$, $d = .39$. Therefore, given that left-handed left-starters trended towards replicating the increased cognitive load seen among right-handed Canadians, the representation-difference effect for left-handed participants was likely not reversed relative to this difference for right-handed participants, which rules out the alternative hypothesis proposed in this investigation to explain the left/right-starter performance difference.

Objective 2: Handedness and SNARC.

The next analyses investigated differences in SNARC-like response compatibility effects across culture, handedness, and starting hand. First, a series of analyses were conducted in order to verify if handedness and starting hand were related. A pair of chi-square analyses indicates that Canadians were more likely to be both cardinal, $\chi^2(1, N = 290) = 55.89, p < .0005, \varphi = -.44$, and ordinal, $\chi^2(1, N = 169) = 5.96, p = .015, \varphi = -.19$, left-starters when they were left-handed than if they were right-handed. Given the rarity of right-handed left starters among Chinese participants, only Fisher's Exact test was performed, which also found that left starters were more common among the left-handed, $p < .0005$, $\varphi = -.71$. Median response time scores were utilized in all analyses, as medians are more robust to violations of normality that are typical of response time data (Whelan, 2008). This is particularly important in a task like this where significant differences in errors and mean response time are expected between different items, independent of the variables of interest.

A SNARC-like response congruity effect is characterized by a participant 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). In most paradigms, SNARC is evaluated by a parity test (even vs. odd), where the degree to which SNARC impacts performance is linear, with the right hand response advantage growing larger with the perceived magnitude of a given number digit, while the left-hand response advantage grows larger when number digits are relatively smaller. This enables researchers to take the mean difference of right and left-hand responses and plot these scores linearly against digit/stimuli magnitude. However, when numeric magnitude is directly part of a participants' decision, such as when judging a digit as larger or smaller, the SNARC effect is expressed as a categorical function rather than a linear one. Therefore, when coding responses in the magnitude comparison test, SNARC congruent and incongruent responses were collapsed across stimuli and the resulting correct response time means were compared, rather than collapsing scores across hands and comparing response times across stimuli. For a visual example of linear and categorical SNARC functions, see Figure 2.2.

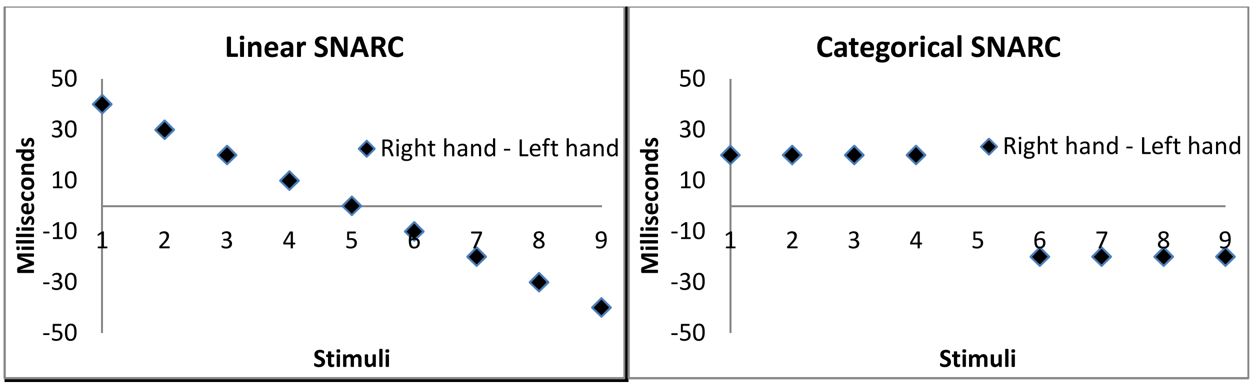

Figure 2.2. Linear vs. categorical SNARC. Represents hypothetical mean RT for right hand responses, minus mean RT for left hand responses. Positive numbers indicate faster right hand responses and negative numbers indicate faster left hand responses.

Data analysis for either the current paradigm or a typical categorical SNARC is essentially the same, and both rely on magnitude comparison rather than parity. There were a few differences from a traditional categorical SNARC, as that is usually a result of a comparison of a series of small individual quantities with some fixed standard, such as 5. In the current task, there was a variable standard, as a larger or smaller number would be selected out of any of 18 different pairs of numbers, but there was always a fixed difference of 2 between the numbers. Still, errors have already been shown in Morrissey et al. (2016) to follow a SNARC-like pattern in this paradigm, with more mistakes made for SNARC-incongruent responses than SNARC-congruent responses. Errors were 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 result in fewer errors. Because of this, data were 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 response times and correct SNARC-incongruent response times were calculated for each number comparison (within each participant). These response 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 SNARC-incongruent. These betas from the resulting regression equations for each number pair were then averaged for each participant.

A 2 (before-test vs. after-test condition) x 2 (country) x 2 (handedness) between-subject ANOVA was conducted with categorical SNARC-like advantage scores as the dependant variable. One Canadian participant and three Chinese participants were excluded due to disproportionate errors on particular number pairs, resulting in empty cells. There was a robust overall effect of SNARC-like response compatibility effects, as indicated by the grand mean test of the intercept, (13.86ms), F (1, 395) = 13.732, p < .0005, $\eta_p^2 = .034$. Consistent with predictions based on the multiple reference frame hypothesis, left-handed participants, m = 3.52 ms, demonstrated less of a SNARC-like response bias than did right-handed participants, m = 16.38, F (1, 395) = 4.252, p = .04, $\eta_p^2 = .011,\ d = .33$. The effect of handedness does not appear to vary by country, with Canadians, M_{diff} = 14.76 ms, SD =43.04, showing a similar decrease in SNARC-like response biases as did Chinese participants, M_{diff} = 8.27 ms, SD = 27.80, F (1, 395) = .338, p = .561, $\eta_p^2 = .001$. The effect of handedness was not moderated by the timing of the finger counting inventory either, F (1, 395) = .590, p = .443, $\eta_p^2 = .001$. There was no apparent mean difference observed in SNARC-like response biases between Canadian, $m = 14.10$, or Chinese participants, $m = 13.26$, F (1, 395) < .0005, p = .997, $\eta_p^2 < .0005$. There was no main effect of before-test vs. after-test condition, F (1, 395) = .002, p = .962, $\eta_p^2 < .0005$, however, inventory timing did interact with country, F (1, 395) = 4.144, p = .042, $\eta_p^2 = .01$. Given that Levene's test indicated that significant heterogeneity of variance was present, F (7, 395) = 2.763, p = .008, and that this difference in variability was driven by a larger standard deviation for Canadians relative to Chinese participants follow-up tests and effect sizes for this interaction use separate error terms. This interaction is driven by Canadian participants demonstrating less of a SNARC-like response bias, M_{diff} = -11.64 ms, d = .27, when a finger counting inventory preceded the number comparison test, while Chinese participants demonstrated a stronger response bias in the same condition, M_{diff} = 11.1 ms. d = .40. Also, while trending towards being significant, the effect of before-test vs. after-test condition was not statistically significant for either Canadian, F (1, 285) = 3.534, p = .061, or Chinese participants when tested independently, F (1, 110) = 2.635, p = .107. This interaction was not further moderated by handedness, F (1, 110) = .079, p = .779, $\eta_p^2 < .0005$.

Next, the effect of cardinal starting-hand was examined for Canadian participants with a 2 (before-test vs. after-test condition) x 2 (handedness) x 2 (cardinal starting hand) ANOVA with categorical SNARC-like advantage scores as the dependant variable. There was a robust overall effect of SNARC-like response compatibility effects, as indicated by the grand mean test of the intercept, (14.1ms), F (1, 281) = 11.231, p = .001, $\eta_p^2 = .038$. Consistent with predictions based on the multiple reference hypothesis, left-handed participants, $m = 2.88$ ms, demonstrated less of a SNARC-like response bias than did right-handed participants, $m = 16.96$, F (1, 281) = 5.649, p = .018, $\eta_p^2 = .020,\ d = .33$. Similar to Study One, there was a main effect of finger counting before-test vs. after-test condition, with participants in the before-test condition, m = 8.24 ms, exhibiting less of a SNARC-like response bias than did participants in the after-test condition, m = 21.06 ms, $F(1, 281) = 7.013$, $p = .009$, $\eta_p^2 = .024$, $d = .30$. However, inventory timing did not interact with handedness, $F(1, 281) = 1.166$, $p = .281$, $\eta_p^2 = .004$. Further, there was no main effect of cardinal starting hand, $F(1, 281) = .021$, $p = .885$, $\eta_p^2 < .0005$, and this did not interact with inventory timing, $F(1, 281) = .499$, $p = .480$, $\eta_p^2 = .002$, nor did cardinal starting hand interact with handedness, $F(1, 281) = .503$, $p = .479$, $\eta_p^2 = .002$. However a three-way interaction was trending towards significance for handedness, inventory timing, and cardinal starting hand, $F(1, 281) = 30.34$, $p = .083$, $\eta_p^2 = .011$. See Figure 2.3 for a breakdown of the results for left-handed Canadians. A similar breakdown for right-handed Canadians is available in Figure 2.4.

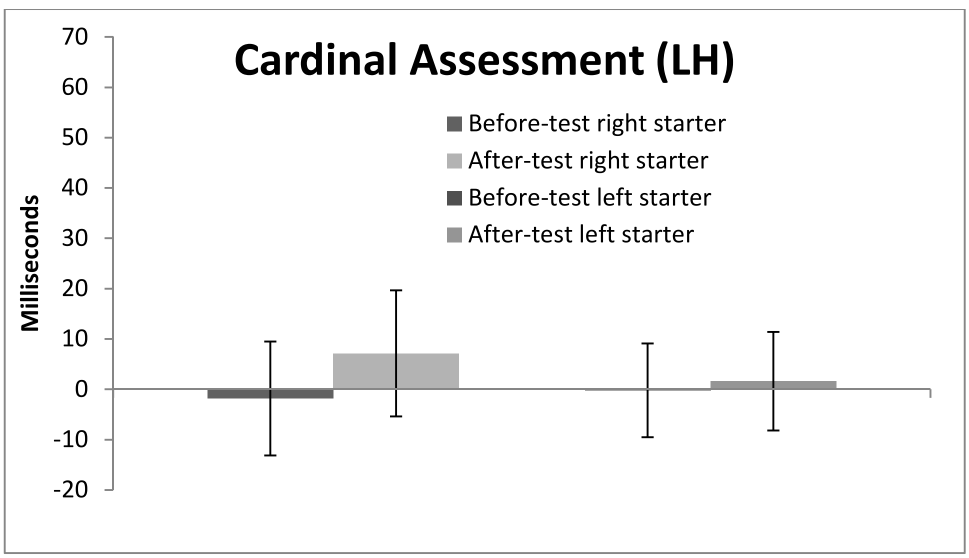

Figure 2.3. SNARC advantage score for before and after-test condition results for left-handed Canadian participants. Positive values indicate a SNARC consistent response bias, while negative values indicate a SNARC inconsistent response bias. Error bars are 95% confidence intervals.

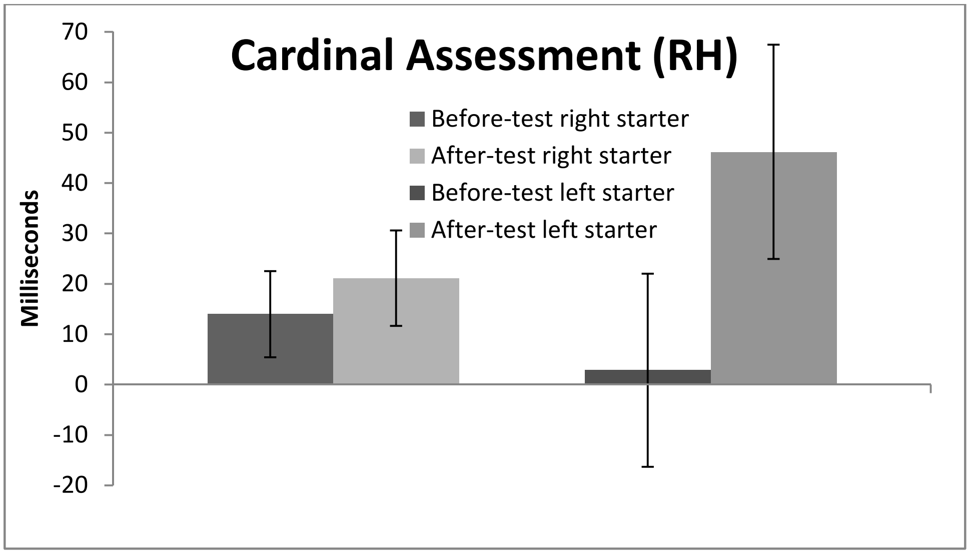

Figure 2.4. SNARC advantage score for before and after-test condition results for right-handed Canadian participants. Positive values indicate a SNARC consistent response bias, while negative values indicate a SNARC inconsistent response bias. Error bars are 95% confidence intervals.

Discussion

This study had two objectives: 1) to test the potential criticism that results seen in Study One and in Morrissey et al. (2016) were incidental consequences of individual differences in finger counting habits interacting with writing habits, and 2) to re-examine the proposed multiple-reference-frame account of SNARC-like response biases. According to the criticism raised about Study One and Morrissey et al. (2016), Chinese participants would simply have better number representations, and so needed to rely less on finger counting habits as a form of representation. The difference in representation effects between Canadian right-starters and left-starters would be a result of some students habitually counting mainly on a different hand than the one that they use to write, suggesting that left-starters developed this habit from an increased reliance on finger counting while writing. These criticisms were examined by conducting a representational analysis similar to Study One, in which starting hand and handedness were both factors predicting log-residualized response time performance for comparing number pairs typically counted using both hands. According to the criticism that spurred this study, it was expected that the effect of starting hand would reverse for left-handed participants, relative to their right-handed peers. Instead, results indicated that left- and right-starter differences in representation effects were similar for left- and right-handed participants, with left-handed participants showing less evidence of finger counting representations than right-handed participants for numbers typically counted on two hands, irrespective of starting hand. When we re-examined the proposed multiple-reference-frame account of SNARC-like response biases, our observations were consistent with scenarios two and three above, indicating that the finger counting direction of each hand contributes to SNARC-like response compatibility effects, and that the effect of these hand-based reference frames are moderated by how readily available they are in consciousness. The results of both of these objectives are elaborated upon next.

Representation effects.

While there are limitations to this dataset in terms of statistical power, which rules out a full and independent replication of the right-starter/left-starter representational differences in Morrissey et al. (2016), it is still possible to positively rule out the alternative model of individual differences between left-starters and right-starters as being responsible for the results from Study One and Morrissey et al. (2016). The difference between starting hands did not reverse for representation effects, as would be expected if the relative increase in processing time associated with left-starters were due to habitual counting during writing. However, both right-starting and left-starting left-handed participants still showed somewhat less of a cognitive load overall, relative to right-handed participants, which was not predicted. These results do not support representation effects as being incidentally associated with hand dominance and habitual finger counting. However, there do appear to be some other extraneous differences in magnitude representations of numbers typically counted on two hands which are associated with handedness itself and not necessarily finger counting habits. So, while handedness does not appear to play a causal role on the effect of starting hand, it still appears that handedness is involved in this phenomenon.

One possible explanation for this handedness effect from the literature is that of more efficient hemispheric interactions among left-handed individuals (Cherbuin & Brinkman, 2006). Given that the number comparisons being evaluated here are comparisons that would have been counted on both hands, it seems likely that a more efficient mental transfer between hands (and, therefore, between hemispheres) could indirectly make these comparisons relatively easier for left-handed individuals. This would also be consistent with studies that indicate that left-handed individuals show superior performance in tasks requiring the use of both hands (Han, Waddington, Adams, & Anson, 2013).

Given that the current observations suggest cardinal left vs. right-starter differences in representational demands of numbers 6 through 9 are not an incidental function of habitually counting (or not) on the hand used for writing, then alternate explanations of this phenomenon must be considered. Past investigations have assumed that the increased cognitive load seen for numbers 6 through 9 is a function of these numbers activating motor representations of two hands rather than one hand. The ideomotor mechanism suggests that such motor simulation occurs because the sense-perception of a concept also activates the motor behaviour associated with generating a response to that concept (Badets et al., 2016). In the case of culturally acquired abstract concepts like numbers, this means that the number 4 likely activates the culturally-acquired finger counting gesture associated with that quantity. At first glance, the current study's findings appears inconsistent with this account as neither handedness, nor starting hand, are associated with more/less complicated finger counts, and thus should not result in differences in performance as a consequence of that motor simulation. However, there is growing research evidence of a special and superior role of the left hemisphere in symbolic number magnitude processing (Sokolowski, Fias, Ononye, & Ansari, 2017). If the motor representations of finger counting habits for left-starters are preferentially activated in the right hemisphere, then this could result in a performance cost in the task. This would also be consistent with the explanation offered above for why left-handed participants exhibited less of a cognitive load at these comparisons. This concept is examined more fully in Study Four.

Handedness and SNARC.

The results appear conditionally consistent with both scenarios two and three of the multiple reference frame hypothesis. Being left-handed is cross culturally associated with less of an impact of SNARC-like response biases. However, SNARC-like response biases are further moderated by whether a participant has been reminded of their finger counting habits, with participants who typically count first on their non-dominant hand appearing more impacted by the salience of their finger counting habits. This makes sense as one's dominant hand is likely already relatively more accessible to consciousness than the non-dominant hand. Also, left-handed participants in both countries would have been holding their dominant hands on a normal keyboard with their thumbs on the right and their little fingers on the left. This hand orientation results in a finger counting direction of right to left for participants' dominant hand.

The observed finger counting priming effects also help further illuminate the possible mechanisms behind how these reference frames interact with SNARC-like response compatibility effects. Rather than seeing right-starters display more SNARC-like response bias in their performance when reminded of their finger counting habits prior to the task, we see that right-handed right-starters appear unaffected by priming their finger counting habits, while left-handed right-starters are showing a trend towards actually being less impacted by SNARC-like response biases when reminded of their finger counting habits. However there was also less evidence for SNARC-like response biases among left-handed participants. Likewise, for Chinese participants, there was no detectable effect of finger counting priming, while there was an apparent effect of handedness. This lack of priming is likely because Chinese participants typically counted on only one hand, and nearly always on their dominant hand. This suggests that the activation of competing reference frames seen among Canadians were not relevant for Chinese participants. The relevant finger counting reference frames for these participants are likely already salient due to nearly all Chinese participants counting on their dominant hand, while there is no finger counting reference frame for a second hand that could be primed, as most of these participants counted on only one hand. Therefore it appears that rather than finger counting habits actually promoting response biases, these results are instead more consistent with there being a separate pair of spatial reference frames for each hand, which interfere with SNARC to varying degrees, depending on an individual's typical counting habits, and how accessible these habits are in a participants' consciousness.

These observations do not exist in a vacuum, despite being unique in their specificity, their accounting for saliency of finger counting habits, and individual differences. Other researchers have identified that numerical response compatibility effects can be moderated by embodied characteristics in ways similar to the current study. For instance, the MARC effect describes the tendency for participants to respond relatively more quickly when an odd number is answered with the left-hand key, while even numbers would be responded to more quickly with a right-hand key (Iversen et al., 2006). Researchers have also observed that the MARC effect is moderated by degree of left-handedness (Huber et al., 2015), as well as specific structural features of learned finger counting habits used in German sign-language (DGS), despite the phenomenon originally being conceived of as being a purely linguistic association (Iversen et al.). In the case of DGS, even/odd associations appear to reverse for digits 6-9 because DGS codes these digits as 5+1, rather than 6, and 5+4, rather than 9. This is conceptually similar to the embodied moderation of SNARC-like response biases that have been detailed in the current study, as SNARC itself was originally conceived of as being a consequence of the mental number line and reading direction. However, a purely linguistic account is not consistent with either the results of the current study, or those seen with the MARC effect, as starting hand and handedness should have no bearing on number words.

