THE UNIVERSITY OF CHICAGO

GIVING NUMBER WORDS A HAND: ICONIC GESTURE'S ROLE IN SUPPORTING CHILDREN'S MATH LANGUAGE DEVELOPMENT

A DISSERTATION SUBMITTED TO

THE FACULTY OF THE DIVISION OF THE SOCIAL SCIENCES

IN CANDIDACY FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

DEPARTMENT OF PSYCHOLOGY

BY

MADELEINE OSWALD

CHICAGO, ILLINOIS

JUNE 2022

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

First and foremost, I want to thank Susan Levine, for her warm mentorship these past 6 years, for embracing and guiding my many evolving ideas, and providing and encouraging opportunities to share my work to a wide range of audiences. Susan, you have always believed in me even the days when I didn't, and I cannot thank you enough for all your support which has allowed me to grow into the proud scientist and person I am.

Thank you to Susan Goldin-Meadow for initiating me into the wonderful world of gesture research, for encouraging me to celebrate even the smallest of victories, and always lending an ear when I need to work through ideas. Your passion for research inspires me every day.

Thank you to the other members of my committee for generously providing their time and sage advice, Diane Brentari for introducing me to new perspectives and Martha Alibali for engaging with me in fruitful discussions at my conference presentations.

Thank you to my friends. Clare Kordyback for being my biggest cheerleader. We've been through all of life's ups and downs together since grade 1 and you've had my back at each and every moment. Here's to a bright future of carrying on our mums' platonic power couple legacy. Cristina Carrazza for being my rock. You've helped me through pretty much every step of my research career from that day in South Bend we spent more time eating peanut butter Snickers than recruiting kids to helping me choose a dissertation title while watching trashy reality TV. Sorry not sorry I keep trying to follow you everywhere. Freddy Rockwood for always being up for an adventure. From comedy shows to minigolf to our quest for the best brunch cocktails in Chicago, you show me the joy in things big and small. And Ally Axelrad for being my sounding board and home away from home.

And thank you to the rest of the Levine Lab for the amazing advice, emotional support, and joy you all bring. In particular, Jake Butts for being a great friend and collaborator, Jalisha Jenifer and Nancy Pantoja for being the best office mates I could have asked for, Dominic Gibson for mentoring me through my master's thesis and paving the way for my exploration into number gestures, and Michelle Hurst for teaching me R and always being available for insightful feedback.

A special thanks to my past mentors who were instrumental in my journey. Karen Mackasey at Havergal College for answering my never-ending questions about math, Anna Shusterman at Wesleyan University for taking a chance on a theater kid who wanted to transition into child development and continuing to cheer me on to this day, and Jill Lany and Nicole McNeil at the University of Notre Dame for helping me carve out my own research path.

Thank you to the outstanding research assistants who helped me collect and code the data for this dissertation, Yesenia Almazan, Annika Christensen, Ryan Curry, Emily Kim, Lakshmi Kumar, and Mia Radovanovic. None of this would have happened without you.

My deepest gratitude goes to the families who participated in these studies, who let us into their homes and put up with the many challenges of online data collection.

To Penelope for her unconditional love which kept me sane during the hardest days of grad school.

Finally, I want to thank my family who have supported my love of learning from day one. My parents, Janet and Jim, for always encouraging my ever-changing passions, for driving 10 hours across international borders multiple times a year to see my plays or cook me dinner during exams, for editing my papers even when you had no idea what the content was about, for letting me vent or cry or laugh at any hour of the day, and for loving me no matter what (even when I don't water my plants). And to my grandpa Bill for the love and encouragement every step of the way.

ABSTRACT

Learning the exact meaning of number words is an important yet difficult milestone in children's mathematic development. A large body of work suggests that iconic number gestures (e.g., raising two fingers to indicate 'two') could play a role in supporting children's mapping of number words to exact quantities. Children are adept at recognizing and using iconic number gestures in laboratory settings by age 3. However, it is unclear if this is reflective of children's use of number gestures and/or observations of others using them during naturalistic interactions. Furthermore, the mechanism(s) by which such gestures benefit symbolic number learning are not well understood. In this dissertation I explore how children's use of and exposure to iconic number gestures in both naturalistic and laboratory environments relates to their understanding and use of number words.

Study 1 examines how and when children spontaneously use iconic number gestures in naturalistic interactions with their parents. I also examine whether parents' and children's use of these gestures are related, and whether usage of these gestures is related to children's later cardinal number knowledge. Iconic number gestures are infrequent as compared to number words. When they are used, they most often accompany a number word, label cardinal sets rather than count items, refer to magnitudes of 1 and 2, and refer to non-visible entities. While parents' and children's iconic gesture use was related, we found no evidence that parents' number gesture use impacted children's later number word production nor their cardinal number knowledge at 46-months-of-age.

Studies 2 and 3 propose that one mechanism by which parents' iconic number gestures facilitate children's cardinal number knowledge is by focusing children's attention on numerical information. In both spontaneous interactions with their parents and in a controlled laboratory experiment, children who viewed an iconic number gesture together with a verbal number word provided more numerically relevant responses than children who heard a number word alone.

Together the studies lend support to the theory that iconic number gestures help children map symbolic number words to quantities.

1. CHAPTER ONE: Introduction

Cardinal number words (e.g., "one", "two", "three") are at the foundation of all other symbolic math. It is important that children master the meanings of these symbols at an early age, as doing so is predictive of future academic achievement (Claessens & Engel, 2013; Jordan et al., 2009). The cardinal meanings of the number words are learned slowly (M. D. Lee & Sarnecka, 2010; Sarnecka & Carey, 2008; Sarnecka & Lee, 2009; Wynn, 1990, 1992) and there are vast individual differences in the age at which children acquire them (Clements & Sarama, 2007; Geary et al., 2018; Klibanoff et al., 2006; Levine et al., 2010; Starkey et al., 2004). Understanding what factors contribute to how and when children learn the cardinal numbers would allow researchers and educators to help children acquire them earlier and more easily.

A number of studies suggest that number gestures could play a role in supporting children's early math skill (B. Butterworth, 1999; Di Luca & Pesenti, 2011; Fuson, 1988; Gelman & Gallistel, 1978; Goldin-Meadow et al., 2014). Iconic number gestures (e.g., raising two fingers to indicate 'two') are thought to be especially useful because they represent number both symbolically and non-symbolically. Iconic number gestures are recognized as conventional symbols as early as age 2 (Gibson, 2017; Nicoladis et al., 2018) yet because they display numeric information in the number of outstretched fingers, unlike number words they are not an arbitrary symbol.

Children begin to recognize the iconicity of gestures around 24-months of age and learn iconic symbols more readily than arbitrary symbols (Namy, 2008; Namy et al., 2004). This coincides with the age at which children also begin to learn the meaning of number words, leading researchers to examine whether children can recognize the numerical information contained in iconic number gestures and if they can use iconic number gestures to quantify sets more easily than number words. However, only a few studies have looked at whether children actually take advantage of iconic number gestures outside the laboratory context. Fewer still explore how viewing iconic number gestures facilitates cardinal number learning. As gestures aid learning in many domains-- particularly learning new words and abstract concepts (e.g., Goldin-Meadow, 2015; Novack & Goldin-Meadow, 2015)--, and exist literally at one's fingertips, we might hypothesize that children use iconic number gestures to help them map number words onto the abstract concept of set size and that being exposed to more iconic number gestures might facilitate learning the meanings of number words.

This dissertation will explore these hypotheses using both observational and experimental data. Chapter 1 will review existing literature on gestures' role in early numerical development. Chapter 2 will examine how and when children spontaneously use gestures outside the laboratory and if the iconic gestures parents' use over many months influences their children's use of number gestures and their later cardinal number knowledge. Chapter 3 will then look at the impact of parents' iconic gestures on children's math talk through a narrower time frame, the moment in which the gesture is used, providing preliminary evidence that gestures engender children to focus on numerical information. Finally, Chapter 4 includes an experimental investigation into iconic number gestures' ability to focus children's attention on numerical information, building on the results of Chapter 3, and presents this as one potential mechanism through which gestures facilitate cardinal number learning.

1.1 How Children Develop Cardinal Number Knowledge

At around age 2, children can recite portions of the count list (e.g., "one" to "ten") but do not yet know the exact meanings of the words. Children may not even realize that these words refer to quantities, instead considering them like any another memorized routine like the alphabet song or "patty-cake" (Fuson, 1988; Wynn, 1990, 1992). Eventually children realize that number words do refer to quantity and will provide a number word when asked "how many?" (Frye et al., 1989; Fuson et al., 1985; Sarnecka & Carey, 2008). However, at this point, children still do not know that numbers have exact meanings. Learning the exact meanings begins in a stepwise fashion. First children figure out that "one" means exactly one item; they become "one-knowers". They can produce sets of one item, but for all larger numbers produce varying quantities that are larger than one. Months later, children become "two-knowers", then sometime later become "three-knowers". Some children pass through a "four-knower" stage, but eventually children figure out the cardinal principle-- that the last number said when counting items in a set represents the cardinal value of the set. These children are called "cardinal-principle (CP) knowers" (knower levels prior to this stage are collectively called "subset-knowers"). Some researchers have argued that becoming a CP-knower represents a conceptual shift in children's understanding of number; asserting that children can now understand the logic of counting and can apply this routine to any number in their count list (Le Corre et al., 2006; Sarnecka & Carey, 2008). Others argue that being classified as a CP-knower does not coincide with such a dramatic semantic induction but rather reflects children's ability to simply deploy a memorized tally procedure (Barner, 2017; Cheung et al., 2017; Davidson et al., 2012; Wagner et al., 2015). Regardless of which theory one agrees with it is still the case that becoming a CP-knower is an important milestone in children's numerical development. Typically, children become CP knowers between age 3 and 5, many months to years after first reciting a count list (Wynn, 1990, 1992). This leads us to ask: Why does number word learning take so long? This is important to know as the age at which children become CP knowers is predictive of future academic outcomes (Chu et al., 2016; Geary et al., 2018; van Marle et al., 2014). Achievement gaps in reaching CP-knower status are apparent early with some children becoming CP knowers at age 3 and other not until age 5 (Clements & Sarama, 2007; Geary et al., 2018). Much work has been devoted to understanding what factors contribute to children's acquiring of the cardinal principle earlier versus later.

One reason number word learning takes so long is that numbers are abstract; they do not describe a property of individual entities but rather the property of a set of entities (P. Bloom & Wynn, 1997). Two red cars on their own have the property of being red but not an inherent two-ness, it is the group of cars that carries two-ness. As such, set size is not always the most obvious aspect of set, as both adults and children are more sensitive to features like colour or shape (Chan & Mazzocco, 2017; Syrett et al., 2012). This theory is supported by decades of research demonstrating children learn words for concrete entities more easily than words for abstract entities (e.g., objects like "ball" vs. mental states like "thinking"); moreover, children map words to more visually salient entities better than less salient entities (L. Bloom, 2000; Pruden et al., 2006; Snedeker & Gleitman, 2004).

This is not to say that children cannot perceive quantity information. In fact, it is well known that babies have an early emerging ability to reason about non-symbolic number (Cantrell & Smith, 2013). By 10 months of age, they can accurately distinguish small numbers 1-3, known as the object file system (Feigenson & Carey, 2005), and by 6 months of age can approximately distinguish large numbers that differ by a 1:2 ratio, known as the approximate number system (ANS) (Xu & Spelke, 2000). But this sensitivity to differences in set size does not naturally translate to the ability to map a summary symbol to exact quantities. The object file system codes each item in a small set as individuals (e.g., this, this this) with no summary symbol whereas the ANS is ratio-dependent and approximate, with increasing inexactness with increasing set size. Thus, neither of these systems, on their own, enable young children to symbolize exact quantities. It is only after increased exposure to symbolic number that children can map the symbols to exact quantities. Indeed, individuals who do not receive such exposure, such as those born profoundly deaf without access to a signed language do not appear to understand exactness (Spaepen et al., 2013). Thus, in children's early years, before they have accumulated experience with symbolic number, they may not realize that exact number is a feature that can be described linguistically *at all*. Additional evidence that this is the case comes from cross-linguistic studies of children exposed to languages with differing singular/plural morphology (Almoammer et al., 2013; Marušič et al., 2016; Sarnecka et al., 2007). English and Russian obligatorily mark singular and plural nouns (e.g., 'car' vs. 'car**s**') whereas Japanese does not. So even prior to understanding number words, children hearing English and Russian are becoming familiar with linguistically distinguishing an exact quantity of one from greater quantities using grammatic morphology. Researchers argue that this can explain, in part, why Japanese children do not become one-knowers as early as English or Russian children (Sarnecka et al., 2007). In sum, it is not distinguishing set sizes that is difficult for children but rather mapping symbols, specifically number words, to exact quantities.

Despite the challenges of number word learning, there are proven ways to make the process easier. One of the strongest predictors of preschooler's cardinal number knowledge is exposure to math language. The quantity and quality of parent's number talk children hear predicts their later cardinal number knowledge over and above socioeconomic status (SES) (Elliott & Bachman, 2018; Gunderson & Levine, 2011; Levine et al., 2010). Interventions can work to lower the age of cardinal-principle acquisition; for example, when parents read their children books which contained rich numerical information, children gained knower-levels faster than children who were read books without numerical information (Carrazza & Levine, under review; Gibson et al., 2020). More number talk in preschool classrooms also is related to children's number word knowledge (Klibanoff et al., 2006).

In addition to number talk, parents and teachers can provide numeric information in non-verbal ways, through gesture. However, we do not yet know if increasing number gestures causes similar increases in cardinal number knowledge. As evidenced through number word intervention studies, the age at which children acquire the cardinal principle is malleable. An open question is whether number gestures might prove to be another avenue for improving children's early math knowledge.