Implications and limitations.

The implications of these results are important for our understanding of the mechanisms behind how motor simulation of finger counting habits impact numerical performance. However, despite collecting data for five years, it was only possible to recruit 59 left-handed Canadian participants and 20 left-handed Chinese participants. As such, any conclusions drawn from left-handed data should be interpreted more cautiously than those for right-handed participants. For instance, the interaction of starting hand and inventory timing for SNARC-like response biases only trended towards statistical significance. Also, while it seems very unlikely that representation effects reverse for left-handed participants, relative to right-handed participants, the left-starter/right-starter difference has not yet been independently replicated among left-handed participants. More participants are needed in order to comment more definitively on those observations.

However, despite the limitations described above, there are several things that can be concluded from this investigation. SNARC was successfully predicted to have less of an overall impact on performance for left-handed participants, and this was true for both Chinese and Canadian participants. Further, left-handed participants performed faster when comparing numbers typically counted on two hands than their right-handed peers. Taken together, these observations are consistent with a motor simulation hypothesis of embodied numerical cognition, as well as with the notion that motor simulation of finger counting habits gives rise to independent reference frames for SNARC as well as both hands. Further, these reference frames contribute differently as a function of individual finger counting habits, with cross-national differences in culturally acquired finger counting habits, as well as with the availability of these finger counting habits in consciousness. This frames the impact of motor simulation on numerical performance as being a function of what motor responses a participant is likely simulating, which is what should be expected if this is, in fact, what people are doing. However, further research is needed with a larger sample of left-handed participants in order to ensure that these findings are replicable, and to describe their performance with better precision.

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Chapter Four: Study Three- Finger counting Habits, not Finger Movements, Predict Simple Arithmetic Problem Solving

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Abstract

Previous research in embodied mathematical cognition has found differences between those who start counting on their left hand and those who start counting on the right hand. However, if starting hand is a finger-embodied effect, then finger-specific interference may affect these differences between left- and right-starters. Furthermore, cultures that demonstrate different finger counting habits may also be differently affected by this interference. In the current study, a total of 66 Canadians and 60 Chinese participants completed a single/dual-task paradigm and were also assessed on their starting hand for counting. The primary task was to verbally answer simple arithmetic problems, while the dual task was to either sequentially tap their fingers or their foot. Contrary to predictions, a specific finger-movement interference pattern that had previously been reported was not evident in this study, despite a much larger sample. Nevertheless, Canadians left starters outperformed right-starters for every operation type, which may be further evidence of individual differences in the lateralization of arithmetic processes. Derived from a combination of a replication, a conceptual replication, and a cross-cultural comparison, this investigation suggests that embodied effects in the published literature are in need of both independent replication as well as investigation of individual differences. This study also further validates the differences between left- and right-starters, and suggests that more research is needed to understand the influence of embodied cognition on mathematical understanding.

Keywords: Arithmetic, mental arithmetic, finger counting, finger movement, embodied cognition, starting hand

Introduction

Recent years have seen considerable research interest in how number concepts may be embodied through finger counting habits (Fischer, Kaufmann, & Domahs, 2012; Moeller et al., 2012). Finger counting habits are used nearly universally to assist in the acquisition of early number concepts (Alibali, & DiRusso, 1999) as well as in the development of arithmetic competence (Moeller et al., 2012). Finger-number representations mix the sense of touch, vision, verbal rehearsal, and the motor system into a single activity (Moeller, Martignon, Wessolowski, Engel, & Nuerk, 2011), which reinforces the connection between finger counting and number concepts (Alibali, & DiRusso, 1999). In addition, while finger counting is a useful tool in the development of numeracy, it may not be a necessary one, as blind children who lack systematic finger counting have been observed showing typical numerical competence, despite reduced working memory performance (Crollen, Mahe, Collignon, & Seron, 2011).

The research reported here considers a particular aspect of finger counting habits: whether participants start counting on their left hand (left-starters) or on their right hand (right-starters). Previous research has demonstrated differences between left starters and right-starters in number representation (e.g., Fabbri, 2013; Fabbri, & Guarini, 2016; Fischer, 2008), as well as cross-cultural differences in finger-number representation (Morrissey, Liu, Kang, Hallett, & Wang, 2016), and these differences offer further support to the notion that numerical cognition is at least partly embodied in one's fingers. The present study, however, examined whether Canadian and Chinese left or right-starters differed on an arithmetic task—in particular, one that has been shown to suffer interference from a concurrent finger-motor task (Michaux, Masson, Pesenti, & Andres, 2013). This task was chosen because the previous investigations demonstrated that left- and right-starters differ in calculation ability (Newman, & Soylu, 2013). However, Newman and Soylu (2013) only examined starting hand, and did not demonstrate any other embodied effects. Therefore, in effect, this study reported here is a combination of a cross-cultural replication of Michaux et al. (2013), and a conceptual replication of Newman and Soylu (2013). In doing so, we sought to both confirm the findings of these studies and expand on them as well.

Numerical cognition and fingers.

Although finger counting is usually thought of as something employed by children when learning numbers, many studies have shown that finger counting habits continue to play a role in adult numerical cognition. Adults perceive finger counting representations in a privileged way compared to other non-symbolic magnitudes (Di Luca, Lefevre, & Pesenti, 2010), and continue to show culturally specific cognitive features of learned finger counting habits in their numeric performance (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Domahs, Klein, Moeller, Nuerk, Yoon, & Willmes, 2012; Morrissey et al., 2016). Other investigations have examined how children's finger gnosis, or sensory awareness of their fingers, predicts later math performance (i.e., finger gnosis) (Costa et al., 2011; Fayol, Barrouillet, & Marinthe, 1998; Marinthe, Fayol, & Barrouillet, 2001; Noel, 2005; Newman, 2016; Reeve, & Humberstone, 2011; Wasner, Nuerk, Martignon, Roesch, & Moeller, 2016; Penner-Wilger, & Anderson, 2013), and predicts current math performance among adults as well (Penner-Wilger, Waring, & Newton, 2014). Past imaging work has also specifically implicated the left angular gyrus as being involved in both finger gnosis and number knowledge (Rusconi, Walsh, & Butterworth, 2005).

There are currently two main models that attempt to explain why internal representations of fingers and numbers become connected mental processes. These are the functional and reuse views (Penner-Wilger, & Anderson, 2013). Both of these views largely address a common literature linking finger-related processes with various aspects of numerical functioning. The functional view posits that fingers and numbers become linked through having been learned together, so it is the very fact that children use their fingers to count that links fingers with mathematical cognition (Butterworth, 1999). The functional view is plausible as fingers are known to serve as calculation aids for more difficult problems, with more difficult problems eliciting greater use of fingers among children (Geary, Hoard, Byrd-Craven, & DeSoto, 2004), and finger agility has been linked to counting and calculation competence (Rusconi, Walsh, & Butterworth, 2005). The functional view is also consistent with work showing that finger counting habits are unnecessary for blind children in learning how to count, although lacking finger counting habits was associated with reduced working memory performance (Crollen et al., 2011).

The reuse view, on the other hand, posits an evolutionary process by which finger-related brain regions have been repurposed to subserve mathematical functions (Penner-Wilger, & Anderson, 2013). More general accounts of the reuse view have garnered some empirical support, with evolutionarily older brain areas being redeployed in a greater number of cognitive tasks (Anderson, 2007). However, specific empirical support for neural reuse in finger counting is currently lacking, as the hypothesis is relatively new. Despite this, neural reuse may also be more compatible with a variety of empirical findings than the functional view. For instance, it has been observed that printing Arabic numerals on blocks can subtly affect the size of a participant's grasp used to pick up the block, such that a block with an “8” written on it will elicit a larger grasp than a block with a “2” written on it (Andres, Ostry, Nicol, & Paus, 2008), and this sort of interference occurs even when these numbers are irrelevant to the task (Namdar, Tzelgov, Algom, & Ganel, 2014). The latter findings are difficult to reconcile with the functional view, as they demonstrate overlap between fingers and number magnitude processing that has no clear parallel in children’s finger counting. While both these views are useful lenses through which to evaluate the literature, they are lacking in clear experimental work that could differentiate one or the other. Even though recent cross-cultural work suggests that the impact of finger counting habits on cognition can be malleable as a function of what finger counting system is learned (Domahs et al., 2010, 2012; Morrissey et al., 2016), it is not clear whether this is strong evidence for functionalism. It is not yet known whether embodying numbers through finger counting habits is something which must be learned in the first place, or whether experience simply changes how this overlap may manifest in certain cognitive paradigms.

The possibility remains that numeracy is necessarily embodied through fingers, while the nature of that embodiment differs in ways consistent with how participants learned to count on their fingers. For instance, in Domahs et al. (2012), researchers were able to match particular profiles of numerical comparison performance for particular pairs of numbers with culturally specific systems of finger-number gestures. For example, participants tended to make more mistakes and respond more slowly to number pairs that would take more than one hand to represent on one’s fingers, which can be used to differentiate German and Canadian from Chinese participants, as Chinese finger counting only requires one hand for most digits (Domahs et al., 2010; Morrissey et al., 2016). Previous work has also linked embodied numerical interference with finger use, which is typically found in research designs when counting is either implied through comparing small quantities, or required by testing characteristics (Imbo, Vandierendonck, and Fias, 2011; Michaux et al., 2013; Soylu, & Newman, 2016). Some imaging work has also been used to show that individual differences in the hand that one begins counting on can have some relation with which hemisphere is more strongly activated by a particular number (Tschentscher, Hauk, Fischer, & Pulvermuller, 2012). Berteletti and Booth (2015) have likewise shown that finger-motor areas of the brain are activated more strongly for subtraction problems than multiplication problems.

Michaux et al. (2013) observed that finger tapping selectively interfered with addition and subtraction performance, while leaving multiplication problems unaffected. Michaux and colleagues gave participants single-digit arithmetic problems in a dual-task design. For some blocks of trials, participants had to answer these questions while tapping their fingers in a predetermined pattern, while for the other blocks, they only had to answer the questions. There was also a different group of participants, whose dual task involved tapping their foot in a predetermined pattern. Overall, the finger-tapping group showed interference in their addition and subtraction performance, but not in their multiplication performance. The foot-tapping group, however, demonstrated interference across all operations. Michaux et al. (2013) argued that this selective interference in the finger-tapping condition demonstrated a special connection between fingers and calculation. A similar study, conducted previously by Imbo et al. (2011), also found selective interference effects for problems that required counting strategies, but not for problems that required recall strategies. This study, however, only had a finger-tapping condition and did not include a foot-tapping control. As a result, Michaux et al. (2013) could better attribute the selective interference effect to fingers themselves and not a simple distraction.

Although Michaux et al. (2013) demonstrated a finger-specific interference effect that was related to calculation, it did not examine if this effect was the same for left starters or right-starters. As mentioned above, Newman and Soylu (2013) did find a difference between left- and right-starters on calculation. They gave adults a series of two-digit addition problems, and right-starters answered more quickly on their correct answers, but they were not more accurate. Given this finding that starting hand has an effect on calculation performance, it seems plausible that starting hand may also influence a calculation task like that used by Michaux et al. (2013), especially as this task demonstrated how calculations can be affected by the finger-based embodiment of numerical cognition. There were some differences between these two studies: the questions in Newman and Soylu (2013) used two-digit numbers that required calculation, while Michaux et al. (2013) used single-digit questions that should rely on recall. Furthermore, Newman and Soylu (2013) only had addition questions, while Michaux et al. (2013) had addition, subtraction, and multiplication question. Nevertheless, both Michaux et al. (2013) and Newman and Soylu (2013) attribute their results to the neural overlap between fingers and numbers. If this neural overlap is the same in each of these works, then there should be a difference between left- and right-starters in the calculation task used by Michaux et al. (2013).

The current study.

The purpose of this investigation was to look at the functional overlap between successive finger movement and single-digit arithmetic recall/computation through a cross-cultural replication of Michaux et al. (2013) and conceptual replication of Newman and

Soylu (2013). A larger and elaborated version of this study could be used to answer a few different questions at the same time. For instance, if there was a general difference between left- and right-starters on this arithmetic task, apart from whether this difference was affected by finger-tapping interference, it would extend Newman and Soylu's (2013) result to include single-digit, recalled problems across different operations. Furthermore, Michaux et al. (2013) had a small sample size (i.e., 16 participants per group), so a replication of the effect observed by Michaux et al. (2013) would be valuable in itself.

The present study also compared a sample of Canadian adults to a sample of Chinese adults. The cross-cultural aspect of this study allowed us to compare theoretical predictions based on the functional view vs. the redeployment view of embodied cognition. Past cross-cultural investigations of finger counting habits have largely relied on the predicted absence of an embodied characteristic in Chinese students' performance in a numerical task, because most Chinese participants employ a one-handed counting system for the numbers up to 9. Namely, it was predicted in Morrissey et al. (2016) that Chinese one-hand counters would not show an increased processing demand for numbers typically counted on both hands by Canadians, as the former group would only be counting these numbers on one hand. While there was an observed increase in proportion of errors for these numbers among the minority Chinese two-hand counters, this was the smallest group in the study and these results were not corroborated in response time scores. However, it is not certain whether these results were due to the absence of embodied numeracy or if numeracy was being embodied differently through the Chinese system. The advantage of a dual-task paradigm is that if there is overlap between finger movements and number representation, then it should be detectable by having participants engage in finger tapping while answering arithmetic questions. This is because both activities should be competing for the same mental resources, regardless of individual or cross-national differences in finger counting habits. The absence of a specific effect of finger tapping among Chinese participants would be evidence against the redeployment view of embodied numeracy. Redeployment views instead suggest that this relationship between fingers and number is evolutionarily driven rather than driven through experience (Penner-Wilger, & Anderson, 2013). Redeployment views would be consistent with the nature of embodied numeracy being changed through experience, such that characteristics of how fingers are used could alter how they interfere with a numeracy task, but a strict redeployment view would not be consistent with a group that shows no evidence of embodiment at all of numbers through finger representations.

Finally, it should be noted that there is more than one way to measure starting hand (Wasner, Moeller, Fischer, & Nuerk, 2015). Cardinal starting hand is indicated by asking participants to represent a selection of numbers, one at a time, using their fingers, and starting hand would be chosen based on which hand is used to represent the numbers from 1 to 5. Ordinal starting hand is indicated by asking participants to count from 1 to 10 using their fingers, and starting hand is indicated by which hand is used to start counting. Previous research has demonstrated that cardinal starting hand is not always the same as ordinal starting hand, with more left starters identified using the ordinal classification (Morrissey & Hallett, *In Press*; Wasner et al., 2015), and these different classifications may be differently related to mathematical cognition. The present study used ordinal starting hand, because that was what was used in Newman and Soylu (2013). However, the one previous study that has investigated starting hand with Chinese adults (Morrissey et al., 2016) used a cardinal classification of starting hand, and almost all Chinese adults were classified as right-starters.

In addition to our other hypotheses, the present study also allowed us to investigate whether Chinese adults would still be disproportionally right-starters when using an ordinal classification method instead of a cardinal one.

Method

Participants.

A total of 66 Canadian participants, *M*= 21.47 years, and 60 Chinese participants, *M*= 20.83 years, were recruited for this study. The goal of recruitment was to double the sample size of Michaux et al. (2013) for each study group. Therefore, given that this study was conducted in both Canada and China, this means 30 participants per condition, per country, totalling a minimum of 120 participants. Canadian participants were oversampled by 10%, to leave room to potentially exclude participants due to poor performance. Canadian participants were incentivised for their participation with course credit as part of the Participant Research Experience Pool program at a university in a mid-sized Canadian city. Chinese participants were recruited from a large university in northeastern China. As there were no volunteer participation systems available at the Chinese university, Chinese participants were recruited using signs posted around the university campus. Compensation for participation consisted of 10 yuan (approximately $2.09 CAD at the time). All procedures utilized were in compliance with the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans, all participants gave their informed consent prior to their participation, and aside from compensation, procedures were identical in both countries. Furthermore, these procedures, including those in China, have all been approved by the local ethics review board at the

Canadian university. All research staffs in China were aware of ethical guidelines at the Canadian university and agreed to follow a parallel set of procedures.

Tasks and stimuli.

Tasks and stimuli were a replication of Michaux et al. (2013). The only differences were the addition of questions to assess starting hand and other demographics, and the fact that the finger-tapping and foot-tapping conditions were conducted simultaneously with random assignment between the conditions. Michaux et al. (2013) had conducted these two conditions as separate experiments. The set of addition questions used in this study were identical to those used by Michaux et al. (2013), while the subtraction and multiplication questions matched these items identically with only the operator changed (see Table 3.1). Prior to any other experimental tasks, participants gave their informed consent. Following this, participants answered a few demographic questions, including date of birth, gender, language, nationality, and ethnicity. However, only nationality and first language were used as exclusionary criteria, with only either Canadian French or English speakers and Chinese Mandarin or Cantonese speakers included as participants.

Participants were told that this was a single-task/dual-task experiment and that the single-task condition would consist of providing verbal responses to single-digit arithmetic problems, while the dual-task condition would consist of either finger or foot tapping to be conducted simultaneously alongside the arithmetic problems. Finger tapping consisted of tapping one's fingers in sequence from thumb through to the little finger at a frequency of one tap per second. Foot tapping consisted of similarly tapping one's foot once per second in a left-to-right sequence on four small equally-spaced felt pads attached to the floor. Experimenters recorded participants' verbal responses, while response time was measured using a voice key trigger. Responses were also recorded, and the recordings were used to separately verify the responses and the response times of the participants. The task was programmed using PsychoPy 1.8 (Peirce, 2007) and presented on a 24″ monitor placed approximately 86 cm away from the participant.

The stimuli consisted of a list of preselected single-digit arithmetic problems. Problems did not include any ties (e.g.: 4 + 4) or include a 1 or a 0. Arithmetic problems were completed in blocks of 18 items, which were divided into sets of nine items, with each set of nine forming either a single- or dual-task block. Participants completed these blocks in pseudo-random order that was predetermined via a Latin square, and with the constraints that two adjacent items would not have the same operand in the same position as well as that participants not complete two blocks in a row with the same operation. There were also a total of 12 block-order conditions, which vary the order of operations (6 different orders, shown in Table 3.2), whether the single-task or dual-task occurs first, and whether they were in the finger-tapping or foot-tapping condition. The order of operations represented in Table 3.2 was repeated one more time. In total, participants each completed 18 blocks of 18 problems, for a total of 324 problems. Table 3.2 lists the problems that were used.

Table 3.1.

Arithmetic question list

Multiplication	Addition	Subtraction
4 x 2	4 + 2	4 - 2
4 x 3	4 + 3	4 - 3
5 x 2	5 + 2	5 - 2
5 x 4	5 + 4	5 - 4
6 x 2	6 + 2	6 - 2
6 x 3	6 + 3	6 - 3
6 x 4	6 + 4	6 - 4
6 x 5	6 + 5	6 - 5
7 x 3	7 + 3	7 - 3
7 x 4	7 + 4	7 - 4
7 x 5	7 + 5	7 - 5
8 x 2	8 + 2	8 - 2
8 x 3	8 + 3	8 - 3
8 x 6	8 + 6	8 - 6
9 x 2	9 + 2	9 - 2
9 x 5	9 + 5	9 - 5
9 x 6	9 + 6	9 - 6
9 x 7	9 + 7	9 - 7

Table 3.2.

Counter-balancing order of question types, with each cell representing 9 arithmetic problems

Order					
1	**2**	**3**	**4**	**5**	**6**
Dual-task Addition	Dual-task Subtraction	Dual-task Multiplication	Single-task Addition	Single-task Subtraction	Single-task Multiplication
Single-task Addition	Single-task Subtraction	Single-task Multiplication	Dual-task Addition	Dual-task Subtraction	Dual-task Multiplication
Dual-task Subtraction	Dual-task Multiplication	Dual-task Addition	Single-task Subtraction	Single-task Multiplication	Single-task Addition
Single-task Subtraction	Single-task Multiplication	Single-task Addition	Dual-task Subtraction	Dual-task Multiplication	Dual-task Addition
Dual-task Multiplication	Dual-task Addition	Dual-task Subtraction	Single-task Multiplication	Single-task Addition	Single-task Subtraction
Single-task Multiplication	Single-task Addition	Single-task Subtraction	Dual-task Multiplication	Dual-task Addition	Dual-task Subtraction
Dual-task Subtraction	Dual-task Multiplication	Dual-task Addition	Single-task Subtraction	Single-task Multiplication	Single-task Addition
Single-task Subtraction	Single-task Multiplication	Single-task Addition	Dual-task Subtraction	Dual-task Multiplication	Dual-task Addition
Dual-task Multiplication	Dual-task Addition	Dual-task Subtraction	Single-task Multiplication	Single-task Addition	Single-task Subtraction
Single-task Multiplication	Single-task Addition	Single-task Subtraction	Dual-task Multiplication	Dual-task Addition	Dual-task Subtraction
Dual-task Addition	Dual-task Subtraction	Dual-task Multiplication	Single-task Addition	Single-task Subtraction	Single-task Multiplication
Single-task Addition	Single-task Subtraction	Single-task Multiplication	Dual-task Addition	Dual-task Subtraction	Dual-task Multiplication
Dual-task Multiplication	Dual-task Addition	Dual-task Subtraction	Single-task Multiplication	Single-task Addition	Single-task Subtraction
Single-task Multiplication	Single-task Addition	Single-task Subtraction	Dual-task Multiplication	Dual-task Addition	Dual-task Subtraction
Dual-task Addition	Dual-task Subtraction	Dual-task Multiplication	Single-task Addition	Single-task Subtraction	Single-task Multiplication
Single-task Addition	Single-task Subtraction	Single-task Multiplication	Dual-task Addition	Dual-task Subtraction	Dual-task Multiplication
Dual-task Subtraction	Dual-task Multiplication	Dual-task Addition	Single-task Subtraction	Single-task Multiplication	Single-task Addition
Single-task	Single-task	Single-task	Dual-task	Dual-task	Dual-task

Subtraction	Multiplication	Addition	Subtraction	Multiplication	Addition

Participants were offered a pause after each set of nine problems with a chance to take a break before continuing. Dual- vs. single-task condition was indicated via a picture of a hand or foot, to be as clear as possible and avoid any potential translation issues. Each equation remained on the screen for 3000 ms for Chinese participants and either 3000 ms (Phase 1) or 3500 ms (Phase 2) for Canadians (see section below for discussion of Phase 1 and Phase 2). There was an inter-trial interval of 1000 ms, and a time limit was set for participants' responses to assure that responses were a result of recall strategies and not more idiosyncratic and exhaustive calculation strategies. The latter was important as there is evidence to suggest that brain processes related to math recall are more heavily implicated in the embodiment of number, and therefore, responses resulting from longer, more exhaustive, calculation strategies were not likely to be as informative (Delazer et al., 2003; Ischebeck et al., 2006).

Following the arithmetic computer test, participants were asked a final series of questions. This included handedness, date of completion of last course in mathematics, frequency of calculator use, and ordinal finger counting habits. Frequency of calculator use was assessed via a single verbal four-point Likert scale item, with '1' indicating that daily calculator use was rare, '2' indicating that daily calculator use was uncommon, '3' indicating that daily calculator use was frequent, or '4' indicating that a calculator was nearly always used. Finger counting habits were assessed via performing a spontaneous ordinal finger count. Participants were asked to count from one to ten on their fingers, and a researcher would record the starting hand.

Data collection phases.

Data for the Canadian participants were collected in two phases. Phase 1 occurred over the summer semester (28 participants), while Phase 2 occurred in the following Fall and Winter semester (38 participants) when students from the first-year Psychology courses were added for the first time to the subject pool. During phase one of data collection, there was a suggestion that Canadian participants were struggling with the allotted time of 3000 ms per trial, as five participants out of the first 28 participants achieved less than 75% accuracy, and two had achieved less than 66% accuracy. Given that the single weakest performing participant among the Chinese sample achieved an accuracy of 95% on this task, Canadian participants' allotted time per question was extended with the intention of reducing loss of data due to errors/non-responses. Therefore, the 38 Canadian participants in Phase 2 had an extra 500 ms to answer each question.

Before combining the data in Phase 1 with the data in Phase 2, we tested for any differences between these cohorts, and found that Canadian participants in Phase 2 (who received more time) correctly answered 8.14% more questions than in Phase 1. A Wilcoxon's rank-sum test confirms that this is difference is statistically significant, W_s= 649.5, $z = 3.747$, $p < .0005$, $\rho\ (64) = 0.465$. However, further analyses demonstrate that this performance difference was not due to the extra response time. Only 0.6% of correct responses among the Phase 2 Canadians actually occurred in the interval between 3000 and 3500 ms. Furthermore, mean correct response time performance for Phase 2 was actually non-significantly faster, M= 1200ms, than response time performance for Phase 1, M= 1257ms, despite differences in accuracy effectively resulting in Phase 1 participants' mean response times being drawn from an easier question set. While it is possible that this small time extension could have also put participants under less pressure, the original 3000 ms interval upper limit was already 7.0 standard deviations above the mean correct response time, and the longer interval of 3500 ms was 8.5 standard deviations above the mean correct response time, which suggests that the significant majority of participants' correct responses were not approaching that time limit to begin with, and therefore, this additional time was unnecessary. Many correct responses that neared this RT range represented the second or third attempts to verbally state an answer.

The higher accuracy rate in Phase 2 appears to be explained by differences in ability rather than a change in the procedure. Phase 2 participants were collected in a different semester, where first-year psychology courses were added to the subject pool for the first time. These subjects had gone fewer days since last enrolled in a math class, $Mdn = 0$, than their peers tested in Phase 1, $Mdn = 91$, $W_s = 1040$, $z = 3.072$, $p = .002$, ρ (64) = 0.38. Phase 2 participants also indicated significantly less everyday calculator use, $Mdn = 2$ (occasionally), than their peers tested in the first phase, $Mdn = 3$ (frequently), $W_s = 1073$, $z = 2.763$, $p = .006$, ρ (64) = 0.34, which is also consistent with the introductory math course having discouraged calculator use. Furthermore, there was a significant negative relationship between self-reported calculator use and mean accuracy, Spearman's ρ (64) = − 0.34, $p = .005$, although the same was not true for mean accuracy and days since last enrolled in a math class, Spearman's ρ (64) = − 0.10, $p = .415$.

Because any differences between these cohorts were not due to the extended maximum response time, Phase 1 and Phase 2 participants were combined for all subsequent analyses, and only correct median response time scores faster than 3000 ms were considered. Answers slower than this were coded as a non-response. Furthermore, participants were also equally distributed across all between-subject conditions, and therefore, this cohort effect was unlikely to confound later analyses. As a final check, all subsequent analyses were repeated using all available response time data, and the pattern of results is identical to that reported below.

Results

Accuracy Rates.

Figures 3.1 and 3.2 display Canadian and Chinese participants' mean accuracy distributions. There was an observed mean accuracy across conditions of 90.2% (*SD*= 9.66%) for Canadian participants, and 98.4% (*SD*= 1.37%) for Chinese participants. This difference was examined using a Wilcoxon's rank-sum test, and Canadian and Chinese participants did still differ in mean accuracy, even when excluding the seven worst Canadian participants, $W_s = 2825$, $z = 6.667$, $p < .0005$, $\rho\ (124) = 0.597$. Results were similar for response time performance, with a response time advantage for Chinese participants, M= 1018 ms, SD= 14.1 ms, over Canadian participants, M= 1221ms, SD= 25.5 ms, $t\ (103.110) = 5.610$, $p < .0005$.

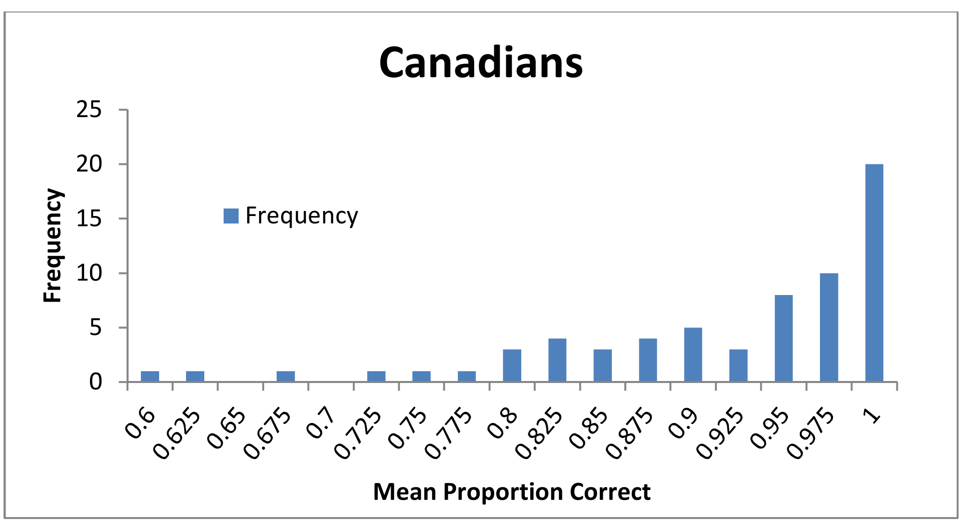

Figure 3.1. Frequency histogram displaying the distribution of Canadians' mean accuracy across conditions.

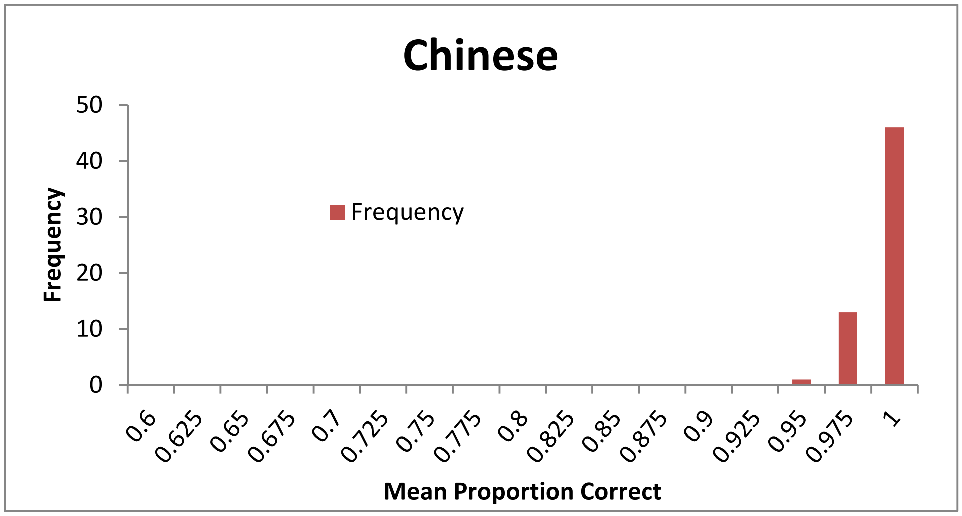

Figure 3.2. Frequency histogram displaying the distribution of Chinese participants' mean accuracy across conditions.

Finally, mean accuracy and response time performance were examined using a Spearman's rank correlation for the presence of a speed–accuracy trade-off. The presence of a speed–accuracy trade-off can be indicative that participants were not answering questions to the best of their ability, as they were not slowing down for more difficult questions. There was no evidence of a speed–accuracy trade-off, as both Canadian, ρ (64) = .657, $p < .0005$, and Chinese participants, ρ (58) = 0.460, $p = .005$, exhibited the opposite pattern of robust positive correlations between errors and response time performance. That is, participants who answered more slowly were also typically more error prone. Results were similar when examined at the level of individual arithmetic questions, where items with the slower response time performance also had lower accuracy among Canadians, ρ (52) = 0.760, $p < .0005$, as well as among Chinese participants, ρ (52) = 0.548, $p < .0005$. This dependency between accuracy and response time performance has the potential to result in under-estimating correct response time performance in conditions where participants may have made substantial errors. Only correct response time scores are typically used in such analyses, and the slower and more difficult items would be answered incorrectly more often. Therefore, when calculating a participant's correct median response time performance, a participant who answered only the least difficult questions correctly would be scored via this easier arithmetic question list, whereas a more accurate participant would be scored by their performance with both the more difficult and the less difficult arithmetic questions. As a way of accounting for this complicated speed/accuracy dependency, we chose to use inverse efficiency scores (Townsend, & Ashby, 1983). Inverse efficiency scores are calculated by dividing correct response time by percentage correct and, as such, take both the speed and the accuracy into account in a single measure. Lower inverse efficiency scores indicate better performance.

Reported finger counting habits.

A total of 38 Canadians reported that they were typically right-starters, while 28 reported that they were left starters. Contrary to expectations for Chinese participants, based on Morrissey et al. (2016), there was actually a substantial number of self-reported two-hand ordinal right-starters, N = 16, traditional one-hand right-starters, N = 19, two-hand left starters, N = 20, one-hand left starters, N = 3, as well as a single right-starter who used both one-hand and two-hand finger counting styles. The proportion of Chinese participants counting on two hands has also been typically quite low, at less than 10% of the tested population, which diverges considerably from the 63% proportion of reported two-hand counting styles among Chinese participants in the current study. There were also no right-handed left starters in prior investigations of this population. However, as mentioned above, prior investigations had all used a cardinal finger counting inventory instead of the ordinal inventory used in this study. Therefore, while outside the scope of the current paper, it does appear that ordinal finger counting habits likely disagree with cardinal finger counting habits for this population to a much greater extent than is typically seen among Canadians, and this would be an interesting area for further investigation. For the duration of data analysis, Chinese finger counting habits are coded as being left vs. right-starters to be consistent with analyses for Canadians.

Primary analyses.

Inverse efficiency scores were first obtained by dividing each participant's correct median response time in each condition by their mean accuracy percentage for that condition. The resulting variable is a composite of both response time and accuracy performance. These scores were analysed for both Canadian and Chinese participants using a 3 (operation: addition, subtraction, and multiplication) × 2 (task: single vs. dual) × 2 (condition: hand vs. foot tapping) × 2 (starting hand: right vs. left) × 2 country (China vs. Canada) mixed within–between ANOVA. All within-subject degrees of freedom and significance values are reported using the Greenhouse–Geisser correction; see Table 3 for the full model.

Table 3.3.

Mixed between-within analysis of variance results: Inverse efficiency scores

	Df	*F*	*p*	η_p^2
Operation	1.369, 161.509	37.980	<.0005*	.243
Condition	1, 118	.010	.919	<.0005
Starting hand	1, 118	7.291	.008*	.058
Country	1,118	32.034	<.0005*	.214
Condition x Starting hand	1, 118	.060	.808	.001
Operation x Condition	1.369, 161.509	.093	.837	.001
Operation x Country	1.369, 161.509	17.411	<.0005*	.129
Operation x Starting hand	1.369, 161.509	4.112	.032*	.034
Operation x Condition x Country	1.369, 161.509	.125	.802	.001
Country x Condition	1, 118	.373	.542	.003

Country x Starting hand	1, 118	4.608	.034*	.038
Country x Condition x Starting hand	1, 118	.383	.537	.003
Operation x Condition x Starting hand	1.369, 161.509	.486	.545	.004
Operation x Country x Starting hand	1.369, 161.509	4.361	.027*	.036
Operation x Condition x Country x Starting hand	1.369, 161.509	.270	.678	.002
Task	1, 118	43.667	<.0005*	.270
Task x Condition	1, 118	.009	.925	<.0005
Task x Country	1, 118	2.551	.113	.021
Task x Starting hand	1, 118	1.741	.190	.015
Task x Condition x Country	1, 118	.761	.385	.006
Task x Condition x Starting hand	1, 118	.122	.727	.001
Task x Country x Starting hand	1, 118	2.399	.124	.020
Task x Condition x Country x Starting hand	1, 118	.032	.859	<.0005
Task x Operation	1.559, 184.014	.398	.621	.003
Task x Operation x Condition	1.559, 184.014	.047	.920	<.0005
Task x Operation x Country	1.559, 184.014	.411	.612	.003
Task x Operation x Starting hand	1.559, 184.014	.520	.550	.004
Task x Operation x Condition x Country	1.559, 184.014	.208	.757	.002
Task x Operation x Condition x Starting hand	1.559, 184.014	1.171	.303	.010
Task x Operation x Condition x Country x Starting hand	1.559, 184.014	.311	.678	.003

Note. * indicates a result significant at the $p < .05$ level.

Among participants, there was a significant effect of arithmetic operation. Bonferroni-corrected pairwise comparisons indicate that subtraction questions, *M*= 1087, *SD* = 250, were performed better than either addition questions, *M*= 1232, *SD* = 333, or multiplication questions, *M*= 1346, *SD* = 414, and addition questions were also performed better than multiplication questions. The latter was not observed to be moderated by participant country. There was also a main effect of single-task, *M*= 1153, *SD* = 294, vs. dual-task condition, *M*= 1291, *SD* = 371, with dual-task performance suffering, relative to single-task performance, which was expected. However, single/dual-task condition did not interact with any other factors, as described below, which was inconsistent with previous results. Chinese participants, *M*= 1034, *SD* = 163, significantly outperformed Canadians in this task, *M*= 1410, *SD* = 502, which was also expected. There was also a main effect of starting hand, $d = 0.38$. Contrary to predictions, left starters, $M = 1132$, $SD = 228$, actually outperformed right-starters, $M = 1311$, $SD = 437$. This appeared to be further moderated by both operation, as well as through an operation by country interaction, as shown in figures 3 and 4. A series of Welch's independent *t* tests using the Bonferroni correction only found a statistically significant difference between Canadian left starters, $M = 1374$, $SD = 329$, and right-starters, $M = 1887$, $SD = 964$, when examining multiplication questions, $d = 0.841$; however, Canadian left starters, $M = 1261$, $SD = 342$, and right-starters, $M = 1560$, $SD = 665$, were marginally different for addition questions, $p = .072$, $d = 0.597$, and left starters had a superior mean inverse efficiency performance score relative to right-starters for every operation among both Canadian and Chinese participants. There was no evidence here that tapping one's fingers had a different impact on performance than tapping one's foot, and therefore, Michaux et al. (2013) cannot be said to have been replicated here.

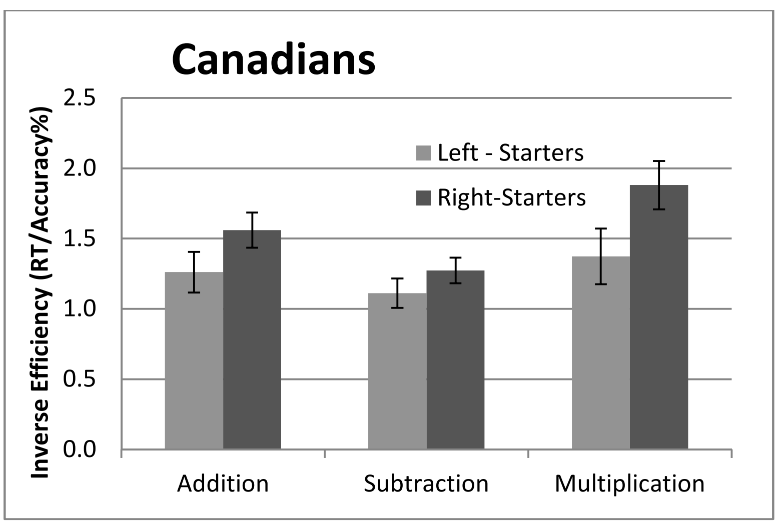

Figure 3.3. Mean inverse efficiency scores for addition, subtraction, and multiplication questions for Canadian left- and right-starters. Confidence intervals indicate 95% confidence of the mean.