1.2 Role of Gestures in learning in other domains

The notion that gestures could be useful for children learning early math concepts stems, in part, from young children's ability to benefit from observing and producing gestures in many other abstract domains. Learning challenging concepts can be improved by observing gestures along with a verbal explanation. For example, children taught about conservation of volume by an experimenter who simultaneously gestured about the size of containers learned more than those taught by an experimenter who did not gesture (Church et al., 2004; Ping & Goldin-Meadow, 2008). In other studies, preschool-aged children learned the concept of symmetry better when their teacher used gestures along with her speech (Valenzeno et al., 2003), and toddlers learned the concept of "under" better when taught with a gesture rather than a picture (Mcgregor et al., 2009). While the specific gestures used to teach the abstract concepts in these examples are different from the gestures one would use to teach children about number, the evidence demonstrates that children as young as two years of age can extract important information from gestures.

However, not all gestures convey the same type of information so some gesture forms might be better served to teach specific concepts. Deictic gestures, i.e., pointing with an extended finger or hand, are distinguished from iconic gestures, which visually represent the referent through hand shape or movement. Deictic gestures are some of the first meaningful gestures children produce, and comprise the majority of infants' gestures (Franco & Butterworth, 1996). They can serve to direct attention or stand in for a word to create a sentence-like phrase (e.g., child says "Daddy" and points to shoes to mean "Daddy's shoes"). They also convey the gesturer's communicative intent, such as the intent to teach, enhancing focus on the referent. In fact, toddlers learned the names of objects better when the teacher pointed to it than when she did not, even though in both conditions children visually attended to the object for the same amount of time (Booth et al., 2008). Deictic gestures can be used to refer to just about anything, but because of this flexibility they can be difficult to interpret without further context (Tomasello et al., 2007). A point to an object could refer to the object itself, a part of the object, or the colour of the object.

Iconic gestures, being a visual cue to their referent, contain more specific information than deictic gestures and therefore may be particularly helpful for learning (Cook, 2018). Firstly, they can provide information that supplements that found in speech; for example, saying "Open the bottle" while performing a twisting gesture clues the listener in to how the bottle should be opened. Secondly, iconic gestures can highlight the aspect of a scene a word is referring to; for example, if you are trying to teach a child the word "twist", a deictic gesture can draw visual attention to a person opening a bottle, but a twisting iconic gesture will highlight that "twist" refers to the action rather than "bottle cap". By the age of two, children can infer meaning from iconic gestures, indicating that they are useful beyond directing visual attention. For example, two- and three-year-olds learned the affordances of a toy better when shown an iconic gesture than a pointing gesture (Novack et al., 2015). And similarly aged children learn to label novel objects better when shown an iconic gesture versus a pointing gesture (Singleton & Saks, 2015). Applying these ideas to the math domain, acquiring the difficult concept that each number word represents a different exact quantity may be aided by observing gestures that represent exact set size iconically.

Learners can benefit not just by observing gestures but by producing them as well. There are many examples of children's gesture production correlating with their language or cognitive abilities. Children's iconic gesture use is related to the grammatical complexity of their speech (Nicoladis et al., 1999). Children who gestured more on explanations of how they solved spatial analogy and transformation tasks performed better on the tasks (Miller et al., 2020). Moreover, children gestured more when asked to explain *why* two quantities differed on Piagetian conservation problems versus when simply asked to describe two quantities, indicating gestures go hand in hand with complex thinking (Alibali et al., 2000). Gestures may also be causally related to learning, as restricting versus allowing or encouraging gesturing affects task performance. Children who are prevented from gesturing perform worse on a conservation of volume task than children who were allowed to gesture spontaneously (Alibali & Kita, 2010). Similarly, elementary school children who were taught to produce gestures while solving math equivalence problems were more likely to succeed at solving such problems than children not encouraged to gesture (Cook & Goldin-Meadow, 2006). Further, encouraging children to perform movement gesture when solving mental rotation problems increased their performance compared to actions or pointing gestures (Goldin-Meadow et al., 2012; Wakefield et al., 2019). We also know that encouraging deictic gesture production in children as young as 18 months of age increases vocabulary size (LeBarton et al., 2015). With benefits of one's own gesture production seen at such a young age, it is likely that that early math concepts, which are beginning to develop around age two, are impacted by performing math related gestures.

In sum, in other domains, gestures help ground abstract concepts in the physical world by transforming the abstract into a visual and embodied representation. Children might thus use gesture as a steppingstone to connect the physical world with the abstract concept of numbers (B. Butterworth, 1999).

1.3 Historical Role of Gestures in the Phylogeny of Number

Observing and producing gestures supports the learning of many abstract concepts, including math. By examining the historical record, we can infer that using fingers to represent number has been an integral part of numerical development in humans over historical time. To understand the significant role gestures may play in the ontogeny of math, we can look to the role they might have played in the phylogeny of math. Gestures are thought to be one of the first symbolic uses of number in human history (Coolidge & Overmann, 2012; Ifrah, 2000). While we do not have written records, we can deduce gesture's influence on the development of symbolic number systems through vestiges in our modern conventions. It is likely not a coincidence that possessing 10 fingers has resulted in the majority of the world's number systems using base 10, rather than a more mathematically convenient base 12 (Ifrah, 2000; Menninger, 1969). We see hints at fingers preceding words as symbols for numbers in vocabulary. In English, the word "digit" refers to "finger" as well as "number", and "five" likely stems from the root of the Proto-Indo-European word for "fist" (Winter, 1992). If gestures helped our ancestors develop their symbolic number systems, it may be the case that they could also support children's early numerical development.

Despite the pervasiveness of number gestures across many cultures, such representations are heavily influenced by cultural context. This is evidenced by the variability in the forms of iconic number gestures, i.e. which specific combination of fingers represent which numbers (Bender & Beller, 2012). For example, many Europeans count to five starting on the thumb while in the Middle East people tend to begin with the pinky. In Papua New Guinea, the number is indicated not by raised fingers but by unraised fingers (such that 5 is a closed fist, while 1 is all but the pinky raised). And the Pirahã peoples, famously studied because they are believed to lack words for exact sets greater than two, do not seem to use any finger-based number representation (Bender & Beller, 2012). Such cultural variation emphasizes the role that gestural input from others plays in the development of number gestures; children likely learn the conventional numeric gestural symbols of their culture by observing those around them using gestures.

1.4 Embodying Gestures in Math Cognition

Number gestures have likely been instrumental to the development of symbolic math in human history. They are still so entrenched in our number system that we can see a deep cognitive and neurological connection between fingers and math. Indeed, evidence suggests that basic math skills are embodied in the fingers—so-called embodied cognition, or the theory that cognition is influenced by bodily interaction with the world (Wilson, 2002). In both adults and children as young as 6, brain regions associated with finger representations are activated when making numerical magnitude judgements and calculations (Berteletti & Booth, 2015; Kaufmann et al., 2008; Krinzinger et al., 2011). Further, finger gnosia, the ability to mentally represent one's fingers, is correlated with, and predicts, numeric ability in 5-6-year-olds (Fayol, 1998; Noël, 2005). Interestingly, the connection between fingers and numbers appears to be malleable, which implies that the frequency of, or manner in which one produces number-related gestures impacts how one thinks about number. Training of finger gnosia leads to improvements in numerical performance (Gracia-Bafalluy & Noël, 2008). Moreover, the direction of finger counting (whether one starts on the left hand or the right hand) is related to the strength of one's numerical-spatial association: associating smaller numbers with the left side of space and larger numbers with the right side of space (SNARC effect), such that left-hand starters demonstrated a robust SNARC effect whereas right-hand starters had a much less robust SNARC effect with approximately 35% of right-hand starters demonstrating a reverse SNARC effect (M. H. Fischer, 2008). Relatedly, when viewing small numerals, left-hand starters show right-hemispheric motor cortex activation while right-hand starters show left-hemispheric motor cortex activation, indicating that even when not moving their hands adults are still associating numbers with the fingers they use to represent them (Tschentscher et al., 2012). Representations become embodied after repeated sensorimotor activation during cognitive processing (e.g., using one's fingers while counting). According to Moeller et al.'s (2012) theory of embodied numerosity, adults' and older children's representations of numbers being embodied in their hands is evidence that the embodiment process is begins at a younger age; multiple instances of using their fingers when children are forming their first representations of symbolic number leads to a robust association when they are older.

1.5 Iconic Number Gestures

The benefit of gesture to learning in multiple domains, the historic record of gestures in human creation of symbolic number systems, and the embodiment of number in older children and adults, lead us to hypothesize that gestures play a role in young children's cardinal number learning.

As mentioned above, some gestures contain more information than others. Deictic gestures can represent entities by pointing at them whereas iconic gestures physically resemble their referents. For number that means depicting discrete quantities with a specific number of outstretched fingers. Previous work has demonstrated the benefit of deictic gestures on early math skill, particularly counting (Alibali & DiRusso, 1999; Fuson, 1988; Graham, 1999; Saxe & Kaplan, 1981). However, we focus on iconic number gestures because they bridge the gap between children's non-symbolic representations of numbers and their learning of number words, due to their depictive nature (Gibson, 2017; Gunderson, Spaepen, Gibson, et al., 2015). The words we use to label sets are arbitrary; there is no inherent 'two-ness' or even 'set-ness' about the word "two", whereas the iconic gesture for two (the index and middle finger held in a V shape) is not only a conventional symbol but also physically describes twoness with the number of outstretched fingers. Iconic number gestures are found in many cultures and were arguably one of the first steps towards developing a verbal count list in language evolution (Ifrah, 2000). Moreover, even though iconic number gestures are not produced by parents or children as frequently as other number related gestures (such as pointing while counting) when children are toddlers (J. Lee et al., 2015), they may support children's early numerical development. We focus on two categories of iconic number gestures: cardinal number (CN) gestures (sometimes referred to as "finger montring") and finger counting.

1.5.1 Cardinal Number Gestures

A CN gesture is the simultaneous display of fingers to indicate a set's size. They can reveal children's conceptual understanding when their words cannot. Gunderson, et al. (2015) found that young children may know more about numbers than they can verbally express. In that study, children were tested on two versions of the "What's on this Card" (WOC) task, in which they were asked to label a picture of a set of items with either a number word or a CN gesture. While CP-knowers were equally successful at labeling set sizes of 1 - 3 in speech and in gesture, subset-knowers were more accurate when using gesture. This effect was strongest for numbers immediately above children's knower-level. These results suggest that CN gestures precede speech in correctly labeling set size, and supports previous findings that children have some knowledge of the next number above their knower-level (Barner & Bachrach, 2010). Moreover, Gibson et al. (2019) found that children classified as 'mismatchers', i.e., those whose gestures did not match their speech on at least one trial of the WOC task, were significantly more likely than non-mismatchers to benefit from an enriched counting training, as measured by an improvement in knower-level. This indicates that CN gestures are a useful window into children's number knowledge and that they index children's readiness to learn their next number.

CN gestures could also be a bridge to connect non-symbolic quantities to symbols, as they can be used as both. Gibson (2017) tested this hypothesis by asking children to verbally label CN gestures (Fast-Gesture task) and to verbally label arrays of dots (Fast-Dots task), each displayed rapidly on a screen to prevent children from answering via counting. The author hypothesized that if children see CN gestures as non-symbolic quantities of fingers they should perform similarly on the Fast-Gestures and the Fast-Dots tasks, showing more errors for larger numbers, in line with utilizing the Approximate Number System (ANS). But if CN gestures are interpreted as symbols, children should perform more accurately on Fast-Gestures than Fast-Dots as their performance on Fast Gestures would not reflect the scalar variability of the ANS. Their results support the latter conclusion: CP-knowers as well as subset knowers were significantly more accurate on the Fast-

Gestures task than the Fast-Dots task, suggesting that children as young as age 3 are already perceiving CN gestures as symbols.

Further supporting the hypothesis that children perceive CN gestures as symbols for quantity, Nicoladas et al. (2018) conducted a modified version of the Give-a-Number task (Wynn, 1992) by using CN gestures to request sets of items instead of words. Children aged 2-5 years of age were more likely to respond accurately when presented with conventional gestures than non-conventional gestures (e.g., one finger raised on each hand to represent 2). This concords with adults' tendency to respond faster to conventional gestures than non-conventional gestures (Di Luca & Pesenti, 2008).

1.5.2 Finger Counting

Finger counting is the sequential raising of fingers to indicate counting items in a set. These gestures have mostly been studied in children learning arithmetic, as they will often employ their fingers when performing addition or subtraction (Berteletti & Booth, 2015; Crollen & Noël, 2015; Dupont-Boime & Thevenot, 2018; Jordan et al., 2008). However, in even younger children, finger counting may help establish number representations. In a study of 4- to 7-year-olds, Lafay and colleagues (2013) found a correlation between spontaneous finger counting and cardinal number knowledge, controlling for age. Preschoolers' finger counting accuracy (labeling each finger correctly while counting and displaying the correct number of fingers) is also related to general numeric abilities (U. Fischer et al., 2020).

Finger counting can make the base 10 structure of the count list salient and help keep track of to-be counted items. Finger counting may also emphasize the connection between counting and cardinality, as the last configuration in a finger counting sequence is often the same as the CN gesture corresponding to the set size. Children's ability to rapidly label fingers raised in canonical counting configurations (e.g., labeling a thumb and pointer finger as "two") is correlated with their verbal counting ability in kindergarten (Van Rinsveld et al., 2020). Moreover, scores on the rapid finger labeling task predicts 1-100 number line performance in 1st grade, even mediating the relationship between counting ability and number line performance, indicating that finger counting can strengthen numerical representations of much higher numbers than can be displayed on two hands.

Tagging each finger as it is raised with a number word can reinforce the one-to-one correspondence between number symbols and objects (Andres et al., 2008), an essential feature of early numeric skill (Gelman & Gallistel, 1978). Finger counting can also help when maintaining one-to-one correspondence becomes more difficult, such as when to-be-counted entities are not visible. For example, children were less accurate at counting sets of sounds when they were prevented from using their fingers (Crollen & Noël, 2015).

In sum, both types of iconic number gestures, CN and finger counting, may allow children to think and communicate about cardinal numbers more easily in the early stages of symbolic math development.