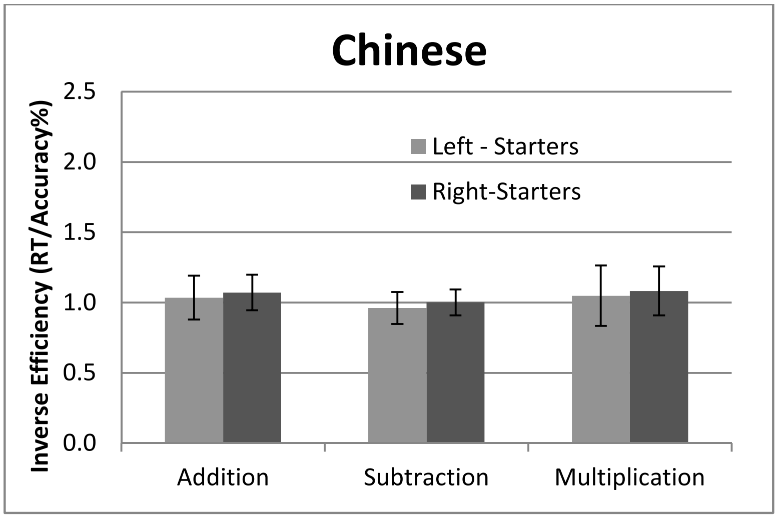

Figure 3.4. Mean inverse efficiency scores for addition, subtraction, and multiplication questions for Chinese left- and right-starters. Confidence intervals indicate 95% confidence of the mean.

Discussion

The current study used two previously documented cases of embodied numerical cognition, as well as a cross-cultural comparison, to further examine the link between numeracy and finger representations. This was accomplished using a simultaneous cross-cultural replication and conceptual replication of Michaux et al. (2013) and Newman and Soylu (2013), respectively. One primary research question was whether the calculation difference between left- and right-starters found by Newman and Soylu (2013) would be evident in the calculation task that demonstrated finger-tapping interference in Michaux et al. (2013). Another research question was whether evidence of embodiment, as illustrated by this finger-tapping interference, would be different in Canadian and Chinese participants, or if numbers were simply not embodied among Chinese participants. Although some results in this study offer evidence for the embodiment of numerical cognition (e.g., the differences between left- and right-starters), the theoretical implications of these results are not straightforward.

First, one of more problematic aspects of these results was the failure to replicate, in our Canadian sample, the specific finger-tapping interference observed in Michaux et al. (2013). It is difficult to evaluate whether the left vs. right-starter difference moderates the finger-tapping interference embodiment effect if the finger-tapping interference effect does not actually exist. It is possible that this failure to replicate this effect is due a difference in the samples (i.e., Canadian vs. Belgian), but there is little theoretical reason to expect that Canadians and Belgians would differ in their embodiment on this task. Given the larger sample size of the present study, another plausible explanation is that this paradigm is not a valid measurement of embodied numerical effects to begin with. In other words, the results of this study suggest that there may not be a selective interference of finger-tapping on single-digit calculation tasks.

Despite the inability to replicate Michaux et al. (2013), other results in this study offer some insight into the embodiment of calculation. Canadian left starters were able to produce more correct answers for all three operation types than Canadian right-starters. Interestingly, the right/left starter performance difference among Canadians was the quite different from what Newman and Soylu (2013) reported with an American sample. Newman and Soylu (2013) found a response time difference but not an error rate difference for left- and right-starters, and the difference that they did observe favoured right-starters over left starters. These different results could be due to the difference in the calculation task. Newman and Soylu (2013) utilized a two-digit addition task to ensure that participants engaged in calculation and not simply retrieval. These researchers also had participants pressing different buttons to indicate a response among different potential solutions that had already been provided. In contrast, the current investigation utilized single-digit problems and a restricted trial interval to encourage retrieval strategies, with answers indicated verbally. Different neural networks may underlay the cognitive demands of these two paradigms (Delazer et al., 2003; Ischebeck et al., 2006). Alternatively, given the small effect sizes observed in Newman and Soylu (2013), it is also possible that left- and right-starter differences are simply much smaller or non-existent when participants engage in thoughtful calculation. If so, the differences between left- and right-starters may be different in nature and much more evident in a relatively faster arithmetic recall task. One other possible reason for the differences in performance between Canadian left- and right-starters is that the procedure had participants tapping either their right hand or their right foot during the dual-task condition. Therefore, it is possible that right-starters may have performed better if they had been instead asked to tap their left hand or left foot. Future research should examine this possibility.

Chinese participants, however, did not demonstrate a difference between left- and right-starters on this task. There are two main implications of this result. The first is that it offers some tentative support for the functional hypothesis. According to this hypothesis, the lack of starting hand difference in Chinese adults, while there was one in Canadian adults, reflects the different ways that these cultures use their fingers to count numbers. This conclusion would have been stronger if the Canadians also demonstrated a specific finger-tapping interference effect, and the Chinese had not. As it is, this lack of starting hand difference may be explained by the increased fluency of the Chinese participants. Whatever advantage left starters have for accuracy on these problems may disappear with Chinese participants, because there is so little variance in their performance. The superior performance seen among Chinese participants, relative to Canadians, is well documented

(Imbo, & LeFevre, 2009). As such, it is difficult to say if the lack of a starting hand difference is reflective of finger counting habit differences.

Nevertheless, it is also important to note that Chinese participants reported ordinal finger counting habits diverged almost categorically from prior studies that reported on only cardinal finger counting habits. Before this study, left starters had not been identified in right-handed Chinese adults, whereas nearly half of the Chinese adults in this study were classified as left starters. This difference highlights the importance of investigating the differences between cardinal and ordinal finger counting habits, as understanding the difference between what these inventories signify will help to clarify why starting hand is related to mathematical cognition.

Finally, the present study, unlike Michaux et al. (2013), found differences between mathematical operations. Canadians performed better on subtraction questions, relative to other questions. In fact only two participants had less than 87% correct responses on subtraction questions. Michaux et al. (2013), in contrast, reported no moderation of errors across conditions, nor did arithmetic operation moderate response time performance. This does not appear to be a consequence of low arithmetic ability among Canadians, as Chinese participants greatly outperformed Canadians, while responding slightly slower, but more accurately, than participants in Michaux et al. (2013), and yet Chinese students also performed best on subtraction questions and produced the most errors for multiplication questions, identical to Canadians. Therefore, despite a considerable cross-national gap in ability, the superiority of subtraction question performance, and the relatively greater difficulty with multiplication questions, was actually cross-culturally consistent in the current investigation, despite being inconsistent with Michaux et al. (2013). These results are probably due to the fact that the subtraction items used by Michaux, and, therefore, in this study as well, were in fact easier than the problems for the other operations because of the problem size effect (LeFevre, Sadesky, & Bisanz, 1996). Subtraction problems are often conceptualized as a reversed form of addition (Baroody, 1984; Kamii, Lewis, & Kirkland, 2001). For that reason, arithmetic researchers will usually not match addition and subtraction problems on the numbers in the problems themselves, but rather researchers will create complimentary problems (Campbell, & Xue, 2001). For example, $4 + 6 = 10$ would be complimentary with 10–4 = 6, and not $6 - 4 = 2$. Therefore, because of how Michaux et al. (2013) matched problems, subtraction problems were systematically smaller problems than the addition problems, and thus would be expected to elicit faster responses. The fact that this was not observed previously in Michaux et al.'s (2013) investigation was likely a function of a lack of statistical power.

Conclusions.

The current study combined a replication, a conceptual replication, and a cross-cultural comparison to examine a novel hypothesis and garner a richer set of information than any one of these types of investigations could provide on their own. However, contrary to predictions, Michaux et al. (2013) were not replicated here, suggesting that the original result may have been spurious. However, the conceptual replication of Newman and Soylu (2013) was more complicated, as Canadian left starters outperformed right-starters for every operation type, which may be further evidence of individual differences in the lateralization of arithmetic processes. This is the opposite of what Newman and Soylu (2013) reported, as they observed a right-starter advantage. However, the latter may be moderated by Newman and Soylu (2013) having used an addition calculation paradigm, while the current test encouraged arithmetic recall. Overall, this investigation suggests that embodied effects in the published literature are in need of both independent replication as well as investigation of individual differences. However, despite these suggestive findings, many questions remain, and more research is needed to better understand how finger counting habits influence mathematical cognition.

Data availability.

The data sets generated during and/or analysed during the current study are available in the Open Science Foundation repository, https://osf.io/p2zr5/.

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Chapter Five: Study Four- A More Precise Left Hemisphere Representation of Numeric Magnitude: Combining the EZ Diffusion Model and the Visual Half-Field Technique

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Abstract

In the math cognition literature, finger counting habits have been shown to be an additional symbolic representational format for numeric information. They persist from childhood into adulthood and influence adults' numeric performance in specific and predictable ways. However, finger counting habits are not simply static symbols, but instead, are gestures that require the use of both hands, and with which Canadian adults report a favoured hand to count small quantities. This observation raises the question as to whether the Canadian finger counting system's use of two hands to represent quantities from 6 through 10 may interact with a more established finding that symbolic number magnitudes are preferentially evaluated in the left hemisphere. In the current study, a total of 69 Canadian participants evaluated the magnitude of binary number pairs in a within-subject divided visual field test paradigm. Participants' response time performance was decomposed, using the EZ-diffusion model, into nondecision time, response conservativeness, and quality of information. Numbers in the right visual field were identified more quickly, despite also being responded to more conservatively, and this result was stronger for number pairs typically counted on both hands. This suggests that Arabic digits are not only implicitly associated with counting habits, but that this is related to finger counting gestures status as symbolic representations of quantity.

Introduction

One of the more important findings of the embodied literature is that mental representations of number magnitude are not entirely abstract, but instead is influenced by bodily experiences, such as finger counting habits (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010). The cognitive implications of finger counting habits for numerical cognition have become a growing area of research in the field of embodied cognition. The most commonly cited model for how numbers are represented in the brain is the triple code model, which posits that number magnitude information may recruit verbal (supported by the left angular gyrus in the parietal lobe), visual (supported by bilateral posterior superior parietal lobules), and more general format independent analogue magnitude representations (supported by bilateral intraparietal sulci) in the brain (Dehaene, Piazza, Pinel, & Cohen, 2003). Some researchers have suggested that finger counting habits are activated as part of the non-verbal analogue magnitude system when mentally representing numeric magnitudes (Moeller, Fischer, Link, Wasner, Huber, Cress, & Nuerk, 2012). However, the left angular gyrus has been repeatedly implicated in both finger gnosis (i.e., the ability to distinguish fingers by tactile stimulation) and numeracy (Rusconi, Walsh & Butterworth, 2005; Roux, Boetto, Sacko, Chollet, & Trémoulet, 2003; Mayer et al., 1999), and impairment of the left angular gyrus has been offered as a possible explanation for the so-called Gerstmann constellation of dyscalculia, left-right confusion, and poor finger gnosis, which is associated with damage in the left parietal lobe (Gerstmann, 1940). Other investigations have implicated the left angular gyrus in left-right discrimination (Hirnstein, Bayer, Ellison, & Hausmann, 2011), and verbal arithmetic fact retrieval (Delazer et al., 2003; Ischebeck et al., 2006).

Rusconi et al. (2005) has observed repetitive transcranial magnetic stimulation (rTMS) of only the left angular gyrus to be associated with impaired finger gnosis and impaired performance on a magnitude comparison task, which implicates this brain structure as the functional intersection of finger movements and number processing. In contrast, Cappelletti, Barth, Fregni, Spelke, and Pascual-Leone (2007) showed that applying rTMS to the intraparietal sulcus reduces numerical performance, though not finger gnosia. Adriano, Diez, and Fernandez (2014) have also used a divided visual field paradigm to document that participants show superior performance in identifying Arabic digits when they are presented to the left hemisphere/right visual field, especially when asked to covertly hold their right hand in the form of a canonical finger counting gesture consistent with the target digit. Adriano et al. (2014) did not find a similar advantage when the finger counting gesture did not match the target digit, or when the number gesture was a non-canonical one that participants would not typically use spontaneously. Adriano et al. (2014) described their findings as being evidence of a left hemisphere advantage in number processing, as well evidence that there is a multimodal interaction between written and finger counting representations of quantity; such that responses are advantaged when these two types of symbols are compatible and feeding into the same hemisphere.

This general finding of hemispheric specialization for numeric processing may help to explain some of the findings in embodied cognition. For example, Morrissey, Liu, Kang, Hallett, and Wang (2016) have found what has been called finger counting representation effects – that those who start counting on their right hand, compared to those who start counting on their left hand, differ in how fast they can make magnitude judgements about numbers that are typically counted on two hands, but only in cultures where two-handed finger counting systems are used.

As hands also have hemispheric specialization, it is possible that hemispheric specialization of numeric processing may affect numeric processing tied to finger representations. The objective of this investigation is to clarify the neural mechanisms behind these finger counting representation effects, specifically by using a divided field study.

The Divided Visual Field Test and Numerical Processing.

The divided visual field test paradigm has previously been used in order to evaluate whether there is hemispheric asymmetry in number magnitude representations. This paradigm involves presenting stimuli on particular sides of a display, while participants are looking straight ahead, but doing so quickly enough that the information should only be visible to one visual field (Bourne, 2006). This forces the stimuli to be initially processed in one hemisphere, so response accuracy and response time differences between the two visual fields reflect differences in initial hemispheric processing.

A number of investigations using the divided visual field test paradigm have shown that there are interhemispheric differences evident in number comparison tasks, with differences generally favouring the left hemisphere in processing numeric magnitude (Delvenne et al., 2011; Lavidor et al., 2004; Notebaert & Reynvoet, 2009; Peereman & Holender, 1984; Ratinckx et al., 2001; Reynvoet et al., 2008). Researchers using the divided visual field test have found that, while symbolic digit-number magnitude is represented bilaterally, there appears to be a left hemisphere response time advantage (Ratinckx, Brysbaert, & Reynvoet, 2001). Some researchers have found that number magnitude representations for single-digit numbers are bilaterally equivalent, while two-digit numbers are processed less precisely in the right hemisphere relative to the left hemisphere (Notebaert & Reynvoet, 2009). Others have suggested faster magnitude processing in the left hemisphere, but that there is an overall response time advantage when stimuli were available to both hemispheres (Delvenne, Castronovo, Demeyere, Humphreys, 2011; Ratinckx, Nuerk, van Dijck, & Willmes, 2006).

A study by Noebaert and Reynvoet (2009) is one of the most recent, and largest, visual half field studies to look at the lateralization of number magnitude representations, with a sample size of 32 and 25 subjects in each of their experiments. They inferred greater precision in the left hemisphere through a numeric priming paradigm, as a function of the degree of implied overlap between mental representations of symbolic number digits. Participants were presented with Arabic-digit primes prior to a target. Based on existing theory, primes that were numerically closer to the target should share overlapping representations, and this would facilitate faster performance. This faster performance would be in proportion to the overlap in representation, so it would be linearly related with numeric distance, and the resulting linear function was referred to as a priming curve. Noebaert and Reynvoet (2009) found that the participants' priming curve was marginally significantly flattened for two-digit numbers presented in the right visual field, relative to the left, which was taken to suggest that magnitude representations were more precise as they appear to overlap less in the left hemisphere. Nevertheless, although there was a trend in this direction, they did not find this effect for single-digit numbers. Noebaert and Reynvoet (2009) proposed that high familiarity with single-digit numbers explained this lack of difference in hemispheric processing. However, it is also possible that certain single-digit numbers actually do have more precise representations in the left hemisphere/right visual field, and this effect is masked by the inclusion of the other single-digit numbers that do not show this difference.

A recent meta-analytic review of brain imaging studies has concluded that symbolic number digit magnitudes are represented by both a format-dependent system in the left hemisphere, as well as by a bilateral, more generalized, magnitude processing system

(Sokolowski, Fias, Ononye, & Ansari, 2017). Another similar review suggests that symbolic number sets are lateralized more in the left parietal lobe, while non-symbolic magnitude sets were more lateralized in the right superior parietal lobule, with brain regions in both the frontal and parietal lobes involved in both symbolic and non-symbolic magnitude processing (Sokolowski, Fias, Mousa, & Ansari, 2017). This suggests that the right and left hemispheres may differ in how they decode the symbolic aspects of Arabic digits. It is likely then that differences between right and left hemisphere processing of Arabic digits across various paradigms are characterized by subtler processing differences than simply being more or less specialized to process numeric magnitude.

Finger Counting Representation Effects.

Using a magnitude comparison task, both Domahs, Moeller, Huber, Willmes, and Nuerk (2010) and Morrissey, Liu, Kang, Hallett, and Wang (2016) have found that adults will respond more slowly when at least one of a pair of number digits being compared is typically counted on two hands (e.g., 7 vs. 9). These representation effects were so named as they were hypothesized to be a specific effect of internal finger counting representations on symbolic magnitude representations. This is similar to Zhang and Norman's (1995) representational system, which posits the structural features of a numeration system have cognitive consequences, such as when a carry or change in power dimension may occur or when counting from one number to another would necessitate representing a second hand. This contention is supported by cross-cultural data, where users of traditional Chinese finger counting, who count exclusively on one hand, do not demonstrate a relative increase in response time for digits between six and nine (Domahs et al, 2010; Morrissey et al., 2016).

Finger counting representation effects appear more pronounced among Canadian right-handed participants who would use their left hand to signal small quantities (left-starters), relative to their right-starter peers (Morrissey et al., 2016). Counting on a left hand versus a right hand suggests no obvious difference in the complexity of internal representations of finger-counts in the way that is demonstrated in cross-cultural comparisons that may employ different numbers of full hands or even hand motion to communicate numeric power or quantity. However, counting on a left hand versus a right hand does imply a difference in which hemisphere of the brain is involved in starting a finger count, with a left-hand count starting in the right hemisphere (Tschentscher et al., 2012).

EZ-diffusion model for two-choice response-time.

Although past investigations utilizing a divided visual field have focused mostly on response time, it is possible to use modelling to extract variables that better reflect the underlying cognitive processes at hand. When somebody reacts more slowly to a stimulus in the left visual field compared to one in the right visual field, this increased response time may be due to longer encoding time, longer decision time, the quality of stimuli, or other factors. Several diffusion models for two-choice response time tasks have been developed in order to model datasets where speed-accuracy trade-offs exist, or where more qualitative information is desired beyond just response time performance (Ratcliff, 2002; Wagenmakers, van der Maas, & Grasman, 2007). Diffusion models attempt to estimate the unobserved variables that actually underlay participants' performance, using a combination of mean response time, accuracy, as well as response time variance. When a speed-accuracy trade-off is present, there is an underlying dependence between errors and response time performance, with some participants answering more cautiously when a question is more difficult, while other participants instead make a greater number of errors while maintaining their response speed. The same is also be true across conditions, as some conditions may elicit greater response caution or may provide participants with a lower quality of information by which to make a decision. As a result, any separate analyses of either response time or accuracy-performance may miss interactions between accuracy and response time, and draw inappropriate conclusions about participants decision making processes.

The EZ-diffusion model (Wagenmakers et al., 2007) is a simplified version of these models, that utilizes three parameters instead of the seven (see Ratcliff, 2002), and which can achieve very similar results to other diffusion models without prohibitively complicated model-fitting procedures. The unobserved variables in the EZ-diffusion model include quality of information (drift rate), response conservativeness (boundary separation), and nondecision time (encoding/response production). A more detailed mathematical breakdown of these parameters is available in Wagenmakers et al. (2007); however, they can be described conceptually for current purposes. Drift rate can be understood as the rate at which information accumulates to reach a decision. It is also called quality of information, implying that higher quality information will lead to quicker accumulation of information towards the decision making point. It is calculated through a transformed ratio between accuracy and variability in response times, so higher drift rates are indicative of fast responses and fewer errors, while lower drift rates are indicative of slower responses and higher errors-rates. Boundary separation can be understood as the threshold of information accumulation at which a decision is made. It is calculated through a transformed ratio between accuracy and drift rate, which works out to be a product of transformed accuracy and transformed RT variability. Higher values of boundary separation indicate more accurate responding at the cost of slower response time, which is another way of characterizing the speed-accuracy trade-off. To better understand drift rate and boundary separation, consider one item with a high error rate and a relatively small response time standard deviation and another item with the same high error rate and a larger standard deviation. These two items probably involve different cognitive processes, as the former suggests more impulsive responding, while the latter should indicate greater difficulty with making a decision. Finally, nondecision time can be understood as response time minus decision making time, where decision making time can be modeled from drift rate and boundary separation. As such, nondecision time consists of time taken to encode a stimulus and time taken to physically enact a response. It is also worth noting that only nondecision time actually utilizes mean response time in its calculation.

The Current Study.

The current study employed a larger than typical sample size for this literature and a binary magnitude comparison test adapted from Morrissey et al. (2016) in order to be used within a divided visual field paradigm. Analyses were also conducted using an EZ diffusion model (Wagenmakers et al., 2007), which should be helpful in characterizing performance differences across particular number pairs that are known to differ considerably in both response time and accuracy performance (Morrissey et al., 2016). This test examined whether Arabic numerals are advantaged by initial right-field/left hemisphere presentation. Given that finger counting effects are likely caused by additional representational demands of finger counting gestures, and finger counting gestures have been experimentally demonstrated to be encoded symbolically (Di Luca, Lefèvre, & Pesenti, 2010), it was hypothesized that numbers typically counted on two hands would exhibit greater hemispheric asymmetry in participants' response time performance, as demonstrated through a relatively greater right visual field advantage.

Participants carried out simple binary magnitude comparisons on a subset of six of the number pairs from Morrissey et al. (2016), including 3 vs. 5, 4 vs. 6, 5 vs. 7, 6 vs. 8, 7 vs. 9, and 8 vs. 10. These number pairs were chosen as the single-digit number pairs typically counted on two hands were where past cross-national and individual differences in performance have been observed (Domahs et al. 2010; 2012; Morrissey et al., 2016). However, unlike previous investigations that presented number pairs to participants to both visual fields simultaneously, number pairs in the current investigation were presented in a stacked format with both numbers either appearing in the left or right visual field in order to assess any resulting impacts on participants' performance. The use of stacked number pairs in this divided visual field test is similar to that of Peereman and Holender (1984); however, neither that task, nor any other study utilizing simple magnitude comparisons, were known at the time of manuscript preparation to have included direct fixation control as part of the experimental design. Failing to include direct fixation control is known to introduce a potential for bias in measurement (Bourne, 2006), which is particularly relevant in tasks involving magnitude comparisons of Arabic digits, which are already shown to have left/right associations as a function of the Spatial Numerical Association of Response Codes (SNARC) that could lead to left/right anticipations of number digits (Dehaene, Bossini, & Giraux, 1993). Therefore, in addition to addressing a novel question regarding differences between number stimuli, the current study is also a more robust test of the lateralization of number magnitude than otherwise currently available.

A relatively stronger right visual field advantage in comparing numbers both typically counted on two hands would be consistent with the hypothesis that left-starters show an increased impact of finger counting representations for comparisons of 6 vs. 8 and 7 vs. 9 because these employ symbolic representations of both hands, with the associated finger-count starting with the right hemisphere (Morrissey et al., 2016). If the left hemisphere and left angular gyrus are specialized for embodied and symbolic number magnitude representation, then greater involvement of the right hemisphere, such as through motor simulation of numbers typically counted on both hands, should be associated with slower responses. Therefore, it was hypothesized that there would be a right-field advantage for number magnitude comparison, and that this advantage would be relatively larger for comparisons of 6 vs. 8 and 7 vs. 9.

As this study employed an EZ diffusion model to analyze the results, we also have hypotheses about the nature of the right-field advantage. As explained earlier, the EZ diffusion model separates out decision time from nondecision time, which is defined as time for encoding and physical responding. In this study, the response hand is equally likely within each visual field and so any differences in nondecision time should reflect differences in encoding rather than response production. We hypothesize that any hemispheric differences in comparisons involving numbers represented by two hands will be differences in encoding internal representations of single digit numbers, and not in the decision making process used once encoding is complete. Therefore, any right-field/left hemisphere advantage be evident primarily in nondecision time, and not in quality of information or response conservativeness.

Method

Participants.

A total of 69 English-speaking Canadians participated in this study, with a mean age of 20.38 years (*SD* = 3.32), with 63 remaining after exclusions discussed below. There were three participants who spoke a different first language, or who were from a country other than Canada, that were excluded prior to analyses to avoid any potential cross-cultural differences that might increase variability in responding. Therefore, this study had the statistical power to reliably detect within-subject effects as small as *d* = .34, 80% of the time. The largest sample size previously available for a similar study included 36 participants (Notebaert & Reynvoet, 2009), with many investigations having as few as 10 participants per experiment (e.g., Cohen, 1975).

Initial exploration of the available data indicated only four participants reported that they were more left-hand dominant than right-hand dominant. It is typical that studies using this paradigm exclude left-handed participants. Also, while not statistically significant, there was a trend observed between degree of handedness and visual field dominance, suggesting that degree of left-handedness was associated with a trend towards a left-visual field advantage, r (65) = .207, p = .093. Therefore, left-handed participants were excluded from the main set of analyses, consistent with other studies, as the current dataset lacks the statistical power to examine this adequately as a potential moderator. Excluding these participants reduced the association between handedness and visual field dominance to zero, r (61) = .002, p = .987.

Apparatus and Stimuli.

Number pairs ranged from 3 to 10, and were presented in stacked pairs separated by a numerical distance of exactly two. Therefore, the number pairs were 3 vs. 5, 4 vs. 6, 5 vs. 7, 6 vs. 8, 7 vs. 9, and 8 vs. 10. Prior to each experimental block, participants had a practice block in which they could attempt four trials, and receive accuracy feedback. Previous experience with this paradigm suggests that these practice trials often help participants overcome misunderstandings of the experimental procedure before attempting the experimental trials. Practice trials were not included in data analysis. There were four experimental blocks. Each block included trials in which either the left hand was the response hand and trials in which the right-hand was the response hand, which were further subdivided as to whether participants were instructed to choose either the larger or the smaller digit of a number pair. The six number pairs (from 3 vs. 5 to 8 vs. 10) were repeated four times per response condition, which included left-field vs. right-field, left-hand response vs. right-hand response, identifying a larger number versus identifying a smaller number, and target number on top vs. target number on bottom. This resulted in a total of 2x2x2x2 conditions with 6x4 items per condition = 384 total experimental trials, totaling 400 when including the 16 practice trials. In order to eliminate response compatibility effects or SNARC effects, participants' response times for each response stimuli and condition were collapsed across whether a larger number digit in a pair appeared on the top or the bottom (i.e., $\frac{6}{8}$ vs. $\frac{8}{6}$), as well as whether participants were instructed to choose the larger or the smaller number, yielding a total of 24 unique mean response times across six number pairs, per participant. These collapsed scores only included response times from correctly answered items. See Figure 4.1 for an example slide series.

Handedness Inventory.

Handedness is related to an increased likelihood of anomalous functional lateralization of functions such as language, and the divided visual field test is typically administered only to participants that are strongly right-handed (Bourne, 2006). This handedness inventory was adapted by Dorthe , Blumenthal, Jason, and Lantz (1995) from the Edinburgh handedness inventory (Oldfield, 1971), and comprises 15 items describing various behaviours with 7-point Likert-scale choice options as to which hand a participant would typically use to complete that action. Choices range from -3 (always left) to +3 (always right). The reason for not employing the Edinburgh handedness inventory itself is because that is better at identifying extreme degrees of handedness, rather than gradations (Bourne, 2006). This inventory is available as Appendix A.

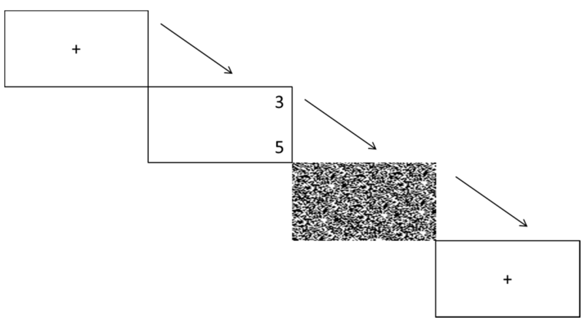
Finger counting Inventories.

This investigation included a cardinal finger counting inventory and an ordinal finger counting inventory. Cardinal finger counting habits –also described as Finger-montring gestures– include finger numeral configurations which may be used to represent an individual number symbolically, such as when showing a number to another person. Ordinal finger counting habits -–also described as spontaneous finger counting habits– refer to the order in which fingers would be used to count privately. While these gestures are related, they only indicate the same starting hand 62% of the time (Wasner et al., 2015). The ordinal inventory consisted of asking participants to count from one to ten on their fingers, and then recording the starting hand, as well as the starting finger of each hand. The cardinal finger counting inventory requires that participants respond to individual spoken number digits with the finger configuration that feels most appropriate. Response configuration and response hand is then recorded. The cardinal inventory is the inventory that has thus far been the most useful predictor of the type of representation effect-differences for comparisons 6 vs. 8 and 7 vs. 9 that are of interest in this experiment (Morrissey et al., 2016). The finger counting inventory is attached as Appendix B.

Procedure.

Participant recruiting took place from November 2016 to May 2017. Given the potential for cross cultural variability in this subject matter, each participant in the study first answered demographic questions about first language, gender, language spoken in primary/elementary school, and nationality. This was followed by the computerized numerical task. An example slide series from this task is provided in Figure 4.1. Participants sat at a distance of about 47cm from the computer screen. Each trial consisted of a white screen for 500ms, followed by a fixation symbol in the centre of the screen, followed by the number pair for another 150ms, followed by a backward mask to prevent any after-image effects on the screen. The fixation stimulus consisted of a single vertical line, 0.6 degrees in height, placed in the exact center of the computer screen. Stimuli presentation was initiated upon participants' central fixation by an experimenter via a key press using an external keyboard in order to not obstruct or distract participants' performance. Each number digit was 0.7 degrees in height and in Times New Roman font. Participants were instructed to provide their answer using two E-prime Psychology Software Tools serial response box keys as indicated by a pair of lights. The response box was turned sideways, with the keys facing a given response hand, such that these keys were in a central position in front of participants, in order to reduce the possibility of left-right response side/hand compatibility effects.

Figure 4.1. Example slide series



The procedure and task were informed here by Bourne's (2006) paper on methodological guidelines for divided field tests. As per those guidelines, direct fixation control was used in order to investigate possible individual differences in hemispheric asymmetry. Direct fixation control was achieved first by monitoring participants' gaze by experimenter via a webcam. Trials were only initiated when participants were staring at the fixation point in the center of the screen. A chinrest was also employed in order to standardize both the viewing distance and the orientation of the head for participants. If participants sit too far away from the screen during the task, this may change the angle of stimuli presentation, and result in both visual fields receiving some of the stimuli, which would degrade the validity of the paradigm. Too long of a stimulus presentation time could also result in participants being able to glance over at the number pair and defeat the paradigm. Bourne (2006) recommended 150ms as ideal for a presentation duration, in order to ensure that participants are not able to glance directly at a stimulus. Further, it was suggested that an optimal viewing angle for stimuli is 2.5-3 degrees from central fixation (Bourne, 2006), although 2 degrees has also been used in number comparison (Reynvoet et al., 2008). Number pairs were presented 2.5 degrees from central fixation. Note that stimuli size and location are discussed in terms of degrees, as this is the standard in this literature. This ensures that studies are comparable despite differently sized monitors and equipment configurations. These controls have been discussed in Bourne (2006) as all being acceptable direct fixation controls for this type of experiment.

This was followed by a pair of brief questionnaires about finger counting habits. The order of the two finger counting inventories was counter-balanced. The cardinal inventory asked participants 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. Each number gesture was recorded on a sheet featuring pictures of various gestures. Ordinal finger counting habits were recorded by asking participants to just count from one to ten on their fingers, while their starting hand was recorded, as well as fingers used. This was followed finally by having participants complete the handedness questionnaire.

Outlier Removal.

Prior to data analysis, responses were screened for both accuracy and response time performance outliers. Unusually slow responses or unusually high rates of mistakes in this paradigm may be a sign of a participant not seeing a number pair due to blinking or glancing away as stimuli were presented, or may be a sign of an undisclosed visual impairment. Such responses would not be representative of the phenomena being studied. Participants' accuracy scores ranged from 72% to 100% on this task, with an mean of 95.81%, *SD* = 4.18. Given that participants were largely highly accurate, a conservative error cut-off was used. In order to set a cut-off for this study, a median absolute deviation was calculated for participants' mean accuracy. This procedure is detailed in Leys, Ley, Klein, Bernard, and Licata (2013), and is a robust-methods variant on the practice of using number of standard deviations as a method for setting an outlier cut-off with continuous variables. The advantage of using median absolute deviation is that it is not itself sensitive to outliers. The presence of a substantial outlier may inflate the standard deviation and skew the mean of a distribution, which reduces the power to detect unusual scores. The median absolute deviation should determine approximately the same acceptable interval, regardless of whether outliers are present. Following Leys et al.'s (2013) guide, if researchers collected a dataset with the values of 1, 1, 2, 2, 4, 4, 89, then the median of this set would be 2, and the absolute median deviations would be 1, 1, 0, 2, 2, 87. The median deviation would therefore be 1, which would be multiplied by a constant of 1.4826, which is related to the assumption of normality. The resulting value of 1*1.4826 would be used in this decision rule: $\frac{x_i - M}{MAD}\ or\ \frac{x_i - 2}{1 * 1.4826} > \pm C$, where C is a level of conservativeness analogous to the number of standard deviations that a score can deviate from the rest of the dataset and still be included in the final analyses. So if the decision rule for any particular score exceeds C, this score would be described as an outlier. The former expression can also be simplified by stating that $2 \pm 1 * 1.4826 * C$ represents the upper and lower limits of what scores are to be included in the final analysis. The median accuracy-rate for participants was 96.88%, and the median absolute deviation of participants' accuracy scores from this value is 1.82%. Therefore, the minimum mean accuracy is calculated 96.88% -(1.82%*1.4826*3) = 88.77%, with a conservative cut off of three, which is analogous to three standard deviations below the mean. This excluded two participants from further analyses. Further explanation of this procedure is available in Leys et al. (2013).

There was no specific recommendation for setting a response time cut-off that was consistent across publications using the divided visual field test. Trimmed means, medians, or log-transformed means have all been endorsed (Bourne, 2006). Some publications examining number comparison using the visual half field technique used only response times between 250 and 1000 ms (Reynvoet et al., 2008), no cut-off specified (Delvenne et al., 2011; Lavidor et al., 2004; Study One; Study Two), participants more than three standard deviations above the mean were excluded (Notebaert & Reynvoet, 2009), or only responses between 150 and 1500 ms (Ratinckx et al., 2001; Ratinckx et al., 2006). However, Morrissey et al. (2016) have previously shown that the number pairs of most interest for this study elicit slower responses than other number pairs, and so any straightforward response time cut-off would disproportionately affect those number pairs of interest. Therefore, responses were excluded if they were slower than 2.5 median absolute deviations above the median for each particular number pair, using the same statistical procedure as was used for mean accuracy for the prior section. Additionally, any responses faster than 250 ms were judged to be anticipatory and unlikely to be a result of a correct judgement of a number pair. These latter exclusions removed approximately 6.3% of response time data prior to data analysis. Following exclusions, a mean correct response time score, variance, and proportion correct was calculated for each combination of visual field (left vs. right), of response hand (left vs. right), and each of the 6 stimuli pairs. The result was 24 individual measurements per type of data, per participant.

Results

Preliminary analyses.

Only eight right-handed participants self-identified as cardinal left-starters, and only 15 participants self-identified as ordinal left-starters. This was not a sufficient sample-size in order to investigate starting-hand as a potential moderator, especially as the underlying hypothesis of this investigation presupposes that manipulating visual field should result in right and left-starters behaving more similarly, not less, to one another than was the case in Study One (Morrissey & Hallett, *in press*). Therefore, analyses comparing individual differences in starting hand were not conducted with the current dataset.

EZ-diffusion statistical assumptions.

The EZ-diffusion model requires certain statistical assumptions, which must be met. These assumptions are 1) a positively skewed response time distribution, 2) similar response times for both accurate and inaccurate responses, and 3) a non-biased starting point. Assumption 1 is met for the currently included 63 participants, with a positive skew, $S = 1.128$, $SE_S = .302$. Likewise, assumption 2 is met, as there was no significant difference in mean response time for accurate and inaccurate responses, $t\ (61) = 1.609$, $p = .113$, although two participants had to be excluded from that check due to not making any errors by which to estimate a response time for error responses. Finally, assumption 3 is actually a function of research design. A bias in starting point is operationally defined as a predisposition to answer one of the two response options. So for instance, if a go/no-go test has 75% 'go' trials and 25% 'no-go' trials, then this would constitute a bias in starting point. Given that no such imbalance exists in this task, this assumption is also met.

Main analyses.

In order to examine the 63 included participants' overall pattern of performance using the EZ-diffusion model, a 2 (visual field) x 2 (response hand) x 6 (number pair) repeated measures MANOVA was employed, with drift rate, boundary separation, and nondecision time as dependent variables. Pillai's Trace was reported for all multivariate analyses in Table 4.1, while Greenhouse-Geisser corrections were reported for all univariate analyses. Significant multivariate effects were observed for number pair, visual field, and a number pair x visual field interaction, so all effects were tested in univariate follow-up tests. Refer to Figures 2-4 for relevant parameters of each number pair.

Univariate tests indicate a main effect of number pair on drift rate, F (3.729, 231.205) = 122.220, $p < .0005$, $\eta_p^2 = .663$. Bonferroni corrected pairwise comparisons, corrected for 15 comparisons, did not indicate any significant differences in drift rate between 3 vs. 5, $m = .368$, 4 vs. 6, $m = .361$, or 8 vs. 10, $m = .382$. Likewise, 5 vs. 7, $m = .283$, did not appear to differ from 7 vs. 9, m =268. All other number pairs differed significantly in all other pairwise comparisons, with 6 vs. 8, $m = .238$, demonstrating a significantly lower quality of information than any other number pair. This was not predicted and is a departure from Morrissey et al. (2016), where the slowest responses and greatest numbers of errors typically occurred for comparisons of 5 vs. 7 and 7 vs. 9, with relatively fewer errors for comparisons of 6 vs. 8.

A univariate test also indicated a main effect of number pair on boundary separation, F (4.560, 282.739) = 15.393, $p < .0005$, $\eta_p^2 = .199$. This effect of number pair was investigated at the univariate level using pairwise comparisons and a Bonferroni correction for 15 post-hoc tests.

These comparisons indicated that 5 vs. 7, *m* = .095, 6 vs. 8, *m* = .097, and 7 vs. 9, *m* = .097, were answered more conservatively than other number pairs, but similarly to one another, indicating participants may have hesitated more for these pairs in order to maintain accuracy. Otherwise, response conservativeness was similar for 4 vs. 6, *m* = .09, and 8 vs. 10, *m* = .089, each of which in turn differed significantly from all other number pairs except 3 vs. 5, *m* = .088, which differed from 4 vs. 6, but not 8 vs. 10.