1.5.3 How might Iconic Number Gestures Benefit Learning?

The research thus far suggests that iconic number gestures are beneficial for some aspects of math; young children use them more accurately than number words and to keep track of items. But we still do not know if using or viewing gestures leads to increased learning. If gestures do help children learn the meanings of number words faster and more easily, we also need to know how, i.e., by what mechanism(s). Identifying the mechanism(s), while adding to our theoretical understanding of gestures and early math, will also dictate what kinds of interventions would be most efficient and effective. There are several possibilities, which are not mutually exclusive:

Gestures as a Reinforcer for Speech: Iconic gestures might serve to reinforce information contained in speech. Clark and Paivio's (1991) dual coding theory posits that redundant information provided in two modalities, specifically verbal and non-verbal, strengthens information encoding and recall. Dual coding is especially helpful for abstract words, which do not evoke as strong of a mental imagery as concrete words. Numbers can be applied to sets of any discrete entity (e.g., two cars, two jumps, two seconds, etc.) and thus do not have a consistent mental image to align to. This means that pairing a gesture with the number word can provide a consistent image to associate with the number word. This phenomenon is evidenced in Gibson (2017); children more easily associate the word "two" with a two gesture than a set of two dots. Additionally, images are more easily associated with other images than words. Again Gibson (2017) supports this; children more easily map sets of two dots to a two gesture than to the word "two". Using a dual code, a number gesture along with a number word can thus help map an image to a word. For example, children who already know that "two" corresponds to the two gesture and that the two gesture corresponds to two dots may infer when exposed to the dual code that "two" must also correspond to two dots.

Gestures as a Bridge: Iconic number gestures could serve as a bridge connecting symbolic and non-symbolic quantities. As previously discussed, iconic gestures contain both symbolic and non-symbolic information. Children recognize them as symbols and can accurately label them with number words (Gibson, 2017; Nicoladis et al., 2018). But they may also be able to recognize the non-symbolic, i.e., iconic, information, that each raised finger of the gesture corresponds, one-to-one, with items in a set. Children find it easier to use iconic than arbitrary symbols. "Two" is an arbitrary symbol, while the two gesture is iconic. This then plays out similarly to the dual coding theory: children learn to associate the word 'two' with two fingers, then they use one-to-one correspondence to map fingers in a gesture to other sets with the same numerosity in the world. Realizing that "two" is mapped to a 2-gesture which is mapped to a set of 2 items they may infer that "two" is also mapped to a set of two items. The key difference between the bridge theory and the dual coding theory is that according to the bridge theory, children notice the non-symbolic properties of the gesture and using one-to-one correspondence, whereas the dual coding theory posits that the gesture is treated more as a symbol and is associatively mapped to quantities (e.g., I see there are "one, two" fingers and "one, two" things (bridge theory) vs. I always use this particular gesture with two things (dual-coding theory).

Gestures Ground Abstract Concepts: For abstract concepts that are difficult to picture, gesture provides a visual stand in, grounding the abstract in the concrete. This might be especially useful for times when numbers refer to intangible numeric entities like units of time. It is also useful when working memory is taxed and one needs to 'hold' information in their hands to free up cognitive resources. Indeed, 5-year-olds use their fingers to count more often when asked to count two sets of sounds than just one set of sounds (Crollen & Noël, 2015).

Gestures as an Attention Director: Finally, gestures draw attention to both speech and visual information. Gestures cause listeners to pay more attention to accompanying speech; listeners rate speech as more interesting, remember it, and comprehend it better when the speaker uses gesture (Guilbert et al., 2021; Krahmer & Swerts, 2007; Llanes-Coromina et al., 2018). Thus, an iconic number gesture might make children more cognisant of spoken number words. Research consistently demonstrates that deictic gestures direct visual attention (e.g., G. Butterworth, 2004; G. Butterworth et al., 2013; Tomasello et al., 2007). Babies can visually follow points from early on in development, knowing that they are to look at the referent of the point rather than the gesture itself (e.g., Desrochers et al., 1995; Leung & Rheingold, 1981; Rohlfing et al., 2012). Iconic gestures can also direct visual attention to relevant features associated with the gesture. When learning math equivalence problems, elementary school children spent more time looking at the problem when the instructor used a gesture to explain a solution strategy, whereas they looked more at the instructor when she did not use a gesture (Wakefield et al., 2018). It might therefore be the case that an iconic number gesture draws children's attention to set size rather than to other features of a visual array (e.g., objects kinds or colour).

While prior work has explored how iconic number gestures act as a bridge between symbolic and non-symbolic quantities (Gibson, 2017), and some research has touched on iconic number gestures grounding abstract concepts (Crollen & Noël, 2015), no work to date has directly investigated whether or not iconic number gestures serve as attentional directors. Addressing this gap in the literature is particularly important as one of the first hurdles children face when learning number word meanings is understanding which feature of a scene the number word refers to, that of set size, when there are other more salient features available (P. Bloom & Wynn, 1997; Syrett et al., 2012). In the following section I outline how I plan to gain a better understanding of this potential mechanism as well as the role iconic number gestures play in learning number words over time.

1.6 Research Questions

Many researchers have inferred that iconic number gestures help children's development of cardinal number concepts but there is still a lack of evidence to support this assumption. The present dissertation seeks to tackle the overarching question of 'do iconic number gestures improve cardinal number knowledge?'. As the cardinal principle takes on average two years to learn (Carey, 2009; Le Corre et al., 2006; Wynn, 1990, 1992), in Chapter 2 I took a longitudinal approach by looking at the impact of parents' gestural input on children's later number knowledge. In similar longitudinal studies, we know that parents' number word use is related to children's cardinal number knowledge (Gunderson & Levine, 2011; Levine et al., 2010). Likewise, parents' overall gesture use predicts children's later vocabulary size (Rowe & Goldin-Meadow, 2009a). Might this same relationship be true of iconic number gestures and cardinal number knowledge?

I then ask, ‘why are iconic number gestures beneficial to learning number word meanings?’. To begin tackling this question I look to naturalistic observations of spontaneous gesture in Chapter 2. The contexts in which individuals choose to use a gesture hints at what purpose the gesture is serving for them. For example, children use finger counting more when counting non-visible sets than visible sets indicating that gesture could be a working memory aid or a grounding of intangible entities. Thus, I explore the age at which children use gesture, if the gestures are used to count or label items, the magnitude of the gesture (e.g., “one” vs “ten”), and what entity the gestures refer to. Further narrowing in on which aspect of gestures is beneficial, I tested one potential mechanism from the list outlined above, asking whether number gestures can serve as an attention director to set size. Using two methodologies, observational (Chapter 3) and experimental (Chapter 4), I ask if viewing an iconic number gesture causes children to notice numerical information as a relevant feature to verbally label more so than hearing a number word alone.

2. CHAPTER TWO Study 1: The role of spontaneous gestures in children's home environment

2.1 Background

Observing meaningful gestures leads to better understanding of challenging concepts in other domains, but it is unknown if this is also true of observing iconic number gestures to learn the concept of cardinality. To explore this possibility, we looked to the home environment, as it is likely the place children are first exposed to such gestures. Furthermore, studies conducted thus far on children's use of iconic number gestures have been performed in highly controlled contexts where experimenters elicit gestures from the participants. But what do spontaneous iconic number gestures look like in everyday life? This is important to know, as the naturalistic contexts in which children employ a gesture could hint at the gesture's function.

2.1.1 Learning from Viewing Gesture

Children benefit from watching others gesture. Firstly, watching gestures encourages children to gesture more themselves; indeed, parents' overall gesture frequency is correlated with that of their children (Namy et al., 2008; Rowe & Goldin-Meadow, 2009b). Moreover, while there is evidence that congenitally blind children use iconic number gestures, they are infrequent, inconsistent, and non-canonical to their culture, suggesting that sighted children are learning to produce these gestures, at least in part, by seeing others use them (Crollen et al., 2011). Secondly, gestural input improves learning of challenging concepts. While little research exists on learning from viewing iconic number gestures, work in other domains suggest this could be the case. Children taught about conservation by an experimenter who simultaneously gestured learned more than those taught by an experimenter who did not gesture (Church et al., 2004; Ping & Goldin-Meadow, 2008). Likewise, students taught by teachers who used gestures to explain how to solve a math equivalence problem did better on solving such problems on their own than students whose teachers did not gesture (Singer & Goldin-Meadow, 2005). Iconic gestures might be especially impactful for learning. Toddlers whose mothers used more iconic gestures when teaching nouns had better comprehension of such nouns (Zammit & Schafer, 2011). Children aged 2-4 years were able to infer the meaning of a novel verb depicted through iconic gesture without ever observing an entity perform the action (Goodrich & Hudson Kam, 2009). Iconic gestures also helped preschoolers comprehend instructions when sentences were complex (McNeil et al., 2000).

Acquiring the difficult concept of the cardinal principle may thus be aided by observing gestures that reinforce the concept. This possibility makes it critical that we understand how parents use iconic number gestures with their children. We know that, outside of gesture, parental number input is very important for children's math learning. In a longitudinal study following children from 14- to 30-months of age, both the quantity (Levine et al., 2010) and quality (Gunderson & Levine, 2011) of parent number talk predicted children's later cardinal number knowledge. In this study we extend those findings by examining the relation of parents' iconic number gestures to children's cardinal number knowledge using the same data set.

2.1.2 Producing Gestures

Speakers do not just gesture to communicate to others as evidence by people continuing to gesture even when their conversation partner is not visible (Iverson & Goldin-Meadow, 1998; Iverson & Goldin-Meadow, 2001). Producing gestures serve a function for the speaker themselves. It is debated on what that function might be, and it may well be the case that the possibilities are not mutual exclusive. One camp contends that gestures aid in retrieving lexical information (Krauss, 1998; Krauss et al., 2000; Krauss & Hadar, 1999), others argue that gesture's purpose is to maintain information in working memory (Goldin-Meadow et al., 2001; Ping & Goldin-Meadow, 2010), still others claim gestures help package complex information into speech (Alibali et al., 2000; Kita, 2000). Researchers base these claims, in part, by observing under which contexts gestures spontaneously arise, as production of iconic gestures varies across contexts. For example adults are more likely to produce gestures when talking about non visible entities than visible entities (Morsella & Krauss, 2004; Wesp et al., 2001), this can be interpreted as gestures facilitating the recall of spatial information. The contexts in which iconic number gestures are used can thus reveal the function they serve.

Iconic number gestures might be used because they are better understood than number words. As Gunderson et al. (2015) demonstrated, subset knowers were more accurate at labeling sets with gestures than words. Studies in other domains have also shown that children asked to explain a difficult concept will express it through gesture if the verbal response is not easily accessible. On a Piagetian conservation task, many children who are not yet able to explain the notion of conservation in speech will use their hands in combination with their speech to demonstrate some understanding of the concept, such as spreading their fingers to indicate sand being poured into a wider container while they verbally express that the taller container has more sand (Alibali et al., 2000; Breckinridge Church & Goldin-Meadow, 1986). Similarly, older children who are on the cusp of learning to solve math-equivalence problems will often use gesture to show a correct strategy while providing an incorrect strategy in speech (Alibali & Goldin-Meadow, 1993). Thus, we might expect an inverted U-shaped curve describing the frequency of iconic number gestures over time, with few gestures in children's early years, an increase prior to children's mastery of the cardinal principle, and a decrease once children are well versed with number words and do not need to rely on gestures.

Gestures could also serve as a stand-in for entities that are not visually present. As children find it more difficult to enumerate non-visual entities, such as events or sounds, than visual objects (Mix, 1999; Mix et al., 1996b), a physical representation of the sets in the form of fingers might be beneficial. Indeed, when asked to count two different sets of sounds children were less accurate when they were prevented from using their fingers (Crollen & Noël, 2015). Kindergartners are more likely to use finger counting to solve verbal calculation problems than problems involving physical manipulatives (Levine et al., 1992). In line with this, gestures are especially useful for those with lower working memory, for whom maintaining non-visual entities in mind is difficult. Noël et al. (2004) showed that first graders with low working memory relied more on finger counting to solve addition problems than children with high working memory (cf. Dupont-Boime & Thevenot, 2018). Those with low working memory also looked at their fingers more during a similar arithmetic task (de Chambrier et al., 2018). It may thus be the case that gestures are used more frequently to describe non-visual sets than visual sets.

2.1.3 The Present Study

In the present study we examine iconic number gestures in two ways. First, we looked at the influence of parental iconic number gesture input on children's own gestures and number knowledge. We know there is a relationship between parents' number word input and children's later cardinal number knowledge (Gunderson & Levine, 2011; Levine et al., 2010). Is the same relationship true for iconic number gestures?

Second, to describe the ways in which iconic number gestures are used spontaneously by both parents and children, we recorded the frequency and function of these gestures comparing them to the usage of number words. Thus, we were able to distinguish between two potential roles for spontaneous number gestions: 1) gestures simply serving to reinforce the number word's meaning in all contexts or 2) gestures being employed under particular circumstances such as when objects are not visually present.

To address these questions, we looked at:

1) The relationship between children's iconic number gestures and their parents' iconic number gestures.

2) The relationship between iconic number gestures (made by parents or children) and children's number word use and cardinal number knowledge.
3) The frequency of iconic number gestures among both parents and their young children compared to number words, including how frequency changes over development.
4) The function of iconic number gestures: whether they occur with number words or alone, what set sizes the describe, and what sorts of entities they refer to (e.g., objects, time, age).

2.2 Methods

2.2.1 Participants:

Participants were 59 typically developing children (27 female) raised in an English-only language environment and their primary caregiver(s) who were participating in a longitudinal study of language development. Families were selected to be demographically representative of the greater Chicago area as reported in the 2000 U.S. Census. 5 additional dyads were tested but were excluded from analysis because they participated in fewer than 10 of the 12 sessions.

The participants were racially and ethnically diverse, including 34 White Non-Hispanic, 5 White Hispanic/Latinx, 12 Black/African American, and 8 children of mixed/other race. At the beginning of the study period, 4 families reported incomes of less than $15,000; 13 had incomes between $15,000 and $34,999; 10 had incomes between $35,000 and $49,999; 10 had incomes between $50,000 and $74,999; 10 had incomes between $75,000 and $99,000, and 12 reported incomes greater than $100,000. Parents were asked to report who was primarily responsible for childcare. 52 families listed the mother as the primary caregiver, one family listed the father as the primary caregiver, and six families reported that both parents equally shared the role (referred to as dual caregivers).