A final univariate test also indicated a main effect of number pair on nondecision time, F (3.742, 232.035) = 71.884, $p < .0005$, $\eta_p^2 = .537$. Bonferroni corrected comparisons of 8 vs. 10, *m* = .463, demonstrated a statistically significantly faster nondecision time than any other number pair. This was expected, as comparisons of 8 vs. 10 were hypothesized in previous studies to be uniquely amenable to visual-magnitude assessment, as a function of the number of digits in each number of the pair (Morrissey et al., 2016). The stimuli pairs 3 vs. 5, *m* = .498, and 4 vs. 6, *m* = .495, did not appear to differ from each other, while differing significantly from every other number pair. Also, 5 vs. 7, *m* = .524, did not appear to differ from 7 vs. 9, *m* = .517, but did differ from every other number pair. The digit pair 6 vs. 8, *m* = .548, had a statistically significantly slower nondecision time than any other number pair. All other pairwise comparisons were statistically significant.

Table 4.1.

Multivariate analysis of boundary separation, nondecision time, and drift rate

	Multivariate effects				
	Df	Pillai's Trace	*F*	*p*	η_p^2
Predictors					
Number pair	15, 930	.902	26.669	<.0005*	.301
Visual field	3, 60	.241	6.365	.001*	.241
Visual field x Number pair	15, 930	.112	2.413	.002*	.037
Response hand	3, 60	.093	2.054	.116	.093
Response hand x Number pair	15, 930	.064	1.359	.160	.021

Response hand x Visual field	3, 60	.034	.697	.557	.034
Number pair x Response hand x Visual field	15, 930	.054	1.132	.323	.018

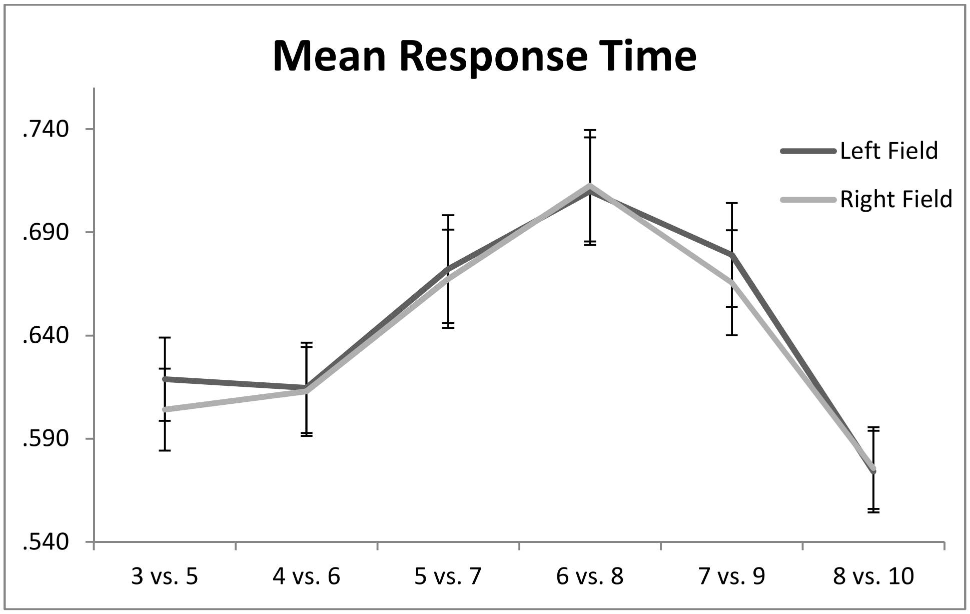


Figure 4.2. Mean response time across tested number pairs

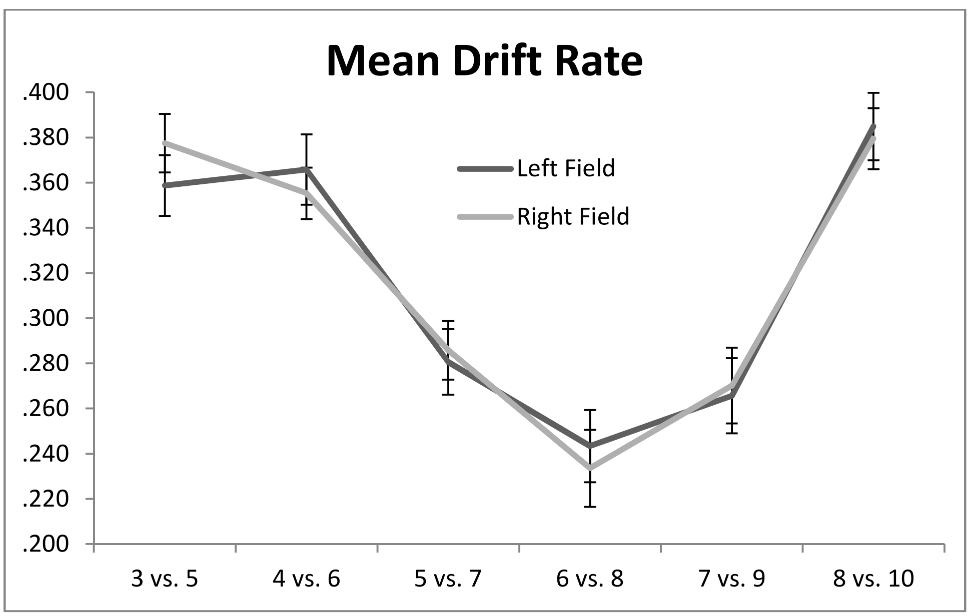


Figure 4.3. Mean drift rate across tested number pairs

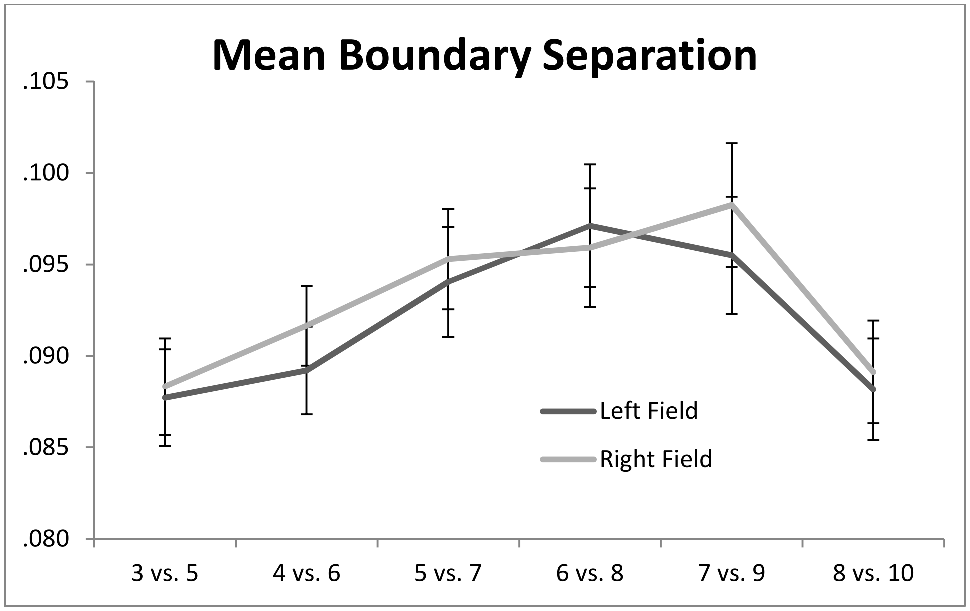


Figure 4.4. Mean boundary separation across tested number pairs

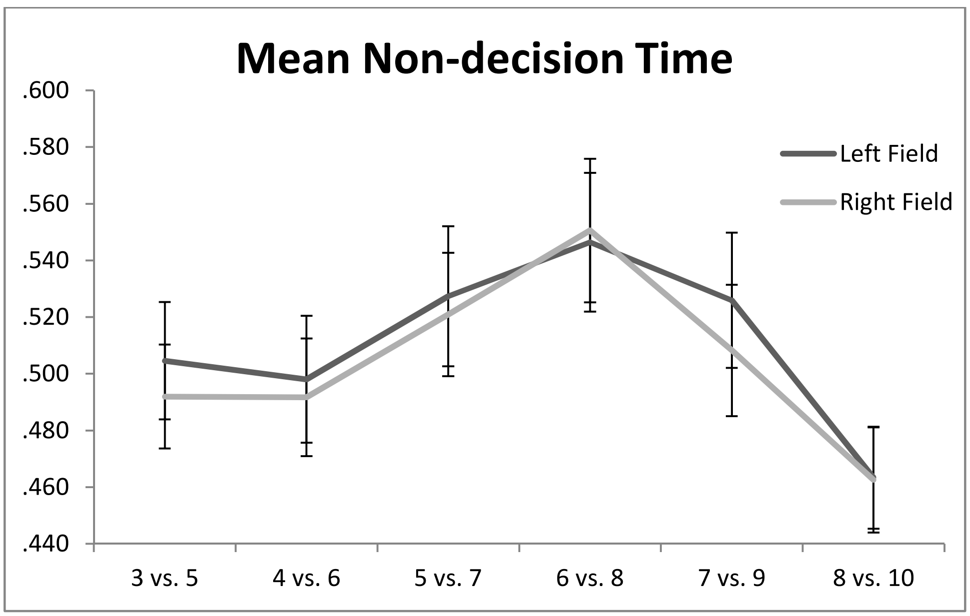


Figure 4.5. Mean nondecision time in milliseconds across tested number pairs

Next, the significant multivariate effect for visual field was examined using univariate tests. These tests indicated that this effect was not driven by drift rate, $F\,(1, 62) = .023$, $p = .880$, $\eta_p^2 < .0005$. Boundary separation was marginally significant, $F\,(1, 62) = 3.330$, $p = .073$, $\eta_p^2 = .051$, indicating a trend towards a more conservative/accurate decision making process for stimuli presented to the right visual field. The only number pair not following the latter pattern was comparisons of 6 vs. 8. Indeed if 6 vs. 8 were dropped from analyses, then the visual field difference for boundary separation becomes statistically significant, F (1, 62) = 5.477, p = .023, η_p^2 = .081.There was, however, a significant univariate effect of nondecision time for visual field as well, F (1, 62) = 17.133, p < .0005, η_p^2 = .217. This appeared to be driven by an average 7 ms right visual field speed advantage in encoding stimuli, suggesting a left hemisphere speed advantage in encoding number stimuli.

Although these main effects of number pair and visual field are interesting in themselves, they are potentially qualified by their interaction. Univariate tests indicated that the multivariate visual field x number pair interaction was not driven by an effect of boundary separation, F (4.605, 285.509) = .690, p = .620, η_p^2 = .011; however, there were significant interaction effects for drift rate, F (4.745, 294.198) = 2.311, p = .047, η_p^2 = .036, and nondecision time, F (4.427, 274.456) = 3.189, p = .011, η_p^2 = .049. Bonferroni corrected pairwise comparisons indicated that the interaction for drift rate was driven by a higher drift rate for the right visual field for comparisons of 3 vs. 5, m = .377, than the left visual field, m = .359, d = .35, but there were no statistically significant differences across visual field for any other number pairs. This may indicate that 3 vs. 5 was easier to visually distinguish when on the right-hand side than on the left-hand side, rather than as a function of initial processing in the left or right hemisphere, as drift rate is indicative of quality of information, rather than speed of processing. For nondecision time, the univariate interaction appears to be driven by a shorter nondecision time for comparisons of 3 vs. 5 when in the right visual field, m = .492, than when in the left visual field, m = .505, d = .39, as well as by a shorter nondecision time for comparisons of 7 vs. 9 when in the right visual field, m = .508, than when in the left visual field, m = .526, d = .48. While the nondecision time visual field difference for comparisons of 3 vs. 5 and 6 vs. 8 may still be affected by visual features of the number digits, when comparing the right-field advantage of 7 vs 9 to the average right-field advantage of all number pairs other than 6 vs. 8, this difference is statistically significant, t (62) = 2.039, p = .046, d = .26, which indicates a greater right-field advantage, relative to other number pairs, which is in line with predictions.

Discussion

The current study examined whether differences in lateralization of number processing may help explain why experimental participants show slower response times when conducting magnitude comparisons of numbers typically counted on both hands. This was accomplished by use of a binary magnitude test administered via a divided visual field paradigm. It was hypothesized that since previous investigations have found that cardinal finger counting first on one's left hand predicts slower responses to only these number pairs (i.e., 6 vs. 8 and 7 vs. 9), and that counting on only one's right hand (i.e., traditional Chinese finger counting) predicts significantly faster responses to these number pairs (Morrissey et al., 2016), slower responses to these numbers may be a consequence of increased right hemisphere involvement in number magnitude comparison. In previous investigations, right-handed left starters have demonstrated greater activation of the right hemisphere when evaluating small quantities, while right-handed right-starters utilized greater specialization of the left hemisphere for small quantities (Tschentscher et al., 2012). Therefore, it was of interest to study whether a left hemisphere advantage was present in this kind of binary magnitude comparison task, as well as whether this advantage was stronger for numbers typically counted on two hands.

The data in this study supported both of these hypotheses. There was a general right-field advantage, and this advantage was stronger for 7 vs. 9, which are typically represented by two hands. The same was not true of 6 vs. 8; however, participants demonstrated significantly poorer quality of information in their performance for this number pair, as compared to all others. This would appear to indicate that 6 vs. 8 were more difficult for participants to differentiate visually in this paradigm. Furthermore, a right-field advantage for 7 vs. 9 was found to be especially large in the nondecision time part of the EZ diffusion model, which we interpret as differences in encoding, rather than a longer decision time as a function of simulating finger counting habits. At the same time, there were also other effects found that were not expected. There is greater response conservativeness for stimuli in the right visual field. The implications of all these effects are explained, starting with number pair differences and then visual field differences.

Number comparison differences.

The interaction analyses demonstrated that the 7 vs. 9 comparison had a stronger right-field advantage on nondecision time than did the other number comparisons. This effect supports the hypothesis that numbers represented by both hands would show a bigger difference in processing depending on the visual field in which it was presented. When 7 vs. 9 are presented in the left visual field, the data suggest that this comparison is encoded more slowly, likely because of a right hemisphere disadvantage in number comparisons. Although this disadvantage is true for all number comparisons, the fact that this disadvantage is even stronger for the 7 vs. 9 comparison suggests that this slower encoding process is more pronounced as a function of these number digits eliciting internal representations of a two-hand finger-count. Furthermore, as this effect was found in nondecision time, and not in drift rate or boundary separation, this suggests that while participants' generally found this number pair more difficult to respond to, the right-field advantage was specifically due to encoding differences with this number pair.

At the same time, this same effect was not found for the 6 vs. 8 comparison, which is also a comparison that involved two numbers that are typically represented on two hands. If our main hypothesis was true, then the 6 vs. 8 comparison should have demonstrated the same pattern as the 7 vs. 9 comparison. The results from the drift rate analyses, however, suggest that the 6 vs. 8 comparison (and the left-field presentation of the 3 vs. 5 comparison) was affected by error due to visual similarity. There were three response conditions where participants had an unexpectedly difficult time providing responses. These were comparisons of 3 vs. 5 (only in the left visual field) and comparisons of 6 vs. 8 in both the left and right visual field. The ease with which a participant is able to make a decision is referred to as drift rate, with lower drift rates indicating high variability in response times and more erroneous responses. This is different from an unusually low boundary rate (i.e., low variability and high error rate), which would have indicated impulsive responses to this number pair. Given that all number pairs were presented in a stacked format with one number of the pair directly above the other, and given the shape of the Arabic digits in question, it seems likely that the digits 3 vs. 5 and 6 vs. 8 were visually more difficult to distinguish for participants, relative to other Arabic digits. All of the other number pairs presented to participants had a digit with a rounded edge paired with a digit with sharper angles (i.e., 4 vs. 6 or 7 vs. 9), or where the number of digits facilitated responses (i.e., 8 vs. 10). It is also worth noting that both the digits ‘6’ and ‘8’ were more easily identified when paired with ‘4’ or ‘10’, which indicates a problem specific to these digits being presented together, rather than a problem with visual angle or other characteristics of these numbers. Also when ‘3’ and ‘5’ were presented together on the left, the common rounded edge is closer to central fixation than when the same pair is presented to the right.

As is shown in figure 4.2, the pairs 5 vs. 7 and 7 vs. 9 also showed a lower drift rate. However, this was expected as these pairs were already slower than other number pairs, while having some of the highest error rates in Morrissey et al. (2016), despite having been in central fixation in that investigation. This may help explain the unexpectedly large right-field advantage for 3 vs. 5, as well as the lack of a visual field advantage for 6 vs. 8, as predicted patterns of performance were likely masked by visual similarity. This is a concern that has not been raised in previous investigations using similar number comparison paradigms, and may be a previously undescribed source of bias and/or heterogeneity in the literature.

Right-field advantage.

After accounting for the unanticipated differences in the visual features of number digits, the current findings are consistent with the notion that greater right hemisphere involvement is detrimental to number comparison performance, and especially so for larger single-digit number magnitude comparisons. The strongest univariate effects were a function of nondecision time, indicating that participants were slower to recognize numbers in the left visual field. However, there was also a small right-field advantage in boundary separation, which means that participants were responding to numbers more conservatively in the right visual field. It may seem counterintuitive that participants' responses would be both faster and more conservative when presented to the right visual field; however, this is partly a function of how drift rate, boundary separation, and nondecision time are calculated (Wagenmakers et al., 2007). Boundary separation is calculated as a function of response time variance and accuracy, but not mean response-time. Therefore, boundary separation is indicative of a decision making process that occurs once a stimulus has been encoded. So while number digit stimuli were encoded more quickly when from the right visual field, this was also followed by a slower decision making process that resulted in slower responses and fewer errors than the decision making process utilized when the same stimuli were in the left visual field. However, this also likely means that if participants had engaged in the same sort of decision making process for both visual fields, either through more conservative responses to left-field stimuli or less conservative responses to right-field stimuli, then the mean response-time difference between the left and right visual fields would likely have been larger. Because of this, an analysis of only mean response-time here would have underestimated the actual right-field advantage, as it would not have identified that the response-time advantage was still present despite responses being somewhat more conservative when comparing digits in the right visual field.

The use of the EZ-diffusion model comes to the same general conclusions as a traditional repeated measure ANOVA (See Appendix D for this analysis). Nevertheless, it allowed for a more nuanced interpretation of participants' performance (Wagenmakers et al., 2007), as well as an evaluation of the heterogeneity in participants' decision making process across different number pairs. It was also important to demonstrate that a right-field response time advantage was observable despite participants answering right-field items with a more conservative decision making process. This speaks to both the usefulness of diffusion modelling, as well as of exploratory data analysis, as the aforementioned associations do not yet appear to have been documented in the literature. The resulting model was also a qualitatively richer explanation of participants' cognitive processes during this task.

Limitations.

There were several limitations of the current investigation. First, while it appears likely that several response conditions were answered differently because they were more difficult to visually distinguish, it is also still possible that there was some other unknown processes difference that led to participants performing differently for these number pairs. The visual angles of stimuli were well within Bourne's (2006) methodological recommendations, with past investigations using both greater (Katz, 1980), and lesser (Notebaert & Reynvoet, 2009), eccentricities with number digits than the current investigation without noting any problems. Future investigations should utilize a slightly smaller visual angle for number pair stimuli, in order to assess whether these results can be replicated with more homogenous performance across items. However, despite this limitation, the use of EZ-diffusion modelling made it possible to identify all three response conditions that had unusually low drift rates, either as the only number pair with a right/left difference in drift rate, 3 vs. 5, or as the number pair with the singularly lowest drift rate, 6 vs. 8 (Wagenmakers et al., 2007). So these response conditions were uniquely characterized by both unexpectedly slow recognition (nondecision time), and poor quality of information (drift rate). This does make the visual recognition explanation for these three response conditions less speculative than it otherwise might have been.

Second, the number of trials used to estimate response time variance is 16 trials per condition when examining response hand, visual field, and number pair. While the EZ-diffusion model is one of the better performing models when trial numbers are low, these types of models often require 100-200 trials per data point in order to estimate parameters with high precision (Lerche & Nagler, 2017). This likely decreases the power of this analysis, especially for drift rate and boundary separation. However, Lerche and Nagler's (2017) simulations were specifically looking at trial numbers necessary for estimating each parameter for each item for each participant. While the estimation precision here was relatively low compared to that standard, it is improved somewhat by this being a within-subject design with a larger participant sample than is typical of a divided visual field paradigm. So while item level parameter estimates for each participant were likely coarse, the average estimate across participants would have been more reliable. Also, while comparing right and left-field performance for individual items was less precise, comparisons of right vs. left-field performance overall were based on averaged parameters computed each from 192 items, which is much more reliable and within Lerche and Nagler's recommendations. It is also worth mentioning that an analysis of correct mean response-time suggested very similar conclusions as the current analysis. So while not ideal, the current use of the EZ-diffusion model should be acceptable, and helps resolve uncertainties of other statistical options while also providing qualitatively richer information about participants' decision making process.

Finally, it is a limitation of this design that a between-groups comparison of left-and right-starters could not be tested. There is a considerable literature indicating that there are differences between left- and right-starters in their numerical performance in a variety of contexts (Fabbri, 2013; Fischer, 2008; Morrissey & Hallett, *In Press*; Morrissey et al., 2016), and that this may have consequences for the lateralization of number representations in the brain (Tschentscher et al., 2012). However, differences in lateralization between the right and left hemisphere are quite small as a function of absolute differences in response time, and our predictions were that left- and right-starters would behave more similarly in a divided visual field test than in other paradigms. With this in mind, the required sample size necessary to detect differences between left- and right-starters would have been considerably larger than the above within-subject comparison, and so was not possible here. It remains possible that left- and right-starters are lateralizing number information differently in a way that was not identified here.

Conclusions.

With the addition of the recommended direct fixation control (Bourne, 2006), the present study used the divided visual field test to more specifically examine the right-field/left hemisphere advantage for magnitude comparisons of single-digit numbers by using EZ-diffusion modelling (Wagenmakers et al., 2007). This visual field difference manifested as both an encoding time advantage for the right visual field, as well as by a more precise and cautious decision making process for items in the right visual field. It was also observed that certain numbers were particularly difficult for participants to distinguish, both when in particular pairs, as well as when at particular eccentricities. However, despite this, the right visual field advantage still appeared most robust when comparing numbers typically counted on two hands. These findings elaborate on the previously observed right-field advantage for number comparisons, while also indicating that additional processing with larger single-digit numbers are at play. At the very least, these results suggest the cognitive processes involved in number comparison are demonstrably more complex than previously thought. We look forward to future research in this area.

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Chapter Six: Meta-Discussion- Summary and Future Directions

This dissertation includes four investigations highlighting different cognitive aspects of embodied numerical cognition. In order to not simply restate the major discussion points of these studies, I will instead focus on how these four investigations fit together in a larger theoretical context. First, I will discuss Bender and Beller's (2012) elaboration on Zhang and Norman's (1995) cognitive taxonomy of numeration systems and relate how this taxonomy can help describe how we empirically estimate the role of specific symbol structures in the numerical performance of study participants. Given the failed replication of Michaux, Masson, Pesenti, and Andres, (2013) in Study Three, this analysis of the symbolic and structural content of finger counting habits may be more useful going forward. This discussion will close out by suggesting where future research may be most fruitful.

A Taxonomy of Finger counting Gestures

Earlier in the introduction to this dissertation, I discussed the work of Badets, Pesenti, and Oliver (2010), Bender and Beller (2012), Di Luca and Pesenti (2008), and Di Luca, Lefevre, and Pesenti (2010), all of whose work is further highlighted in importance by the current dissertation and worth revisiting when outlining the most useful future work in this field to pursue. Each of these publications discussed cardinal finger counting gestures as forms of internalized numeric symbols rather than motor procedures that students might go through in order to help decode numeric information. For Bender and Beller (2012), finger counting habits can be understood through Zhang and Norman's (1995) taxonomy as symbolic representations of number digits, with each finger counting system having different cognitive implications as a function of their overt complexity, as well as by the internal and external cognitive steps necessary to decode the meaning of a given finger-number gesture. In order to use this sort of taxonomy appropriately, it is necessary to explain how numeration systems are described structurally, followed by an explanation how this structure is tested empirically.

In Zhang and Norman's (1995) taxonomy, the Arabic base-ten numeration system typically used in most modern nations is described as a 1x1D system containing a base dimension and a power dimension which together communicate a numerical magnitude. The concept of "ten" is an objective quantity that exists independent of a thinker. However, it is important to clarify that the way that a "ten" is represented externally and internally may vary by culture or context. For example, the base of the Arabic system is ten differently shaped digits (e.g., 0, 1, 2, 3, etc.) with a quantitative meaning ascribed to the shape of the symbols. These symbols take on further meaning that is denoted by their relative position. In this way, a notation of '01' refers to a magnitude of one while a notation of '10' refers to a magnitude of ten despite each containing the same characters. By placing the digit '1' to the left of the digit '0', this denotes that the value of '1' is modified by a power that can be described as$\sum a_i x^j$, with "a_i" referring to the value of the given digit, "j" referring to how many digits are placed to the right of that digit, and "x" referring to the base number of that system (in this case ten). So the written form of "10" is decoded as $\sum 1 * 10^1 + 0 * 10^0 = 10$. This written expression works for other systems as well. The written form of "10", if intended as an expression in base 16 hexadecimal, would be decoded as $\sum 1 * 16^1 + 0 * 16^0 = 16$, and "10" in binary would be decoded as $\sum 1 * 2^1 + 0 * 2^0 = 2$.

These properties of a numeration system have cognitive and practical consequences for thinkers. One of the more obvious of these consequences being that, despite similar visual encoding properties to Arabic base 10, a base 16 system would require that learners master 256 single-digit multiplications in a table instead of the 100 required by Arabic base-ten. Other ways in which numeration systems impose cognitive costs on thinkers is in terms of efficiency, compactness, and complexity. A 1D system, such a simple tally, has relatively little complexity, is readily learned by new learners, and is only susceptible to lexical errors when in use. However, the lack of a power dimension in a tally requires that there be as many symbols as there are items to be counted, which is prohibitively inefficient for larger counts. A polynomial 1x1D system, such as Arabic base ten, is a more complex system than a 1D system and is prone to problems such as carry errors and syntactic errors. It also requires new learners to master ten symbols with distinct cardinal and ordinal meanings. The advantage of this system is that much larger quantities can be clearly represented with a much smaller absolute number of symbols. The overall cognitive efficiency of a numeration system can be understood sufficiently for the purposes of this dissertation as a balance between the exhaustive quantity of symbols to be learned or manipulated, the number of distinct symbols necessary to denote a specific quantity (e.g., the compactness of a system), and the complexity of any power dimensions (Bender & Beller, 2012). Systems with a smaller base number, such as binary, require many fewer symbols to be learned, and a single-digit multiplication table with only four possible operations, but they are not compact and require much more complex rules for human beings to add, subtract, or multiply large quantities.

These rules can be applied to finger counting habits in both structural and empirical manners. For instance, traditional Canadian finger counting habits could be described at a glance as being a quantitative 1D system, as the number of raised fingers corresponds in a linear fashion with the intended numerosity. That is to say, five raised fingers indicate a quantity of five and not some other quantity. Traditional Chinese finger counting habits, by contrast, utilize a combination of quantitative and symbolic representations, with quantities smaller than five represented in a one-to-one correspondence, and quantities larger than five represented symbolically. This would imply that the Chinese finger counting system has a break at the number five that is not present for the Canadian system. However, a different interpretation could be that the Canadian system does possess a sub-base of five when one considers that quantities larger than five require an extra hand in order to represent. Likewise, despite appearances, Chinese finger counting gestures are all intended to replicate traditional Chinese number characters, and so would not have a break if they were all understood symbolically.

When investigated empirically, it is the latter interpretation that better matches actual numerical performance. In one of the first cross-cultural investigations of the impact of finger counting structure on cognition, Domahs, Moeller, Huber, Willmes, and Nuerk (2010) observed that number digits typically counted on two hands by Germans require more time to respond to, and participants with culturally acquired finger counting habits that require only one hand to count (e.g., traditional Chinese finger counting) show no such performance cost (also replicated among Canadians and domestic Chinese students by Morrissey, Liu, Kang, Hallett, & Wang, 2016). This was notable as all participants in these former investigations used the same written form of Arabic base ten, which implicates this cross-cultural difference as being a result of an implicit finger counting decoding step at the sub-base of five for only Canadian and German participants, which would lend these systems the (1x1)x1D designation in practice, while the Chinese system exhibits a pattern of performance more like a 1x1D system. Extending this initial work, Domahs et al. (2012) observed that finger counting systems that require hand motion in order to represent a cardinal digit are associated with a similar performance decrease, even if these motions are typically performed by a single hand.

These aspects of finger counting habits should be expected to impact the learning of arithmetic, as well as the efficiency of numeric information encoding and retrieval. Bender and Beller (2012) also argue that the diversity of finger counting representations across cultures is underestimated by the field at large, and that this represents a missed opportunity for understanding the diverse impacts of different finger counting systems. Di Luca and Pesenti (2008) support these assertions by showing that finger counting gestures were cognitively processed by participants in a way that suggested that these images were being interpreted as symbols, rather than as non-symbolic magnitudes. In that work, a finger-count with four raised fingers was treated more similarly to the number digit “4” than to a dot array with the same quantity. Badets et al., (2010) showed that pictures of finger counting habits were more privileged by participants’ cognition than photos of vertical bars meant to represent a count. Also, this symbolic status of cardinal finger counting gestures appears to be limited to situations when those cardinal finger counting gestures were those typically used by the participants (Di Luca et al., 2010). The latter work is important here as researchers observed that images of novel combinations of fingers were not simply decoded more slowly, but failed to activate place-value associations. So a novel gesture with a raised thumb, index, ring, and little finger would lead participants to quickly “count” four fingers, while a familiar gesture with the index, middle, ring, and little finger would activate the place value of ‘4’ on the mental number line.

This role of finger counting gestures has also been shown to extend beyond knowledge of magnitude, but also to impact how adults experience other cognitive numerical phenomena, such as the so-called SNARC effect (Dehaene, Bossini, & Giraux, 1993). This long-studied phenomena describes the tendency for larger magnitudes to be responded to more quickly in right-hand space, and smaller magnitudes to be responded to more quickly in left-hand space. It was Fischer (2008) who first observed that adult individuals who typically count first on their left hand experience this response bias more strongly than those who typically count first on their right hand. Other researchers have shown that the effect of SNARC can be modified by changing an individual participant's hand orientation (Riello and Rusconi, 2011). These observations, when understood through Zhang and Norman's (1995) cognitive taxonomy, would suggest that Arabic number digits not only activate internal symbolic representations of cardinal number gestures, but that the left-right structure of these gestures has an impact on adult's numerical cognition (see also Conson, Mazzarella, & Trojano, 2009). This would be consistent with Bender and Beller's (2012) suggestion that numeration systems can have spatial characteristics that also impact cognition. Given this privileged place that finger counting gestures maintain in adults' cognition, it is important to understand how the structure of finger counting habits continue to shape adults' internal representation of quantity. It is with this in mind that I discuss how studies One through Four inform us of this ongoing role in thinking about numbers.

Studies One and Two

Studies One and Two were complimentary investigations that investigated how individual differences in structural features of finger counting habits may impact numerical cognition. These investigations were novel in several ways: 1) they described how procedure-order conditions and structural aspects of finger counting habits can interact to impact the cognitive representation of symbolic number digits in a way that interacts with SNARC-like associations of space and quantity; 2) they described how cardinal and ordinal finger counting assessments may be useful in different ways when investigating the link between fingers and numbers; 3) they demonstrated that handedness also appears to impact the relationship between finger counting habits and numbers, and; 4) they showed how exposure to one's own finger counting habits impacts the subsequent relationship of those finger counting habits with numerical performance.

Participants in Study One demonstrated that patterns of cognitive performance while engaging in binary magnitude comparisons of Arabic numerals were associated with starting hand, as was seen in Morrissey et al. (2016), but that this difference was moderated by the method used to assess a participant's starting hand. For example, in Study One, cardinal left-starters performed more slowly than cardinal right-starters when comparing numbers typically counted on both hands, likely as a result of a difference in the internal representation of the sub-base of five that is implicit in Canadians' finger counting habits. The same difference was not evident for ordinal left- and right-starters, although all of these groups did all, on average, still demonstrate this sub-base five effect. Put another way, each group of Canadians demonstrated evidence of their finger counting habits in their performance, but cardinal left starters exhibited this effect to a larger degree. This suggests that it is something particular about cardinal finger counting habits, but not ordinal finger counting habits, that is related to judgments of numbers typically counted on two hands, and this manifests in association with starting hand despite no difference in objective complexity of finger counting habits for either ordinal or cardinal left- and right-starters. One possible reason for this is that being a cardinal left starter is associated with a greater reliance on finger counting representations (Soylu & Newman, 2016). Another possibility is that there may be differences between cardinal left- and right-starters that affect the way that numbers are lateralized in the brain, similar to what was observed in Tschentscher, Hauk, Fischer, and Pulvermuller (2012). This explanation is touched on in Study Four, but it is not definitive. Further work is required to explain such results.

Additionally, in Study One, both ordinal and cardinal left-starters demonstrated a relatively greater SNARC-like association of larger digits with right-hand space and smaller digits with left-hand space, unless they were questioned about their finger counting habits prior to a task. When reminded of their finger counting habits prior to the magnitude comparison task, left-starters showed little or no evidence of SNARC-like associations of response hand and magnitude. This result implies that the structure of finger counting habits not only has an effect on the cognitive load due to accessing particular number representations, but that the directionality of finger counting habits has an impact on how an individual perceives numeric magnitude. This also implies that the strength of that effect can be modified by whether participants have been reminded of their finger counting habits prior to a numerical task. The fact that left-starters showed less SNARC-like response compatibility effects immediately after being asked to finger-count may indicate a competition between finger counting and other spatial representations of quantity. However it should be noted that there was no evidence that this procedure order manipulation affected sub-base five effects described previously, and so these various performance features may operate according to different mechanisms.

When left-handed Canadian and Chinese participants were included in Study Two, it was evident that handedness also had an effect on how starting hand predicted participants' performance. This is important, as Bender and Beller (2012) made a sound argument for the lost opportunities in engaging with the cognitive implications of the cultural diversity of finger counting habits, and so the fact that I observed differences as a function of both cross-culture and within-culture differences in finger counting habits only highlights the importance of individual differences even further. Canadian left-handed participants show less impact of a sub-base five effect when making binary magnitude comparisons and both left-handed Chinese and Canadian participants demonstrate less evidence of SNARC-like response compatibility effects overall. This is similar to left/right-starter differences discussed in Study One, as there are also no obvious differences in structural complexity of finger counting that correlated with handedness. However, even without obvious structural differences in finger counting habits, these participants did not differ in spoken language or any other characteristics that might explain this result. Therefore, finger counting habits themselves are the most likely explanation. This also seems to suggest that SNARC-like associations of response hand and magnitude are impacted by finger counting direction within a particular hand, as well as by the availability of finger counting habits to consciousness. These findings also extend Bender and Beller's (2012) point to include the diversity of finger counting habits within individuals, and not only between cultures.

Study Three

Study Three differed from the other investigations contained in this dissertation in two main ways: 1) participants completed simple arithmetic problems rather than evaluating pairs of number digits, and; 2) rather than evaluating participants' judgments of written number digits for features consistent with their culturally acquired finger counting habits, we required participants to move either their fingers or their feet to examine their performance for evidence of selective competition between finger movements and arithmetic performance. This was accomplished through a cross-cultural replication of Michaux et al. (2013), with the addition of an ordinal finger counting inventory meant to conceptually replicate a right-starter arithmetic advantage previously described by Soylu and Newman (2016).

In Study Three, both Canadian and Chinese participants took part in a single/dual-task paradigm adapted from Michaux et al. (2013), with half of participants engaged in a finger-tapping dual-task condition and half of participants engaged in a foot-tapping dual-task condition. Michaux et al. (2013) had previously observed a selective interference effect of finger tapping when performing addition and subtraction problems, with no interference for multiplication problems. Unlike Michaux et al.'s (2013) observations, there was no apparent difference between participants who were asked to tap on one hand, versus those who were asked to tap on one foot, while answering simple arithmetic questions. In other words, the results of this study suggest that there is not a selective interference of finger-tapping on single-digit calculation tasks for either Canadian or Chinese participants. This does not suggest that arithmetic was not embodied, as there was a difference between Canadians who were ordinal left starters and ordinal right-starters. Canadian left starters performed the task significantly more accurately in both the single- and dual-task conditions, suggesting that the difference between right and left-starters here is unrelated to finger movement. This left-starter advantage appeared to be greatest for multiplication questions and smallest for subtraction questions. However, there is no clear evidence that this was due to a difference in strategy regarding the different problem types, but instead a function of the problem size effect (LeFevre, Sadesky, & Bisanz, 1996) as all subgroups within Study Three performed worst for multiplication and best for subtraction questions. This result is also in contrast with Newman and Soylu's (2013) observation of a right-starter advantage in arithmetic, although Newman and Soylu's (2013) study did encourage participants to engage in arithmetic calculation instead of arithmetic recall, which may have advantaged right-starters over left-starters

Study Three did lack a condition where participants were asked to tap their fingers on their left hand or foot, and so some alternative explanations of this result cannot be ruled out. For instance, it is possible that this study design led to participants being preoccupied with their right hand or right foot even when in the single task condition, and so participants who typically count on their left hand may have been advantaged by using only their right hand/foot to tap in the dual-task condition. However, the fact that Canadian left-starters continued to outperform Canadian right-starters in the single-task condition, and even when asked to tap only their right foot, is not consistent with the notion that the source of this performance difference stemmed from interference originating in processes necessary for finger motion. What appears more likely is that being a left starter or a right-starter correlated with a difference in arithmetic strategy or numerical representation, which influenced their subsequent performance.

Study Four

The premise of the investigation in Study Four was that Arabic digits activated symbolic representations of cardinal finger counts, and so numbers that require two hands to count would require greater cognitive resources to represent in cognition. Notebaert and Reynvoet (2009) recently demonstrated that although performance for single-digit numbers is similar for both the left and right hemispheres of the brain, there is a greater right-field advantage for two-digit numbers when using a divided visual field paradigm. These magnitudes are used less often, are less iconic, and the left hemisphere is more precise in decoding symbolic magnitudes, leading to a greater advantage when digits are made available first to the left hemisphere. According to Bender and Beller (2012) and Domahs et al. (2010) a base-10 finger counting system that employs two hands would contain an implicit sub-base of five, which indicates a number of full hands to which a quantity corresponds. Also, while digits between five and ten are not necessarily less iconic than numbers less than five, they have been shown to require more effortful processing among Canadians (Morrissey et al., 2016).