2.2.2 Procedure:

Families were filmed in their homes for 90 minutes every 4 months, from when the child was 14 months old to when the child was 58 months old (a total of 12 sessions). The experimenter was instructed to focus the camera on the child. The videos consisted of typical daily activities such as eating meals, reading books, and playing with toys. No particular activities were requested – parents were simply told to do what they ordinarily do at home.

All speech and gestures produced by the child and the primary caregiver(s) were transcribed. We searched the transcriptions for the iconic number gestures 1-10. Iconic number gestures were defined as the raising of fingers to indicate quantity; they did not have to be conventional forms of the gesture (e.g., raising the index and middle finger in a V shape to represent 2 rather than raising the index finger on both hands) but most (92% of parents' and 88% of children's) were conventional. We considered both cardinal number (CN) gestures, which statically describe set sizes and finger counting (FC) gestures, which sequentially count entities. We excluded instances where a 5 hand shape was used for "high-five" as this is more like an idiom than a quantitative gesture. So as not to overweight individuals who happened to count to higher numbers, unless otherwise indicated, each FC sequence was coded as one instance of iconic number gesture, such that gesturing "one, two, three" counted as one instance. For CN gestures, each gesture was coded as one instance.

2.2.3 Gesture Coding scheme:

Each iconic number gesture was further described by four variables: (1) the numerical magnitude (i.e., the number of fingers; 1-10); (2) the type of iconic gesture (i.e., whether it was a CN or FC gesture, with the former defined as simultaneously raising a number of fingers and the latter defined as gestures sequentially presented less than 5 seconds apart; (3) whether it was accompanied by a spoken number word or not; and (4) the category of referent.

In terms of category of referent, children and parents use iconic number gestures to refer to a variety of entities, from stories to stairs to somersaults to time units such as minutes. We classified each referent into 6 broad categories: present objects (animate or inanimate entities that were visually available), non-present objects (animate or inanimate entities that were not visually available), time units (minutes, years -including age-), other non-objects (actions and entities not related to time or age), rote counting, and numbers themselves (Arabic numerals and other talk about number not related to specific sets). See Table 1 for examples.

Referent Category	Examples
Objects	P: How many cookies do you want? C: [*gestures 3*]. C: There are two fish [*gestures 2*].
Time	C: [*gestures 5*] Five more minutes. P: How old are you? C: [*gestures 2*]
Other Non-Objects	P: Two more bites. C: No, one more [*gestures 1*]. P: There are three letters in your name [*gestures 3*].
Rote Counting	P: [*gestures 1,2,3*] C: One, two, three. C: One, two, three [*gestures 3*], four [*gestures 4*].
Numbers	C: Count to 5 [*gestures 5*]. P: What number is that? [*point to Arabic numeral*] C: [*gestures 2*].

Table 1. Examples of iconic number gesture referent categories

2.2.4 Word Coding Scheme:

We also searched the transcriptions for verbal uses, by both parent and child, of the numbers 1-10. Instances in which the word "one" was used non-numerically (e.g., "Can you pass me that one?") were excluded. As with gestures, counting sequences (strings of sequential number words) were coded as one instance. Each number instance was further described by three variables: (1) numerical magnitude; (2) type of number instance (labeling cardinal sets or counting); and (3) category of referent (using the same 6 referent categories as in the gesture coding scheme).

2.2.5 Cardinal Number Knowledge:

At 46-months of age, children's cardinal number knowledge was assessed using the Point-to-X task (Wynn, 1992). The task consisted of 16 items, each a piece of paper, divided in half by a vertical line with a set of squares on the left and right sides. Each set represented the cardinal values 1 through 6. For each item, children were asked to "Point to X", X being the cardinal value of one of the two sets on the page. Each child's score was the number of items correct out of 16.

2.3 Results:

2.3.1 Frequency of overall iconic number gesture and number word use

Iconic number gestures are far less frequent than number words. Across all 12 sessions, parents produced an average of 3.05 iconic number gesture instances (SD = 5.32), with a range of 0-35 and a median of 1, and children produced an average of 6.27 (SD = 7.69), with a range of 0-43 and a median of 5. The average number of spoken number word instances across all sessions was 190.01 (SD= 139.58) for parents and 120.34 (SD = 77.47) for children.

Iconic number gestures were more frequent in children than their parents ($t(57) = 2.64$, $p < 0.01$). 20 parents (33.9%) and 10 children (16.9%) never produced an iconic number gesture. In contrast, parents produced more number words than children ($t(57) = 3.35$, $p < 0.01$), and all parents and children in our sample produced number words.

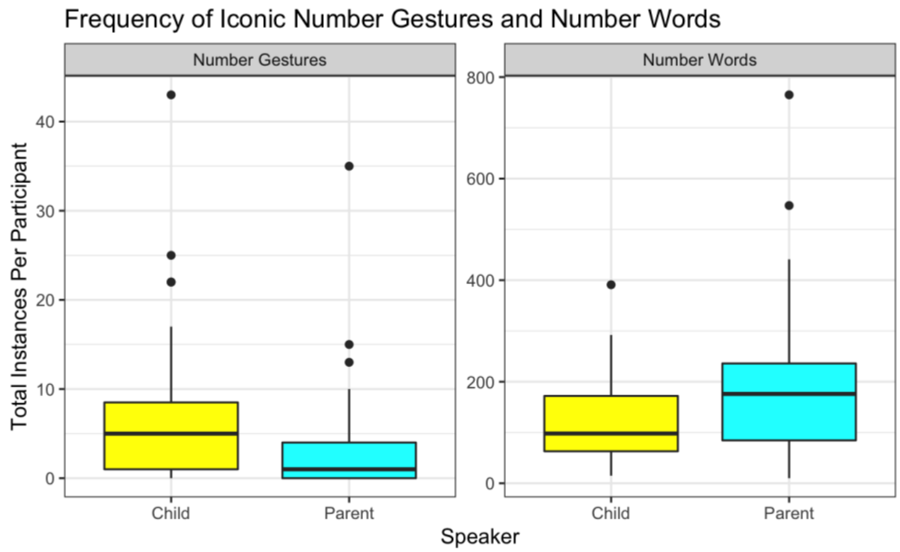


Figure 1. Frequency of Iconic Number Gestures and Number Words from ages 14- to 58-months

2.3.2 Relationship between children's iconic number and their parents' iconic number gestures

Children's iconic gesture instances were not significantly correlated with parents' iconic gesture instances ($r(57) = 0.15$, $p = 0.25$). However, when we grouped children and parents into 'Ever-Gesturers' (those who produced at least one iconic number gesture token over all 12 sessions) ($N_{Child} = 49$, $N_{Parent} = 39$) versus 'Never-Gesturers' (those who did not produce any iconic number gesture tokens) ($N_{Child} = 10$, $N_{Parent} = 20$), we found a significant association between parents' group and children's group $\chi^2(1) = 3.63$, $p < 0.05$, such that 'Ever-Gesturer' parents were more likely to have an 'Ever-Gesturer' child, and 'Never-Gesturer' parents were more likely to have a 'Never-Gesturer' child. Moreover, an independent samples t-test reveals that children of 'Ever-Gesturer' parents produced more iconic gestures than children of 'Never-Gesturer' parents ($t(57) = 3.11$, $p <$

0.01). It appears that at least by some measures, children's and parents' iconic number gesture use is related.

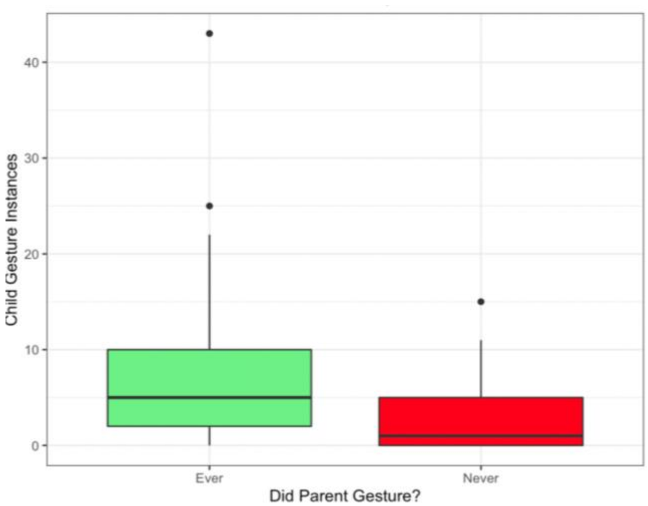


Figure 2 Children's number Gesture Instances by Parent Ever/Never Status

2.3.3 Relationship between iconic number gestures and children's number word use and number knowledge

Overall, children's iconic gesture instances were not significantly correlated with their own number words (r (57) = 0.21, p = 0.12) nor with their parents' number words (r (57) = -0.04, p = 0.75). Similarly, parent's iconic gesture instances were not significantly correlated with their own number words (r (57) = 0.17, p = 0.20) nor children's (r (57) = -0.10, p = 0.43).

We next explored if gestural input at earlier time points predicts number word use at later time points. We compared parents' and children's total gesture instances from child aged 14- to 34-months to children's number word instances from age 38- to 58-months. Neither parent's earlier gesture instances (r (57) = -0.16, p = 0.21) nor children's earlier gestures instances (r (57) = -0.09, p = 0.49) were correlated with children's later number word production.

Finally, we explored how gesture production and input related to children's cardinal number knowledge, as measured by performance on the Point-to-X task administered at 48-months-of-age. We predicted scores using the total iconic number gesture instances from child's age 14- to 42-months. We found that cardinal number knowledge was not predicted by parents' (r (57) = -0.07, p = 0.57) nor children's (r (57) = 0.087, p = 0.51) iconic number gesture instances. Thus, unlike number words (Levine 2010, Gunderson 2011), cardinal number knowledge does not appear to be related to iconic number gesture input or use by the child in this data set.

2.3.4 Frequency of different types of iconic number gestures across development compared to number words

We next looked at how iconic number gesture use changes over time. Child age was significantly positively related to the number of child iconic number gesture instances (r (57) = 0.19, $p < 0.01$) but not to the number of parent iconic gesture instances (r (57) = 0.04, p = 0.3) such that as children grew older, their iconic gesture instances became more frequent, while parent's use of iconic gesture instances remained relatively stable. In contrast, for number words, both parents (r (57) = 0.12, $p < 0.01$) and children's (r (57) = 0.34, $p < 0.001$) production increased with child's age.

We separated iconic number gesture instances into the two different types, CN and FC gestures. CN gestures were used much more frequently than finger counting by both parents $Mean_{CN}$ = 2.8 (SD_{CN} = 5.28), $Mean_{FC}$ = 0.25 (SD_{FC} = 0.66) and children $Mean_{CN}$ = 5.72 (SD_{CN} = 7.36), $Mean_{FC}$ = 0.54 (SD_{FC} = 1.09). 37 parents and 48 children produced at least one CN gesture instance. 9 parents and 14 children produced at least one finger counting instance. While we coded all numbers within a finger counting sequence as one instance, we also looked at how many gestures made up the sequence. Of the individuals who finger counted, the mean length of sequence for parents was 8.22 (SD = 6.8) and 4.02 (SD = 1.46) for children.

Mirroring this pattern, number words were also used more frequently for cardinal labeling than for counting by both parents ($Mean_{Cardinal}$ = 163.08 ($SD_{Cardinal}$ = 121.04), $Mean_{Counting}$ = 27.88 ($SD_{Counting}$ = 22.93)) and children ($Mean_{Cardinal}$ = 89.19 ($SD_{Cardinal}$ = 57.81), $Mean_{Counting}$ = 31.15 ($SD_{Counting}$ = 26.34)).

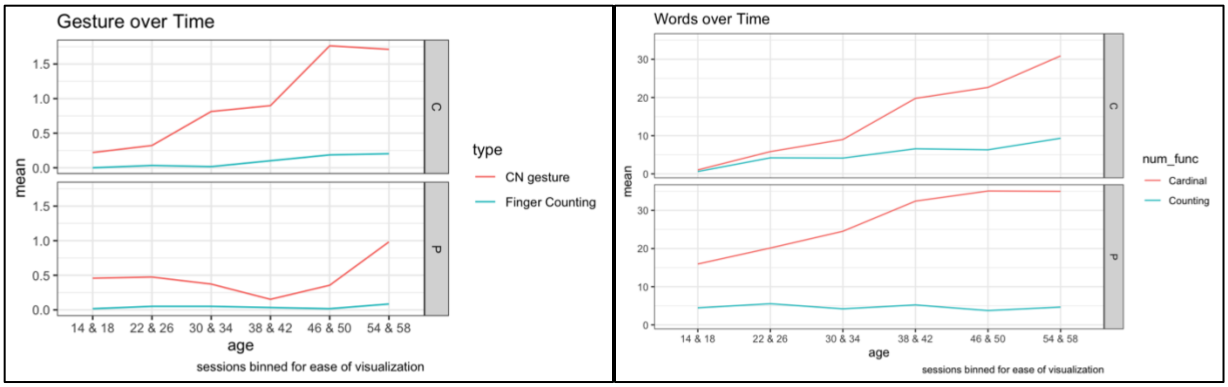


Figure 3 Frequency of different types of gestures and number words over time

Like number words, children and parents use iconic gestures more for cardinal labeling than for counting, and children's production of both types of iconic gestures (CN and FC) increases over time whereas parents use of these gesture remains stable over increases in child age.

2.3.5 Function of iconic number gestures

In this section we discuss the function of iconic gestures and therefore focus on the 39 parents and 49 children who produced at least one iconic number gesture.

Numerical Magnitude

This section focuses on unique types of gestures rather than number of instances, thus we treated finger counting sequences as individual tokens rather than an entire sequence. Children produced an average of 3.1 types (SD = 2.43) of iconic gestures over all 12 sessions while parents produced an average of 2.12 types (SD = 2.67). Numerical magnitude was negatively correlated with frequency of production for both children ($r(590) = -0.44$, $p < 0.001$) and parents ($r(590) = -0.3$, $p < 0.001$) such that smaller numbers were produced most frequently while larger numbers were produced least frequently.

This pattern mirrors number word production; children ($r(590) = 0.58$, $p < 0.01$) and parent's ($r(590) = -0.06$, $p < 0.01$) magnitude negatively correlated with frequency.

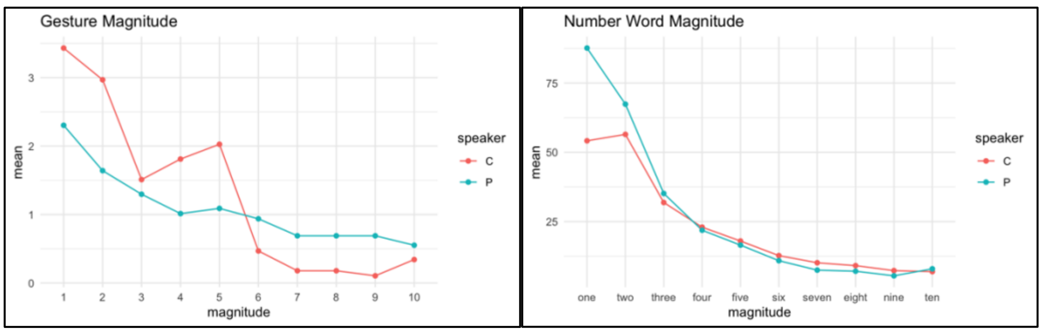


Figure 4. Numerical magnitude by modality

Number accompaniment

When both parents and children produce gestures, they were most likely to utter a number word alongside it. (Parents: $t(57) = 2.25$, $p < 0.05$; Children: $t(57) = 2.77$, $p < 0.05$). Parents' gestures will occasionally be labeled verbally by their child and vice versa, but more often they label it themselves (Parents: $t(57) = -2.88$, $p < 0.05$; Children $t(57) = 5.52$, $p < 0.05$). The majority of gestures matched the verbal number (in that they are of the same magnitude) for both parents M = 4.28 (SD = 4.58) and children M = 5.23 (SD = 6.45), however some did not (Parents M = 0.44 (SD = 1.68). Children M = 1.88 (SD = 2.67)).

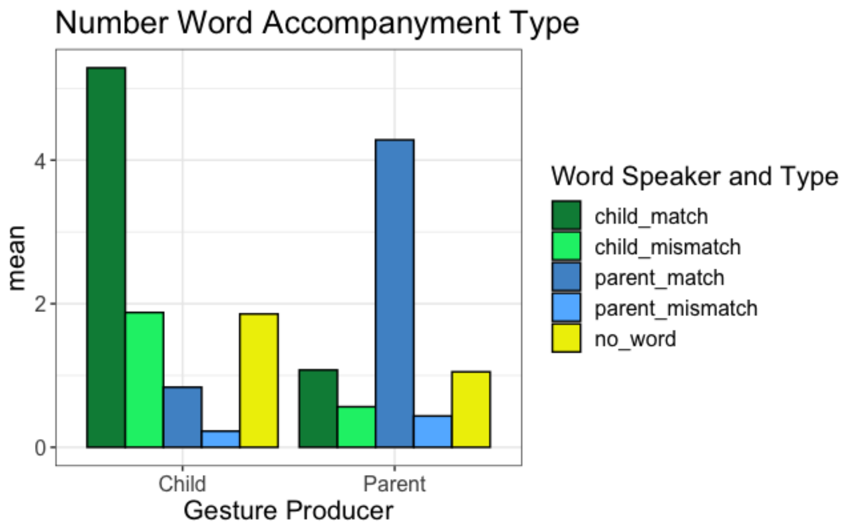


Figure 5. Breakdown of speaker and type of word accompanying gestures

Referent Category

Table 2 shows the means and standard deviations of referent type for iconic gestures and number words by speaker. For children, iconic gestures most frequently referred to objects followed by time. For parents, the entities most referenced by iconic gestures were objects, closely followed by non-objects and numbers.

Referent	Child		Parent	
	Gesture	Word	Gesture	Word
Object	3.14 (2.97)	71.53 (54.11)	1.33 (1.56)	119.11 (97.04)
- Object Present	1.39 (2.06)	66.86 (51.78)	0.90 (1.27)	111.42 (94.96)
- Object Not Present	1.76 (2.18)	4.66 (4.55)	0.44 (0.91)	7.69 (6.73)
Non-Object	0.59 (1.86)	7.19 (5.84)	1.13 (5.11)	15.51 (14.60)
Time	2.37 (4.76)	8.83 (12.08)	1.1 (2.62)	14.39 (11.18)
Rote Counting	0.41 (0.96)	15.78 (9.97)	0.23 (0.53)	13.14 (11.03)
Numbers	0.59 (1.86)	16.58 (21.15)	1.13 (5.11)	26.24 (34.66)
Unclassifiable	0.41 (1.26)	0	0.10 (0.31)	0

Table 2. Mean frequency of gesture and word referent types

We noticed that the pattern of referents of gestures did not align with number words. While children and parents refer to objects the most out of all the categories in both gestural and verbal modalities, in the verbal modality objects make up the majority of referents whereas in the gestural modality there is more variability in referents. To explore this in more depth, we compared the referents of gestures to the referents of number words in a linear model.

We collapsed all referent categories other than "object" and "unclassifiable" into one category of non-objects. On average, 3.95 (SD = 5.88) of children's iconic number gestures referred to non-objects while 3.14 (SD=2.98) referred to objects. For parents 3.18 (SD=6.02) referred to non-objects while 1.33 (SD=1.57) referred to objects.

Because the difference in scale between iconic gestures and number words was so great, we log transformed counts of gesture frequency to make them comparable and to normalize the data, which was right-skewed.

We performed a linear mixed effects model with log number of number instances as the outcome variable; modality (gesture or word), referent (object or non-object), and their interaction as fixed effects; and participant as a random effect. These analyses were performed separately for parents and children. For both parents and children, the analyses revealed a significant main effect of modality (both $p < 0.0001$), a main effect of referent (both $p < 0.05$), and crucially, a significant interaction between modality and referent such that iconic number gestures are more likely to be used in reference to non-objects whereas number words are more likely to refer to objects (child $p < 0.005$, parent $p < 0.001$).

Children

	Estimate	Std. Error	*t*-ratio	*p*-value
Intercept	3.71	0.12	31.81	
Modality	-2.39	0.14	-16.66	0.000
Referent	0.31	0.14	2.18	0.03
Modality*Referent	-0.59	0.2	-2.92	0.004

Table 3. Linear fixed effects of modality and referent on log number of children's number instances

Parents

	Estimate	Std. Error	*t*-ratio	*p*-value
Intercept	4.19	0.12	34.29	
Modality	-3.1	0.16	-19.39	0.000
Referent	0.37	0.16	2.29	0.02
Modality*Referent	-0.86	0.23	-3.8	0.0002

Table 4. Linear fixed effects of modality and referent on log number of parents' number instances

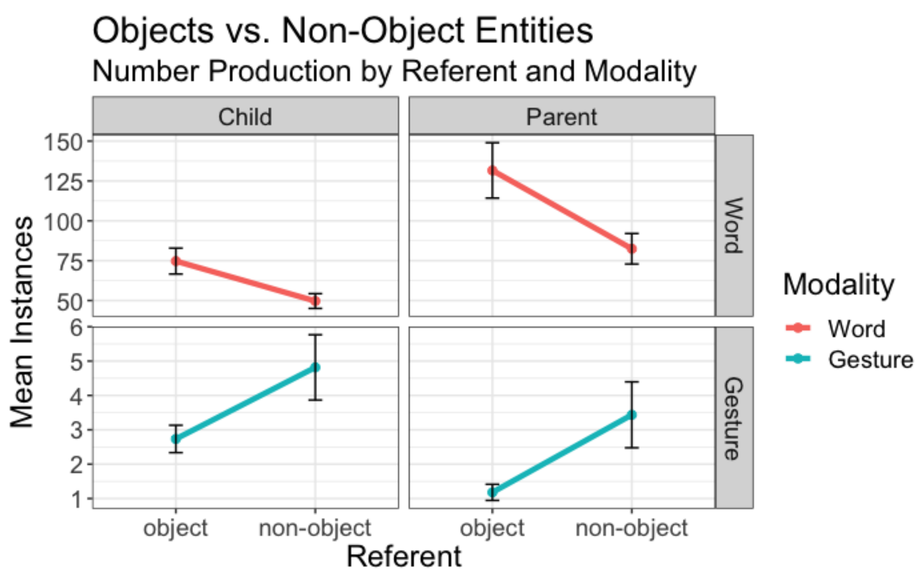


Figure 6. Instances of number by modality and referent type

We also noticed that in the verbal modality, both parents and children quantify present objects more so than non-present objects whereas when using gesture they refer to present and non-present objects more or less equally [see Table 2]. This is interesting as it not only appears that individuals choose to use gestures differentially than number words for tangible entities (objects) than intangible entities but also for present entities and non-present entities. We thus conducted a similar model as before but this time combining all non-object entities with non-present objects to form a category of "non-present entities" and compared this to present objects. Again, we used a linear mixed effects model with log number of number instances as the outcome variable; modality (gesture or word), referent presence (present objects or non-present entities), and their interaction as fixed effects; and participant as a random effect. These analyses were performed separately for parents and children. For both parents and children, the analyses revealed a significant main effect of modality (both $p < 0.0001$), no main effect of referent presence (both $p \sim 0.3$), and crucially, a significant interaction between modality and referent such that iconic number gestures are more likely to be used in reference to all non-present entities whereas number words are more likely to refer specifically to present objects (both $p < 0.001$).

Children

	Estimate	Std. Error	*t*-ratio	*p*-value
Intercept	3.81	0.11	33.92	
Modality	-2.21	0.14	-15.70	0.000
Referent Presence	0.14	0.14	1.04	0.30
Modality*Referent Presence	-1.15	0.2	-5.75	0.000

Table 5. Linear fixed effects of modality and referent presence on log number of children's number instances

Parents

	Estimate	Std. Error	*t*-ratio	*p*-value
Intercept	4.31	0.12	35.86	
Modality	-3.14	0.16	-20.01	0.000
Referent	0.15	0.16	1.00	0.32
Modality*Referent	-0.84	0.22	-3.8	0.0002

Table 6. Linear fixed effects of modality and referent presence on log number of parents' number instances

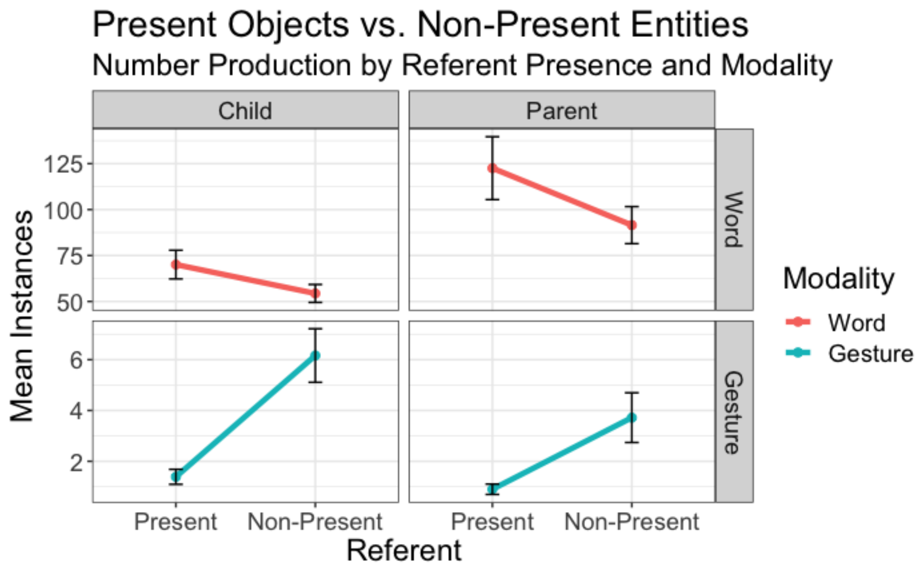


Figure 7. Instances of number by modality and referent presence

These findings suggest that iconic number gestures are selectively deployed to meet the needs of the situation. In other words, they do not simply serve to reinforce any number word. If we take number word referents as the baseline for what sets of entities individuals choose to quantify, we see that objects, particularly present objects are the predominant category. If iconic number gestures are deployed randomly rather than systematically, merely serving to add emphasis to words at random, the rate of reference to objects should match the 'baseline' or rate of number words referring to objects. Because we don't see that we conclude that iconic gestures are being produced selectively in reference to quantifiable entities that are not physically present. Thus, iconic finger gesture may serve to stand in for and concretize these more abstract entities.

2.4 Discussion

In this study we observed parents' and children's spontaneous use of iconic number gestures to better understand the role such gestures play in how children understand cardinal numbers.

In assessing the developmental trajectory of iconic number gesture production, our data reveal that children's iconic gesture frequency increases over time whereas parents' iconic gestures use are stable. Comparing iconic gestures frequency to number word frequency reveals that iconic number gestures are quite rare. This was surprising given that children as young as 2 years of age are adept at recognizing and accurately producing iconic gestures (Gibson, 2017; Gunderson, Spaepen, Gibson, et al., 2015). The contrast of what we see in the lab versus input in the home suggests that children can understand iconic number gestures with minimal input. This is especially striking when contrasted with the difficulty children have assigning meaning to number words despite a relatively large amount of verbal number word input.

In many ways, the usage patterns of iconic number gestures mirrors that of number words; they are used more for cardinal labeling than counting, more for smaller numerical magnitudes than larger ones, and increase in frequency as children get older during the preschool years. Considering the majority of iconic number gestures accompany number words, one might conclude that these gestures are merely used to emphasize speech. However, the similarities diverge when we examine the referents of the numbers. Iconic number gestures appear to be deployed primarily as visual stand-ins for non-visible entities, while number words without gestures are primarily used to label present objects, indicating that iconic gestures are used as *selective* supplements to speech. This hints at the potential functions that lead children and parents to use iconic number gestures; they help with the quantification of abstract entities such as actions and units of time perhaps because these gestures ease the demands of conceptualizing of sets. Because objects have a physical form that can be more easily represented there is less need for a gestural aid.

This study also provides evidence that parents' use of iconic number gestures is related to their children's use of iconic number gestures. Parents who produced at least one such gesture during our observations were more likely to have children who produced at least one such gesture.