Study Four utilized a divided visual field paradigm and an EZ-diffusion data analysis plan (see Wagenmakers, van der Maas, & Grasman, 2007) in order to demonstrate that numbers typically counted on two hands were relatively more advantaged by being presented to the right visual field, similar to two-digit numbers in Notebaert and Reynvoet (2009), and that this advantage took place during encoding rather than during decision making. This advantage was detectable despite the additional observation that numbers in the right visual field were also responded to somewhat more conservatively than numbers presented to the left visual field, as evidenced by a greater variability in response time alongside a lower error rate. However this result was complicated somewhat by one of the number pairs of interest (i.e., 6 vs. 8), which evidenced a significantly lower quality of information in participants' performance in both visual fields. This has not been previously reported in the literature and occurred despite following typical protocols for this type of procedure (Bourne, 2006). This inconsistency is likely because of the visual similarity of the digits '6' and '8'.

Study Four provides additional evidence that the sub-base five effect previously described in Domahs et al. (2010; 2012) and Morrissey et al. (2016) is disproportionately benefited by initial left hemisphere processing, similar to two digit numbers (see Notebaert & Reynvoet, 2009). The additional observation that this difference can be isolated to mainly encoding rather than decision making is consistent with research conducted by Di Luca and Pesenti (2008), Badets et al. (2010), and Di Luca et al. (2010), which suggest that finger counting gestures are treated symbolically rather than being subtly performed as part of a participant's decision making process. This is also consistent with observations in Study Three, which suggests together that it is not finger movement that connects finger counting habits to numerical cognition, but rather that cardinal finger counting gestures are linked with differences in internal symbolic representations of numbers that continue to manifest even among university-educated adults.

Theoretical Implications

As mentioned in the discussion of Study Three, it is difficult to rule on the question of whether the functionalist or reuse views are better descriptions of the embodiment of numbers (Penner-Wilger & Anderson, 2013; Dehaene & Cohen, 2007). However, the diversity of performance effects described in this dissertation, as well as the broader literature, does suggest that the functional hypothesis requires fewer assumptions. The functional hypothesis posits that the embodiment of numbers is a learned activity, and is ultimately a function of our learning history involving counting on our fingers. While it remains possible that numeracy must be embodied to some extent regardless of personal learning history, as reuse models require, it can be said with much greater certainty that experience and habits do appear to affect how numeracy is embodied. This is demonstrated even in Study One, where left-starters either do or do not demonstrate a SNARC-like association of space and quantity, depending on whether participants were asked to finger count prior to the number comparison task. This would suggest that the way in which numbers may manifest as embodied is not only subject to personal learning history, but due to experience immediately prior to an activity. This lends some credence to Bender and Beller's (2012) argument that the underrepresentation of the diversity of finger counting habits from the real world in the experimental literature is a detriment to that literature. Presumably any number performance difference between a left- and right-starter from the same culture is going to be much less obvious than differences between other finger counting systems that differ in much more fundamental ways.

Aside from discussions of the origination of embodied numeracy, there is also the question of how numeracy is being embodied by participants at a given moment. One of the best supported models appears to be the ideomotor model, discussed by Badets, Koch, & Philipp

(2016) and Badets et al. (2010). The ideomotor mechanism suggests that embodied numerosity occurs because the sense-perception of a concept also activates the motor behaviour associated with generating a response to that concept (Badets et al., 2016). For instance, Badets et al. (2010) have previously shown that individuals are faster at answering an arithmetic question if showed a picture of a finger counting gesture that is consistent with the correct answer. Adriano, Diez, and Fernandez (2014) have also shown that individuals are faster at verbally responding to arithmetic questions when covertly holding their hand in the form of a finger counting gesture that is consistent with their answer, and that this is especially true when both the visual field and the gesturing hand were on the right hand side, feeding into the left hemisphere.

The ideomotor explanation of embodied numerosity is a good fit with the observations in this dissertation, as it suggests an explanation for why the individual finger counting habits of participants would correspond in so many ways with their numeric performance, and yet tapping one's fingers did not appear to affect the arithmetic performance of either Canadian or Chinese participants any differently than tapping their foot. According to this model, seeing a number activates several representational formats that might be used to respond to, or to communicate, that quantity. So for example, when a participant sees the number digit '6' this results in the activation of finger counting gestures that might be used to communicate that quantity. The complexity of the gesture that is activated, whether a one or two hand gesture, has an impact on processing time necessary for that representation. Also, whether that gesture would occur on the right or left hand would also impact other existing SNARC-like associations of quantity and space. However, if a participant is asked to tap either their right hand or right foot, then neither of these actions are likely consistent with the gesture representing the correct answer to an arithmetic question, and so this may well be why there was no difference between these conditions in Study Three.

Conclusions and Future Directions

There are a number of unanswered questions about this topic that future research should address. Future research should employ a more typical SNARC paradigm than the SNARC-like response compatibility effects observed using the categorical paradigm in Studies One and Two. The latter was used in this study in order to take advantage of a large existing database from Morrissey et al. (2016) and in order to examine the existence of sub-base five representation effects and spatial compatibility effects within the same task. However, Wood, Willmes, Nuerk, and Fischer (2008) have indicated that the more common parity tasks typically produce larger effect sizes and, thus, have greater statistical power. If this were combined with a within-subject design comparing SNARC performance before and after questioning about finger counting habits, then this would greatly increase the sensitivity of the paradigm to detect differences across experimental conditions. If the results of Studies One and Two were replicated in this sort of design, this would also have a relatively greater impact on the literature as the results would be generalizable to the greater number of parity SNARC paradigms. This would also have disproportionate statistical power benefits for the examination of less common categories of participants, such as left-handed participants, left-starters, and participants who are fluent in sign language. It would also be useful to include several different finger counting inventories from the literature, in order to evaluate their relative performance in predicting individual differences. Currently there is a large gap in the literature regarding recommendations as to how to evaluate participants' finger counting habits.

Riello and Rusconi's (2011) method of having participants answer with one hand at a time may also be a useful tool for investigating individual differences in finger counting habits, as they relate to SNARC. This is because finger counting habits not only have a left-right spatial aspect regarding which hand someone starts counting on, but they also have a left-right spatial aspect regarding the order in which fingers are used when counting. Someone who typically counts first on their left hand from their little finger through to their thumb may differ from someone who typically counts on their left hand from their thumb through to their little finger. It was suspected that one of the differences between having participants count on their fingers prior to the task versus after the task may be as a result of a shift from a hand-based frame of reference to a finger-based frame of reference. This would be similar to Viarouge, Hubbard, and Dehaene (2014), who primed hand versus button-based left-right frames of reference for SNARC. A unimanual approach may be helpful for disentangling any effects of hands versus fingers.

Study Three would also benefit from replication with participants asked to tap on either their right or their left hands. This would help answer any lingering questions as to whether the right/left-starter difference described by Study Three was a function of having participants tap on only their right hands/feet. However, it would also be useful is to employ a larger variety of arithmetic and mathematical tasks when examining differences between left- and right-starters. The procedure of Study Three was very laborious, requiring many hours in order to code each participant's performance. The task also took nearly an hour to complete and was quite difficult for many Canadian participants. These procedural aspects limited both the number of types of questions that could be asked, as well as the number of participants recruited. However, this procedure from Study Three was designed in this manner as to allow participants to respond verbally to arithmetic questions while tapping their fingers, as per Michaux et al. (2013).

However, there is little evidence to suggest that this was a valid paradigm to begin with, as the original result in Michaux et al. (2013) was only marginally statistically significant and Study Three failed to validate the selective effect of finger tapping despite utilizing four times as many participants as were tasked in Michaux et al. (2013). Additionally, the left/right-starter difference in arithmetic performance during Study Three persisted in both the single- and dual-task conditions, and so it would not be absolutely necessary to utilize this paradigm again in order to compare left-starters and right-starters. Further work could additionally investigate the different outcome seen in Newman and Soylu (2013), who observed a right-starter advantage and not a left-starter advantage. This may have been a function of a difference between arithmetic calculation in Newman and Soylu (2013), versus arithmetic recall in Study Three. Future investigations could provide participants with the opportunity to perform both types of arithmetic problems in order to observe whether the effect of handedness is moderated by arithmetic procedure.

Finally, Study Four would benefit from changing how stimuli are presented. The visual similarity of digits ‘6’ and ‘8’ in Study Four could be solved by changing the procedure such that only one number digit appears on the screen at a time. Participants were shown stimuli in pairs because this best simulated the task from Morrissey et al. (2016). Participants could instead be asked to compare a digit to a variable standard by separating the procedure into blocks. For example, block one could have a standard of ‘7’, and in each trial participants would be asked to make a judgment on ‘5’, or ‘9’ as being either larger or smaller than the standard. This arrangement may also have some advantages in terms of trial efficiency, as there would be no need to counter balance whether the first or second number of a pair appears on top on the screen (e.g., $\frac{6}{8}$ or $\frac{8}{6}$). This would enable the examination of very similar comparisons as were used in Study Four, while hopefully yielding a cleaner result.

Taken together, these four studies further our understanding of how finger counting habits are related to numerical cognition. These investigations emphasize the importance of clearer reporting of how finger counting habits are assessed, but also the opportunities for discovery first discussed by Bender and Beller (2012) regarding the diversity of finger counting habits. Studies One and Two showed that there is variability in finger counting habits within individuals and within cultures and that these differences have cognitive consequences that may help explain the functional role of finger counting habits. Study Three showed that while finger movement failed to evidence any selective effect on arithmetic, self-reported finger counting habits did correspond to a large difference in arithmetic performance. This result may be synergistic with Study Four and other earlier work addressing the symbolic function played by the structural properties of finger counting habits in numerical cognition, and future work should follow up on these results, as well as those of Tschentscher et al. (2012), in order to better describe how numerical representations may differ between left- and right-starters. Nevertheless, this dissertation has helped to identify and further specify these finger counting effects, and serve as a basis for future research to devise a more complex model that disentangles the exact mechanisms by which finger counting habits interact with numerical cognition.

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Appendix A

Handedness Inventory

Please circle the appropriate response for each of the following questions. Some of these activities require both hands. In these cases, the part of the task or object for which hand preference should be identified is indicated in brackets. Some of the activities may be unfamiliar to you, but try to imagine the situation and then answer accordingly.

Indicate your degree of hand preference on the following scale:

Always With Left -3	Almost Always With Left -2	More Often With Left -1	Equal or No Preference 0	More Often With Right -1	Almost Always With Right -2	Always With Right -3
1. Writing						
2. Drawing						
3. Throwing						
4. Scissors						
5. Toothbrush						
6. Knife (without fork)						
7. Spoon						
8. Broom (upper hand)						
9. Striking a match (match)						
10. Opening box (lid)						
11. With which foot do you prefer to kick?						
12. Which eye do you use when using only one?						
13. On which arm do you wear a wristwatch?						

14. Which hand pulls the trigger when firing a handgun?						
15. O you have any physical or other handicap which might influence your answers to these questions?						
Yes	No					

Appendix B

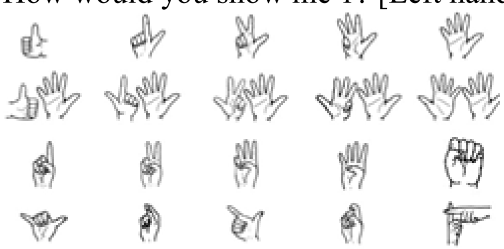
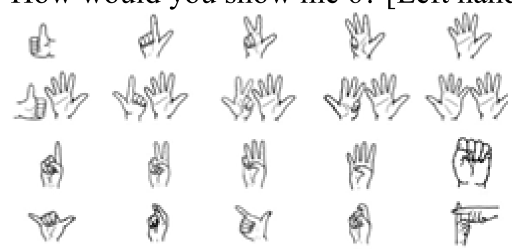
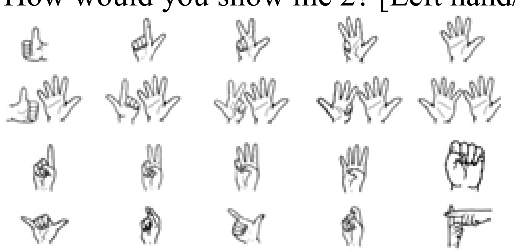
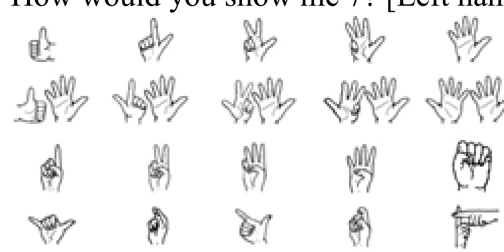
Finger Counting and Demographic Question Script (English)

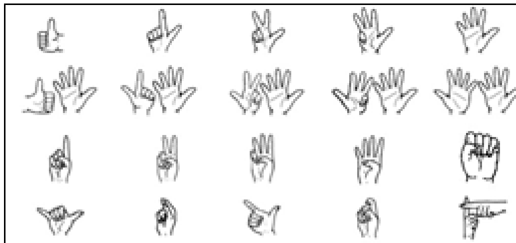
Subject id Number: ______________________
Subject Group/Handedness: ___ (#1 for one-handed counting method, #2 for two handed)

Name:_______________	Nationality:____________	Year in University__________
Gender:______________	First language:__________	Assessment start time:______
Date of Birth:_________	Second language:_______	Language used in preschool:____________
Ethnicity:_____________	Assessment date: ________	Language used in elementary school:________________

Spoken: "You will be given a series of numbers for the purpose of identifying your finger counting habits. When you are given a number, try and respond as quickly as possible by giving the corresponding number gesture that feels most natural. "

When two hands are used for a particular number gesture, please indicate which hand corresponds to which gesture.

How would you show me 1? [Left hand/Right hand]  ?	How would you show me 6? [Left hand/Right hand]  ?
How would you show me 2? [Left hand/Right hand]  ?	How would you show me 7? [Left hand/Right hand]  ?
How would you show me 3? [Left hand/Right hand]	How would you show me 8? [Left hand/Right hand]

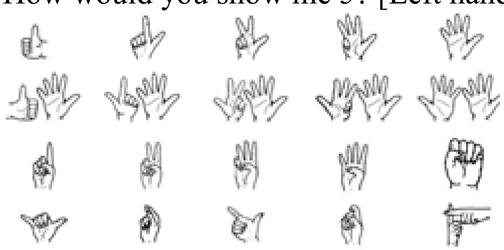


?

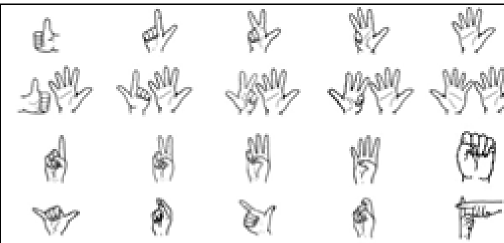
How would you show me 4? [Left hand/Right hand]

?

How would you show me 5? [Left hand/Right hand]

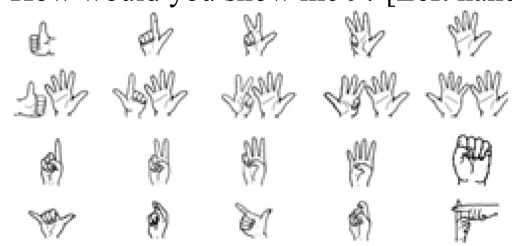


?



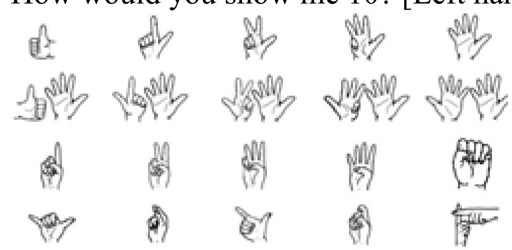
?

How would you show me 9? [Left hand/Right hand]



?

How would you show me 10? [Left hand/Right hand]



?

Appendix C

Study Three, accuracy by item

Addition			Subtraction			Multiplication		
Item	Canadian	Chinese	Item	Canadian	Chinese	Item	Canadian	Chinese
4 + 2	.95	.98	4 - 2	.99	1.00	4 x 2	.95	.99
4 + 3	.98	.99	4 - 3	.98	.99	4 x 3	.95	1.00
5 + 2	.97	.99	5 - 2	.97	1.00	5 x 2	.98	.99
5 + 4	.94	1.00	5 - 4	1.00	1.00	5 x 4	.97	1.00
6 + 2	.97	1.00	6 - 2	.96	1.00	6 x 2	.95	.96
6 + 3	.97	1.00	6 - 3	.97	.99	6 x 3	.85	.99
6 + 4	.97	.98	6 - 4	.98	1.00	6 x 4	.84	.99
6 + 5	.93	.99	6 - 5	.98	.99	6 x 5	.88	1.00
7 + 3	.92	1.00	7 - 3	.96	.98	7 x 3	.90	.99
7 + 4	.80	.99	7 - 4	.96	1.00	7 x 4	.71	.96
7 + 5	.78	.96	7 - 5	.94	1.00	7 x 5	.88	.99
8 + 2	.98	.99	8 - 2	.98	.99	8 x 2	.93	.99
8 + 3	.92	.99	8 - 3	.94	.94	8 x 3	.74	.99
8 + 6	.75	.99	8 - 6	.95	1.00	8 x 6	.57	.98
9 + 2	.96	1.00	9 - 2	.97	.99	9 x 2	.98	1.00
9 + 5	.88	.99	9 - 5	.94	1.00	9 x 5	.81	.98
9 + 6	.87	.99	9 - 6	.96	1.00	9 x 6	.61	.96
9 + 7	.84	.99	9 - 7	.97	.98	9 x 7	.57	.93

Appendix D

Alternate analyses for Study Four, using reaction time instead of EZ diffusion

The 63 included participants' mean response time performance was examined using a 2 (visual field) x 2 (response hand) x 6 (number pair) repeated measures ANOVA. Greenhouse-Geisser corrections were reported for all univariate analyses. Responses in the right visual field, *m* = 640ms, were significantly faster than in the left visual field, *m* = 645ms, F (1, 62) = 11.750, p = .001, η_p^2 = .159. Results indicated a significant difference in response time as a function of which number pair participants were responding to, F (3.3839, 209.747) = 199.435, $p < .0005$, η_p^2 = .763. Pairwise comparisons using the Bonferroni correction found that magnitude judgments of 3 vs. 5, *m* = 611ms, and 4 vs. 6, *m* = 614ms, did not differ significantly in their response time. Magnitude judgments of 5 vs. 7, *m* = 670ms, and 7 vs. 9, *m* = 672ms, also did not differ significantly. All other pairwise comparisons differed significantly, with 6 vs. 8, *m* = 711ms responded to slowest of all and 8 vs. 10, *m* = 575ms, responded to fastest of all. The observed right-field advantage did interact with response pair, F (4.302, 266.727) = 4.522, p = .001, η_p^2 = .068. Bonferroni corrected post-hoc tests suggest that the right-field advantage was larger for 3 vs. 5, *m*= 15ms, than 4 vs. 6, *m*= 2ms, 6 vs. 8, *m*= -3ms, and 8 vs. 10, *m*= -2ms. However, 3 vs. 5 did not demonstrate a significantly greater right-field advantage than 5 vs. 7, *m*= 5ms, or 7 vs. 8, *m*= 14ms. No other pairwise comparisons were statistically significant. Participants were not significantly faster at responding with a left or right hand, F (1, 62) = 2.715, p = .104, η_p^2 = .42, and there was no interaction observed between response pair and response hand, F (4.239, 262.789) = 1.429, p = .222, η_p^2 = .023. The observed right-field advantage did not interact with response pair, F (1,

62) = .348, p = .557, η_p^2 = .006, however there was a small three-way interaction between response pair, response hand, and visual field, F (4.394, 272.418) = 2.522, p = .036, η_p^2 = .039. Bonferroni corrected post-hoc tests indicate that this three-way interaction was driven by a larger right-field advantage for comparisons of 3 vs 5 when making a left hand response, m = 20ms, than when making a right hand response, m = 9ms.