This is not surprising as parent input is related to children's production of both speech and total gesture frequency (Huttenlocher et al., 2010; Rowe & Goldin-Meadow, 2009a). Yet, this insight suggests it may be possible to increase children's use of iconic gestures by encouraging parents to gesture more themselves. Alternatively, children may be the ones driving this correlation with parents responding to children's iconic gesture use by increasing their own. Future work could explore a possible feedback loop.

We still do not know whether increasing children's iconic number gesture input and/or use has any relation to their learning the meaning of number words. We found no evidence that children's use of iconic gestures was related to either their production of number words or their cardinal number knowledge, nor was there evidence for an impact of parents' iconic gesture use on these outcomes. This went against our predictions based on multiple studies demonstrating gestures benefit on learning in other domains (e.g., Mcgregor et al., 2009; Ping & Goldin-Meadow, 2008; Valenzeno et al., 2003). It could be that iconic gesture input truly is unrelated to children's cardinal number knowledge, or perhaps because iconic gestures are so rare children do not have enough opportunities to learn from them. However, it is also possible that our study design did not capture a true relationship between iconic number gesture input and cardinal number knowledge. The number of iconic number gestures in our sample could be too low to detect an effect. We recorded only a small portion of children's environment in which families were free to choose whatever activities they wished. Iconic number gestures might be used more frequently during some activities than others, but if a family never engaged in that activity while we were filming we would never know. Moreover, because the camera was always trained on the child, sometimes the parent would be offscreen preventing us from recording any gestures they may be producing. Future research observing parent child interactions during activities that encourage number talk and that may encourage iconic number gestures, such as reference to non-visible entities, may shed light on this question.

3. CHAPTER 3 Study 2: Gesture encourages number words in the home

In study 1 we did not find an effect of frequency of iconic number gestures on children's later cardinal number knowledge. This was a somewhat surprising result given that we know children are able to recognize iconic number gestures as numerical representations from an early age in laboratory settings (Gibson, 2017). Indeed, it seems unlikely that these children extracted no information from observing their parents' iconic number gestures. We followed the methodology of (Gunderson & Levine, 2011; Levine et al., 2010) by predicting children's number knowledge at 46-months of age using cumulative input from ages 14- to 42- months of age. As discussed previously, perhaps this long-term outcome of a few months was too long of a time to detect an effect of gestural input. So rather than looking at the cumulative effects of iconic number gesture exposure on a long-term outcome, we narrowed our lens to a much shorter-term outcome, the moment directly following exposure. In this study we analyse how children's attention to numerical information is benefitted from iconic number gestures the moment they observe the gesture.

3.1 Background

A hurdle for learning new words is the disambiguating the word's referent from the myriad of possibilities; known as Quine's (1960) "Gavagai" problem. A speaker of a foreign language points to a rabbit and says "gavagai". Does "gavagai" mean rabbit, animal, long ears, hopping? Now imagine there are multiple rabbits. Is "gavagai" referring to just one of the rabbits, all of them, a property that all the rabbits share, or something else entirely? This metaphor simulates the puzzle children face when hearing a number word for the first time. Number words are especially tricky as they do not describe an attribute of any individual item but rather the property of a set, an abstract concept not as salient as other properties such as colour or shape. In a match to sample task where participants must select the 'best match' to a target set of items from a series of choices that either match the target set on shape, colour, or number, children rarely select the number match, just 2% of trials. (Chan & Mazzocco, 2017). When pitted against what the experimenters deem as 'low salience' competing features, pattern and location, children are slightly more likely to notice number, 14% of trials, but still prefer to match on other features. The low saliency of numerical information thus makes solving the "gavagai" problem even harder; mapping the number word "two" to a set of two items cannot be accomplished if the two-ness of the set isn't obvious.

However, number words are not used in isolation, they are often accompanied by syntactic, pragmatic, and socio-pragmatic cues that might help children disambiguate their meaning. By the age of two, English speaking children recognize that nouns marked with syntactic plural markings, quantifiers and -s endings (e.g. "**some** blicket**s**), map onto sets of more than one (Kouider et al., 2006; Wood et al., 2009). Recognition of the grammatic singular/plural distinction has been associated with greater understanding of number words (Almoammer et al., 2013; Sarnecka et al., 2007). Furthermore, children may be sensitive to the linguistic constraints surrounding number words: they can only be used with count and not mass nouns (e.g. two cups v. two water), cannot accompany modifiers (e.g. very two v. very big), must precede adjectives (e.g. two big cars v. big two cars), and can occur in the partitive frame unlike adjectives (e.g. two of the cars v. red of the cars) (P. Bloom & Wynn, 1997). But even with multiple verbal cues, children still struggle to take a numerical interpretation of novel words when competing features, such as physical size or colour, are present (Syrett et al., 2012). Therefore, children need additional supports to understand that numbers are used to describe quantities.

It is important that children can deduce that a number word refers to quantity as this is one of the first steps towards understanding the cardinal principle. Indeed, children with higher cardinal number knowledge provide numerical labels for sets, even if it is an incorrect label, more often than children with low cardinal number knowledge who will often label sets with a bare noun e.g., "fish" for a set of 3 fish (Oswald, unpublished data). Moreover, being aware of numerical information in the absence of prompting, also called spontaneous focus on number (SFON), is related to math ability (Rathé et al., 2021). SFON in preschoolers is correlated to their concurrent counting and cardinality understanding (Hannula & Lehtinen, 2005). SFON also predicts math achievement up to 7 years later (Hannula-Sormunen et al., 2015). Of note in the SFON literature is the differing methods to measure SFON. Some tasks use action based responses such as measuring if children copy the same number of actions performed by an experimenter. Other tasks use verbal based responses such as measuring how frequently children mention numerical information when describing a picture. In particular, tasks which specifically measure verbal SFON are more related to concurrent math ability than action based SFON tasks (Batchelor et al., 2015). We can see that while attending to numerical information when there are competing features is difficult for children it is not impossible and those who do it more frequently, especially those who verbally mention number, have better mathematical outcomes.

One tool that could help children disambiguate the meaning of number words is gesture. In many domains gestures enhance learning by demonstrating communicative intent, highlighting relevant information, and adding emphasis to particular words. Deictic gestures, pointing with an extended finger or hand, have long been implicated in word learning (Booth et al., 2008). Deictic gesture signal that the speaker is intending to communicate. 12-month-olds map words to objects better when the object is pointed to rather than just gazed at (Booth et al., 2008) or grasped (Pomiechowska & Csibra, 2020) indicating they understand that the experimenter was attempting to teach them the object label.

Gestures also focus the observer's attention to relevant information (Novack & Goldin-Meadow, 2015), particularly by helping them identify what aspect of an often crowded visual scene to focus on. When used during formal lessons, children pay more visual attention to relevant items when the instructor uses gestures (Guarino et al., 2021; Wakefield et al., 2018). In studies aimed to teach children novel verbs, children who viewed iconic gestures depicting actions were better able to interpret a novel word as referring to an action rather than the shape of an object (Goodrich & Hudson Kam, 2009; Mumford & Kita, 2014). Preschoolers had better comprehension of directional words ("above", "below", "up", "down") used in complex sentences when accompanied by iconic gestures that reinforced the target words (McNeil et al., 2000). However, gestures can be used for attentional purposes even when there are no visual referents to attend to. Gestures add emphasis to particular words leading to more attention being paid to those words; in fact, adults perceive words paired with gestures as more prosodically prominent than other words in the sentence (Krahmer & Swerts, 2007). Such attention improves recall and comprehension. Adults and children have better recall of sentences that are accompanied by gestures (Thompson et al., 1998). 3-5 year old children have better comprehension of stories when the storyteller gestured (Guilbert et al., 2021; Llanes-Coromina et al., 2018). In particular, iconic gestures have the ability to enhance attention as they represent similar information as that contained in speech. Redundant information provided in two modalities reinforces learning according to Clark and Paivio's (1991) dual coding theory. While non-representational gestures such as beat gestures, moving hands to the rhythm of speech, also enhance comprehension memory (Austin & Sweller, 2014; Igualada et al., 2017; Llanes-Coromina et al., 2018), iconic gestures lead to even better encoding of information (Feyereisen, 2006; Kartalkanat & Göksun, 2020; So et al., 2012). Thus, not only can gestures, particularly iconic gestures, help listeners attend to relevant visual features of a scene, but they can also alert listeners to the importance of words in the sentence.

With numerical information being especially difficult for children to attend to, gestures seem like a good candidate for making such information salient. Iconic gestures, compared to deictic gestures, could be especially helpful in getting children to notice numerosity. Deictic gestures are useful for directing visual attention to a referent (Desrochers et al., 1995; Rohlfing et al., 2017) but could prove confusing when labeling a set. One reason children struggle to notice set size as a relevant feature is that they are too focused on the features of individuals within the set (Chan & Mazzocco, 2017; Syrett et al., 2012). Pointing gestures outside of the math domain are frequently associated with noun labels in children's first years of life. Infants expect object labels in response to their gestures (Lucca & Wilbourn, 2019) and parent's verbal responses to infant points are most frequently object labels (Wu & Gros-Louis, 2015). Accumulated experience with points referring to object names might exacerbate children's already tenuous ability to appreciate the set as a whole.

Iconic number gestures, on the other hand, visually describe the aspect of an array they are referring to with the number of fingers being raised. So not only would using this type of gesture draw attention to number but also further emphasize the accompanying number word's meaning. For visually present sets, an iconic number gesture can indicate which aspect of a scene the listener should focus on. For sets that are not visually present, an iconic number gesture can serve as a physical representation of the set, again drawing attention to the set size. And, as in the aforementioned studies in non-number domains (Feyereisen, 2006; Kartalkanat & Göksun, 2020; So et al., 2012), an iconic number gesture can indicate that the accompanying number word is important to remember, comprehend, and is relevant to the conversation.

The Present Study

In the present study we examined how parents' use of iconic number gestures helps direct children's attention to numerical information in the moment. Using observational data of naturalistic parent-child interactions, we compared children's immediate responses to parents' spoken number words and parents' iconic number gestures. We hypothesized that observing iconic number gestures would help children focus on number rather than another aspect of their environment or word in the sentence. Due to the observational nature of this study, we relied on verbal and gestural responses to indicate attention to number, rather than eye gaze or behavioural measures. Eye gaze direction could not reliably be measured on our video recordings, and behavioural responses could have many possible interpretations. For example, if a parent asks a child for two red cars and the child obliges, we cannot be sure that the child meant to provide exactly two or was rather giving all the red cars they could find. Moreover, one of our overarching questions of this dissertation is if gestures serve to help children notice that set size is a feature that can be mapped to a number word, so it is most appropriate to use a measure of math language as our outcome variable.

We examined the time period prior to when most children learn their first number word meanings, ages 14- to 30-months (Wynn, 1992). Once children become subset-knowers it is likely they have an understanding that number words are mapped to quantities even if they cannot assign them to exact quantities. This is evidenced by subset-knowers providing numbers, albeit inaccurate numbers, on assessments of cardinal number knowledge (Barner & Bachrach, 2010; Gunderson, Spaepen, & Levine, 2015; Wagner et al., 2019). Iconic number gestures might thus be most useful for children who are not yet subset-knowers by supporting the concept that number words refer to quantities.

3.2 Methods

3.2.1 Participants

Participants were from the same longitudinal naturalistic observational study as Study 1. For this study we limited our analyses to the first 5 sessions when children are 14- to 30-months of age. We included the full sample of 64 children (31 Female) and caregivers. 56 of the families completed all 5 sessions, 8 families completed 4 sessions (three families missed session 5, two missed session 4, two missed session 3, and one missed session 2). The filming procedure was identical to study 1.

Participants included 36 White Non-Hispanic, 6 White Hispanic/Latinx, 14 Black/African American, and 8 children of mixed/other race. At the beginning of the study period, 4 families reported incomes of less than $15,000; 14 had incomes between $15,000 and $34,999; 10 had incomes between $35,000 and $49,999; 11 had incomes between $50,000 and $74,999; 11 had incomes between $75,000 and $99,000, and 14 reported incomes greater than $100,000. 56 families listed the mother as the primary caregiver, one child listed the father as the primary caregiver, and seven families reported that both parents equally shared the role (dual caregivers).

3.2.2 Coding Scheme

The procedure for finding iconic number gestures and numbers in the transcripts was the same as in study 1. Transcripts were searched for parent's use of iconic number gestures 1-10 and number words "one"-"ten". Counting sequences (strings of sequential gestures or number words) were coded as one instance. Instances in which the word "one" was used non-numerically (e.g., "Can you pass me that one?") were excluded.

For every parent iconic number gesture and number word instance, the child's immediate response was coded as either non-numeric or numeric. Non-numeric responses were defined as the child not responding at all to the parent's input or not responding with a number word or iconic number gesture. Numeric responses were defined as the child using any number word or iconic number gesture.

Numeric responses were further described as being either consistent or inconsistent with what the parent had just said or gestured. Consistent numeric responses either repeated the number the parent had just used, except when being specifically asked for a different number (e.g., parent says, “what comes after four?” and child responds, “five”), or built upon the number the parent had used, such as counting on from the number the parent said. Inconsistent numeric responses included all other uses of a number. See Table 7 for examples.

Parent utterance	Non-numeric response	Consistent numeric response	Inconsistent numeric response
Statements: *there are three dogs*	No response Unrelated: *I'm hungry.* Related: *Doggies*	Repeating number: *three* *three dogs* Counting to number: *one, two, three*	*five*
Prompts: *say two*		*two*	*three*
Prompts: *what number comes after four?*		*five*	*four*
Counting: *one, two, three*		Repeating count: *one, two, three.* Continuing count: *four, five.*	*seven* *seven, eight, nine*

Table 7. Examples of child responses and corresponding codes

3.3 Results

3.3.1 Description of number input and responses

Across all sessions parents produced an average of 48.03 (SD = 37.47) number word instances (range 1-144) and 2.43 (SD = 4.32) iconic number gesture instances (range 0-21). The majority of iconic number gesture instances were also accompanied by a number word (M = 83.6%, SD = 26.3%). Whereas the majority of number word instances were not accompanied by an iconic number gesture (M = 4.7%, SD = 11.3%). To maintain two mutually exclusive categories, we considered instances where parents used an iconic number gesture with or without a number word as an *iconic gesture instance* and instances where parents used a number word without an iconic number gesture as a *number word alone instance*. Parents produced an average of 46.49 (SD = 36.68) number word alone instances (range 1-141).

30 parents never produced an iconic number gesture during the observations, we referred to these parents as Never-Gesturers and those that produced at least 1 iconic number gesture as Ever-Gesturers. We separated parents into Ever-Gesturers and Never-Gesturers for subsequent analyses.

		Ever-Gesturer Parents (n=34)		**Never-Gesturer Parents (n=30)**
		Iconic Number Gesture (with or without a number word)	Number Word Alone	Number Word Alone
Child Response	Numeric	1.53 (2.63)	6.85 (7.66)	2.72 (3.82)
	- Consistent	*1.18 (1.96)*	*5.88 (6.62)*	*2.52 (3.46)*
	- Inconsistent	*0.35 (1.15)*	*0.97 (1.55)*	*0.21 (0.56)*
	Non-Numeric	2.97 (3.29)	50.06 (36.32)	31.55 (24.81)
	Total	**4.5 (5.04)**	**56.91 (40.67)**	**34.28 (27.22)**

Table 8: Average instances of children's responses to parent uses of number

		Ever-Gesturer Parents (n=34)		**Never-Gesturer Parents (n=30)**
		Iconic Number Gesture (with or without a number word)	Number Word Alone	Number Word Alone
Child Response	Numeric	0.32 (0.38)	0.13 (0.12)	0.07 (0.07)
	- Correct	*0.28 (0.36)*	*0.10 (0.12)*	*0.07 (0.08)*
	- Incorrect	*0.05 (0.14)*	*0.03 (0.06)*	*0.005 (0.01)*
	Non-Numeric	0.67 (0.38)	0.87 (0.12)	0.92 (0.08)

Table 9: Proportion of parent's iconic number gestures and number word alone instances by child response

3.3.2 Comparing responses to number gesture and number word alone input

For each type of parent instance, iconic number gesture (with or without a number word) and number word alone, we calculated a proportion numeric response score by dividing the number of children's numeric responses by the total number of instances [Table 9]. We first compared proportion of numeric responses to iconic number gestures and number word alone for children of Ever-Gesturers. We used a weighted binomial mixed effects model with proportion of numeric responses as the outcome variable; input type (iconic number gesture or number word alone) as a fixed effect, participant as a random effect, and total number of instances of input type as weights. The weights were necessary in the model to account for the low instances of parents' iconic number gestures, compared to parents' number words alone. There was a significant effect of input type such that children's responses to iconic number gestures were proportionally more numerical than responses to number words alone ($\beta = -1.32$, SE = 0.18, $z(34) = -7.18$, $p < 0.001$). This suggests that children are paying more attention to numerical information when parents use an iconic number gesture than when they use a number word alone.

We ran two more similar models predicting children's consistent numeric responses and children's incorrect numeric responses respectively. We again found a significant effect of input type such that children's' responses to iconic number gestures were proportionally more numerically correct ($\beta = -1.12$, SE = 0.2, $z(34) = -5.65$, $p < 0.01$) and numerically inconsistent ($\beta = -1.59$, SE = 0.35, $z(34) = -4.57$, $p < 0.01$) than responses to number words alone.

3.3.2 Comparing responses to Ever-Gesturer and Never-Gesturer parents' input

We next compared Ever-Gesturer parents to Never-Gesturer parents to determine if parents' tendency to gesture was related to their own uses of number words alone or children's responses to number word input. Ever-Gesturer parents produced more number word instances than Never-Gesturer parents $t(62) = -2.62$, $p < 0.05$.

A binomial model with proportion of numeric responses as the outcome variable, parent category (Ever-Gesturer, Never-Gesturer) as a fixed effect, and number of instances of input as weights revealed that children of Ever-Gesturer parents produced proportionally more numerical responses to number words than children of Never-Gesturer parents (β = -0.46, SE = 0.14, z(64) = -3.38, $p < 0.01$). (Z=-3.378 p< 0.01). This indicates that parents who are Ever-Gesturers are providing more numeric input to their children not only through gesture but also by using more number words. In turn, their children are focusing on numerical information more than children of Never-Gesturer parents.

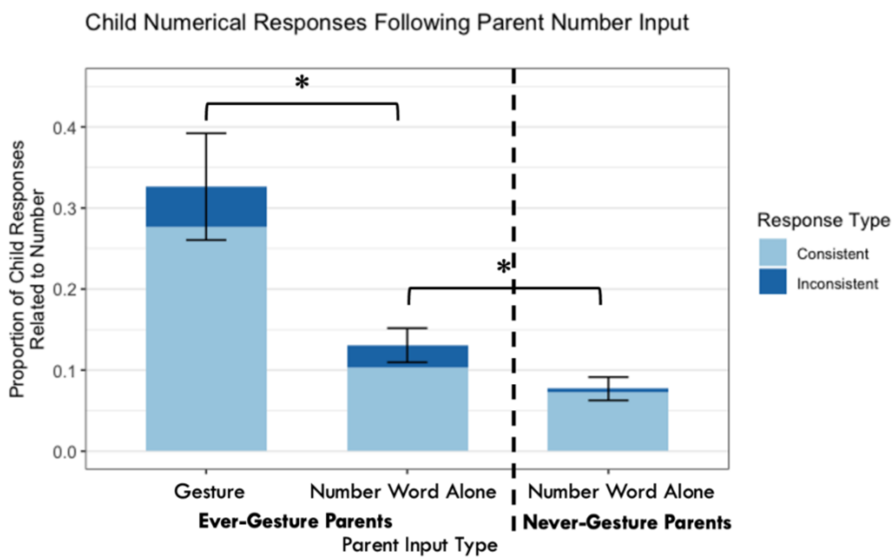


Figure 8. Proportion of child numerical responses following different modalities of parent number input

3.3.3 Description of Children's Response Modality

In prior analyses we focused on children's responses as a whole and did not differentiate the modality of children's numeric responses. Here we describe the frequency of such responses. We classified children's responses into 4 different modality types: Speech, Gesture, Speech+Gesture Match (children said a number word and produced a gesture that matched their number word in magnitude), and Speech+Gesture Mismatch (children said a number word and produced a gesture that did not match their number word in magnitude). Those were further classified into if the response was Consistent or Inconsistent with the parent's prompt, except for the Speech+Gesture

Mismatches because they could not be easily classified as often the gesture was consistent and the speech was not or vice versa.

Table 10 lists the average proportion of children's numerically relevant responses that fall into each of the modality categories. The vast majority of children's responses were in the speech modality; this is not surprising given the rarity of iconic number gestures in Study 1. Interestingly, children rarely used an iconic number gesture as a response to their parents' number words alone. When children did respond with gestures they were often accompanied by speech, also consistent with Study 1. Children of Never-Gesturer parents exclusively responded in the speech modality.

This description suggests that while children use more number words than iconic number gestures, they are more motivated to use an iconic number gesture when they have immediately seen their parent use one.

		Ever-Gesturer Parents (n=34)		Never-Gesturer Parents (n=30)
		Iconic Number Gesture	Number Word Alone	Number Word Alone
Child Response Modality and Type	Speech Consistent	**0.63 (0.43)**	**0.78 (0.3)**	**0.92 (0.23)**
	Speech Inconsistent	0.06 (0.15)	0.09 (0.14)	0.08 (0.23)
	Gesture Consistent	0.08 (0.16)	0 (0)	0 (0)
	Gesture Inconsistent	0.01 (0.06)	0.02 (0.09)	0 (0)
	Speech+Gesture Consistent	**0.13 (0.22)**	0.03 (0.17)	0 (0)
	Speech+Gesture Inconsistent	0.06 (0.24)	0.01 (0.03)	0 (0)
	Speech+Gesture Mismatch	0.03 (0.1)	0.08 (0.22)	0 (0)

Table 10. Proportion of numerical responses by child's response modality

3.4 Discussion

This study investigated the effect of seeing a parent produce an iconic number gesture on a toddler's attention to numerical information. The results indicate that viewing an iconic number gesture increases focus on numerical information, compared to hearing a number word alone.

The majority of children's responses to parent's number input was consistent, in that they aligned with the numerical information provided by the parent. There was still a portion of responses of inconsistent numbers, i.e., numbers that were incorrect in the context of the conversation. Responding incorrectly is not surprising in these cases as children at this age likely have a limited grasp of the *exact* meanings of number words. However, it appears as if iconic number gestures, more so than number words alone, help children realize that number is a feature worth mentioning even if they don't know which exact number to use.

These results concord with other studies showing that iconic gestures in other domains help children to focus on relevant information, particularly when competing information may be more salient (e.g., verbs Mumford & Kita, 2014; directional words, McNeil et al., 2020). Indeed, children are more likely to notice colour or object size than number (Syrett et al., 2012). In experimental word mapping studies, children typically have only one competing aspect to contend with (e.g., the word could either be mapped to set size or to object colour), whereas in the home environment there are a multitude of stimuli that could be more salient than number. The visual objects in the room or the non-number words the parent is using could draw children's attention away from numerical information. Yet we still find that iconic number gestures mitigate these distracting features.

We also find that children tend to use iconic number gestures in response to parent number gestures more so than in response to parent's number words alone. This is similar to our results in Study 1 showing that that parents' and children's iconic number gesture use is related.

Together, our data indicate iconic gestures make an impact on children's number talk at an age when most children are not yet one-knowers (Le Corre et al., 2006; Wynn, 1992). This emphasizes the importance of providing children with numerical input early in life. Many parents believe that math is meant to be learned once children enter school and do not believe they have a role to play in fostering their children's math skills prior (Cannon & Ginsburg, 2008). However, results from this study add to the body of research showing the positive impact of parents engaging their toddlers in math (Gunderson & Levine, 2011; Levine et al., 2010; Napoli & Purpura, 2018). One of the first steps to understanding the cardinal principle is knowing that number is a relevant feature one can label with a number word. By adding a simple gesture to their speech, parents can encourage children to make this connection between number words and set sizes.

The observational nature of this study meant that we could not control the contexts in which parents used iconic number gestures and number words. At least some aspects of these different contexts are likely to have an effect on children's focus on number. As noted in Study 1, parents tend to use iconic number gestures to refer to non-objects more so than objects, whereas number words are used to refer to objects more frequently. Thus, it could be that children are more inclined to focus on numerical information in reference to non-objects regardless of their parents' input. This seems an unlikely explanation because, in experimental studies, children begin quantifying visual items before they quantify non-visual items, such as sounds or actions (Mix, 1999; Mix et al., 1996b). Another avenue we did not explore was the intent of the parent when using number gestures and number words. There could be a difference in response patterns to parents explicitly prompting for numerical information (e.g., "Can you say two?") and merely commenting on numerical information that does not necessitate a response (e.g., "There are two cars.") It may be the case that iconic number gestures are used more frequently with explicit prompting resulting in proportionally more numeric responses. Future work should address these factors. If they are not relevant, this will make us more confident that iconic number gestures have a unique role to play in increasing attention to numerical information.

We also found that the proportion of numerical responses to number words alone was lower for children of Never-Gesturers than children of Ever-Gesturers, even controlling for total number words used. This may suggest that more gestural input helps children attend to numerical information even in the absence of an iconic number gesture. However, due to the aforementioned uncontrolled variables it may also be the case that parents who gesture more also provide an environment for their children which encourages more attention to number. For example, if it turns out that gestures always occur when parents are explicitly prompting children to talk about number, it could be that Ever-Gesturer parents also provided more explicit prompting than Never-Gesturer parents. Explicit prompting, rather than gestures, might then be causing children being more numerically focused.

This observational study provides evidence that iconic number gestures are worth pursuing further as a tool to increase children's attention to number and number word learning. As such, I sought to overcome the limitations of the study by designing an experiment to more directly test if iconic gestures make numerical information salient.

4. CHAPTER FOUR Study 3: Gestures encourage number words in the lab

In study 2, we explored one potential mechanism by which iconic number gestures benefit number learning, by drawing attention to numerical information. We found that viewing an iconic number gesture caused children to immediately focus on numerical information more so than hearing a number word without a gesture. In an observational study of this kind, we cannot control for all variables which may contribute to children's propensity to notice numerical information. Indeed, in Study 1 we found that parents' number input varied in regard to the referent, magnitude, and type of number (cardinal or counting), which we did not control for in study 2. Moreover, we were not able to measure other potentially confounding variables such as speech prosody, sentence type (prompt or statement), and conversation context (e.g., playing or reading a book). Such variability in the ways parents use number words and iconic number gestures makes it difficult to determine if it was truly the iconic number gesture that engaged children, or if iconic number gestures happen to accompany other factors that draw children to attend to number.

To address the question of whether iconic number gestures increase children's attention to number, we designed an experimental study that varies the presence of iconic number gestures while holding set size, referent type, number type, sentence type and conversation context constant. Two groups of children were randomized to be presented stimuli that were identical except for the presence/absence of iconic number gestures. This enabled us to examine whether the group that received a number word accompanied by an iconic number gesture (Gesture+Speech group) was more likely label a visual set with a number word than the group that received a number word alone (Speech-alone group). Tor preview our findings, we found that iconic number gestures engendered more correct numerical responses, as well as more incorrect numerical responses, than number words alone.

4.1 Background

As discussed in Chapter 3, set size is not a highly salient feature for children (Chan & Mazzocco, 2017; Syrett et al., 2012). This could make mapping number words onto the concept of set size difficult (Barner, 2017). Preschool and kindergarten aged children's ability to notice numerical information is related to their later math outcomes (Hannula-Sormunen et al., 2015; Rathé et al., 2021). This suggest that finding ways to increase the salience of set size for children may benefit their math learning trajectories. In other domains children take advantage of information contained in iconic gesture to disambiguate the meaning of novel words or complex sentences (Goodrich & Hudson Kam, 2009; McNeil et al., 2000; Mumford & Kita, 2014). Based on these findings and the results of Study 2 we hypothesise that iconic number gestures my enhance children's focus on number.

In this study we take advantage of a common error young children make on a task that is used to measure their cardinal number knowledge. In the What's On This Card (WOC) task, children are shown a set of objects and asked "What's on this card?" (Le Corre et al., 2006). The expected response is a number word, or a number word in conjunction with whatever noun is depicted (e.g., "3 fish). However, 2- and 3-year-olds will sometimes provide just the noun label even when prompted, indicating that they may not be focusing on the numerical information on the card (Oswald, unpublished data). Here, we adapt this task to include a priming phase in which children are either exposed to an iconic number gesture along with a number word, or a number word alone. If iconic number gestures serve a role in focusing children on numerical information, we predict children who receive an iconic number gesture prime will be more likely to use a number word (even if it is an incorrect number word) to describe the set they are looking at than children who receive a speech-alone prime.

It may also be the case that iconic number gestures provide an advantage only for children who have low cardinal number knowledge. Indeed, Gunderson et al. (2015) found that only subset-knowers were more accurate at labeling sets with gestures than number words, and particularly so for numbers above their knower level. Cardinal principal knowers were equally accurate at labeling small set sizes in speech and in gesture and actually showed a speech advantage for labeling sets of four. Thus, children with high number knowledge may be easily able to attend to numerical information regardless of iconic number gesture priming, whereas those with low cardinal number knowledge will benefit from gestural input.

This study will also extend prior research on the effects of iconic gesture on attention towards relevant information by examining whether iconic gestures that do not match the visual information the child sees are still effective at focusing attention. Prior work has not looked at this. For example, Mumford & Kita (2014) used an iconic gesture to describe either the end state of an object in motion or the manner of motion of the object. Children who say a gesture describing the manner of motion were able to identify a novel word as referring to the motion rather than the object's end state. In this case the iconic gesture mapped directly onto the object's manner of motion. Might the results have been the same if children were presented with any manner gesture? In study 2 we saw that iconic number gestures engendered numerical responses even when the magnitude of the numerical response did not match the magnitude of the gesture (e.g., parent used a two gesture and child responded "three"). This indicates that iconic number gestures may cue children that they should be focusing on number *in general* even if they don't label the exact number the gesture refers to. Our study design allows us to see if viewing an iconic number gesture leads children to notice numerical information that differs from that in the gesture.

4.1.1 Research Questions

1) Does observing an iconic number gesture along with a number word cause children to focus on and verbally express numerical information more so than hearing a number word alone?
2) Is this relationship driven by children with low cardinal number knowledge?

4.2 Methods

4.2.1 Participants

Sample size was calculated using the statistical program G*Power (Faul et al., 2007). The sample required to detect statistically significant differences between two independent means for a one-tailed test with an effect size of 0.5, an alpha of 0.05, and a power of 0.85 is 118 (59 per group). As of writing of this dissertation we have collected 95 participants. We will continue to collect the full sample of 118 usable participants and perform the same analyses outlined here, but for the purposes of this dissertation we focus on the usable participants collected to date.

Our current sample consists of 95 children aged 28-50 months (55 female, Mean=35.73 months). 16 additional children (6 female, Mean age=37 months) were tested but excluded, 5 for shyness resulting in no verbal responses, 2 for excessive fussiness, 8 for parental interference, and 1 for being older than our target age range. We instructed parents to refrain from helping their child answer questions, however some did interject in ways that could have influenced the child's numerical response. Because we are interested in children's attention to number without explicit prompting, we excluded children whose parents used any of the terms "count", "how many", or "number" during the tasks. If the parent provided behavioural intervention such as redirecting children's attention towards the screen (e.g., "look over here") or general encouragement to respond (e.g., "tell her the answer") that did not include explicit prompts towards numerical information we included the child.

Parents were recruited through a database maintained by the University of Chicago Center for Early Childhood Research of families interested in participating in research, families were recruited through targeted social media ads and ads posted around the Chicago area. We asked families to report the ethnicity and race of their child and the primary caregiver's highest level of education. Our sample was ethnically and racial diverse. 68% of children were White non-Hispanic, 7% were White Hispanic, 5% were Asian, 5% were Black/African American, and 15% were mixed/other race. <1% of caregivers held a high school diploma, 2% had a Highschool degree or equivalent, 3% had attended at least 1 year of college but had not obtained a post-secondary degree, 6% held an Associate's degree, 37% had a Bachelor's degree, 38% held a Master's degree, and 13% had a Doctorate or professional degree.

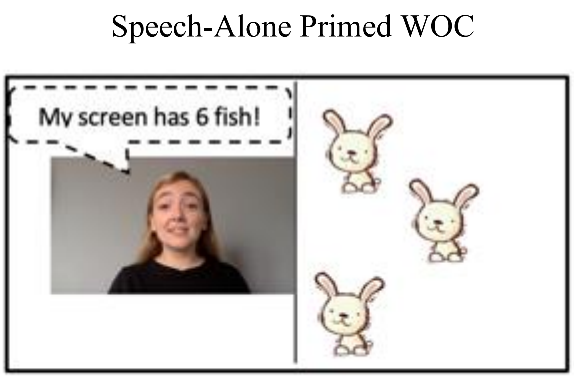
4.2.2 Measures

Primed What's on this Card (WOC)

This task was adapted from the What's on this Card task (Le Corre et al., 2006). Children are told they are playing a game where they will take turns with a woman telling each other what they see on their computer screens. Children are instructed that the woman cannot see what is on the child's screen, nor can the child see what is on the woman's screen. There are 12 trials divided into 2 blocks of 6, presented in a fixed, pseudo-random order, ensuring that there was not an overrepresentation of any particular set size in the first or second block of trials. On each trial, children see a video of the woman on the left half of their screen and a homogenous array of objects (e.g., 4 fish) on the right half. The arrays are composed of either fish, basketballs, or rabbits; the number of objects is either 2, 3, 4, or 6. Each trial begins with the woman in the video describing what she can see (e.g., "My screen has 2 fish! What does your screen have?"). The experimenter provides encouragement if the child does not respond. (e.g., "What do you see?"). On each trial, the number the woman says never matches the number of objects the child sees. On half of the trials, the objects the woman mentions are the same kind of the objects the child sees. No feedback is given except general encouragement from the experimenter (e.g., "good job!", "great!") regardless of performance.

Conditions: Speech-Alone Primed WOC vs. Gesture+Speech Primed WOC:

The Speech-Alone and Gesture+Speech conditions are identical except on each trial in the Gesture+Speech condition the woman displays an iconic number gesture, specifically a cardinal number (CN) gesture along with her speech. (e.g., [holds up 2 fingers] "My screen has 2 fish!")



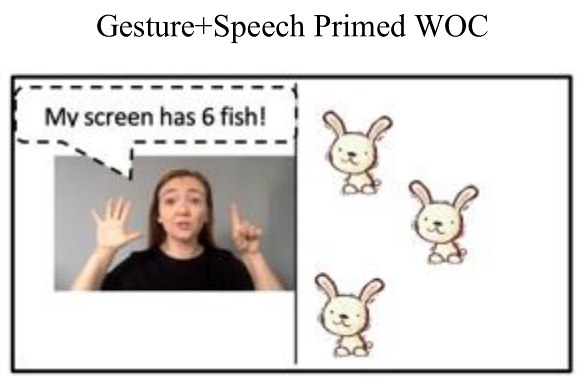


Figure 9. Example Trials of the Primed WOC Task

Previous work indicates adults add greater emphasis to words and sound more engaging when they gesture (Bernardis & Gentilucci, 2006; Krahmer & Swerts, 2007). To ensure that the actor in the primed WOC videos did not inadvertently differ in her verbal prosodic quality in the gesture condition than the speech condition, we had 6 adults blind to the purposes of the experiment rate the audio from each trial. Adults were presented with just the audio clips from both the speech condition and the gesture condition in a random order. For half the trials adults indicated on a 1-7 Likert scale how expressive the audio clip was. The other half of trials adults indicated on a 1-7 Likert scale how prominent the number word was relative to the other words in the sentence.

Ratings of expressiveness were quite high for both the gesture+speech condition (M = 6.10, SD = 1.18) and the speech-alone condition (M = 5.93, SD = 1.07). Ratings of prominence were also on the higher end of the Likert scale for both gesture+speech (M = 5.61, SD = 1.26) and the speech-alone condition (M = 5.75, SD = 1.08). There was no statistically significant condition difference between the perceived expressiveness, $t(27) = 0.35$, $p = 0.73$, or perceived prominence of the number word, $t(28) = -0.72$, $p = 0.47$.

Which-is-X

We adapted this task from Wynn et al., (1992). Children are introduced to two characters, Cookie Monster and Elmo each standing next to the box of their corresponding colour, blue and red. The side each character/box appears on is counterbalanced across children. Children are told that the characters like to keep different things in their boxes. The experimenter confirms that the child knows who each character is and can say their names. If children struggle with the character's names, they are instead instructed to say "blue" or "red" in place of "Cookie Monster" or "Elmo" respectively.

Training trials: To ensure children understand the task, two trials with no explicit verbal numerical information are administered. A set of 2 flowers appears in Cookie Monster's box and a set of 2 watermelon slices appears in Elmo's box. On each trial, children are asked to indicate which character has which type of object in their box (e.g., "Who has watermelon, Cookie Monster or Elmo?"). Children are given feedback until they can provide the correct answer.

Test trials: On each test trial an array of objects appears (1-6) in the boxes; the type of objects is the same for each character, but the number differs. Children are asked to indicate which character has a particular number of objects in their box (e.g., "Who has 3 donuts, Cookie Monster or Elmo?"). The order the characters are listed in by the experimenter corresponds to the left-right order they appear on the screen. No feedback is given except general encouragement from the experimenter (e.g., "good job!", "great!") regardless of performance. There are 20 trials in a fixed, pseudo-random order.

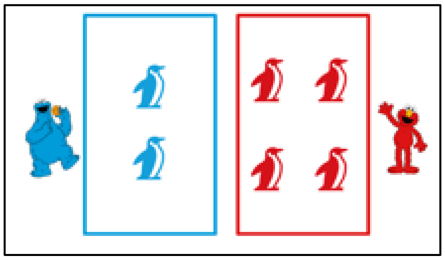


Figure 10 Example trial of the Which-is-X task

Count List Fluency

Children are asked to count 30 images of cartoon cats arranged in a 6x5 grid. If children stop counting before reaching 30 the experimenter offers a prompt to continue: "what comes after [last number child said]". The task ends after the child stops a second time or if they refuse to continue after the prompt. The highest number children can count to without a mistake (i.e., skipping a number) is recorded.

4.2.3 Procedure

This study was conducted live over Zoom. Parents received a link to a Slides.com virtual slide show containing all stimuli for the tasks, which was opened in a web browser on the parent's device. The slide show was controlled by the experimenter. Parents were encouraged to use a computer or laptop, although some used tablets (n=10) or a smart phone (n=1). Children sat either next to their parent or on their parent's lap.

Pilot work revealed children had difficulty maintaining focus throughout the tasks, so we introduced a minor goal and rewards to sustain attention. Children were initially introduced to a cartoon snowman, Olaf. They were told "For these games, Olaf can't see your computer screen, but he really wants to know what is on it. If you do a good job telling Olaf what you see he will sing you a song." After the 6th trial of the Primed WOC task and after every 5th trial of the Which-is-X task children were shown a ~10-second-long video clip of Olaf singing.

After being introduced to Olaf, children receive a brief warm-up activity allowing them to become more comfortable with the experimenter and practiced describing what they saw on the screen. Children were shown 6 cartoon images (car, fish, flower, basketball, bumble bee, rabbit) and asked to name them. If the child was reticent to respond, the experimenter provided encouragement (e.g., "Hmm what do you think this red thing with wheels is? Could it be a car?"). This activity also ensured that children knew the names for the 3 objects (fish, ball, rabbit[1]) to be used in the Primed WOC task. If a child did not initially know the name of the object the experimenter provided it for them (e.g., "This is called a fish! Can you say fish?").

Children were randomly assigned to receive either Speech-Alone Primed WOC or Gesture+Speech Primed WOC. Afterwards, all children completed Which-is-X followed by the Count List Fluency task.

4.3 Results

4.3.1 Effects of prime on focus on number

On the Primed WOC task children's numeric responses on the 12 trials were categorized into three groups: correct number (child labeled the set size correctly), repeated prompt number (child repeated the number heard in the prompt), and other number (child said a number that was neither correct nor the number from the prompt). As seen in Figure 12, children in both conditions primarily said the correct number or another number.

[1] Most children called it a "bunny"

A two-way Condition x Answer Type ANOVA reveled an effect of Condition, $F(1, 330) = 7.58$, $p < 0.01$, and of Answer Type, $F(2, 330) = 11.92$, $p<0.01$, but no interaction between Condition and Answer Type, $F(2, 330) = 1.83$, $p=0.062$. Overall, children primed with a gesture mentioned *any* number M = 7.58 (SD = 4.28) on significantly more trials than children who were primed with speech alone M = 5.38 (SD = 3.98), $t(94) = 2.58$, $p < 0.05$; $d = 0.53$. Breaking numerical responses into answer types, children mention the *correct* number more in the gesture+speech condition M = 3.29 (SD = 2.85) than in the speech-alone condition M=2.14 (SD = 2.62), $t(94) = 2.04$, $p < 0.05$; $d = 0.42$. Likewise, children mentioned more *other* numbers in the gesture+speech condition M = 3.09 (SD = 2.73) than the speech-alone condition M = 1.96 (SD = 2.46), $t(94) = 2.10$, $p < 0.05$; $d = 0.43$. There was no statistically significant difference in repeating prompt number responses between the conditions $t(94) = -0.21$, $p = 0.85$. In general, repeating the number from the prompt was the least common response, indicating that when children did mention number they were (mostly) not simply parroting back what they had heard. Thus, overall, iconic number gestures facilitate correct labeling of set sizes, as well as attention to numerical information in general.

CONDITION	RESPONSE TYPE			
	Correct Number	Incorrect Number	Repeated Prompt Number	**Total: Any Number**
Gesture+Speech	3.29 (2.85)	3.08 (2.74)	1.20 (1.49)	**7.58 (4.28)**
Speech-Alone	2.14 (2.62)	1.96 (2.46)	1.28 (2.26)	**5.38 (3.98)**

Table 11. Average numerical response types by condition

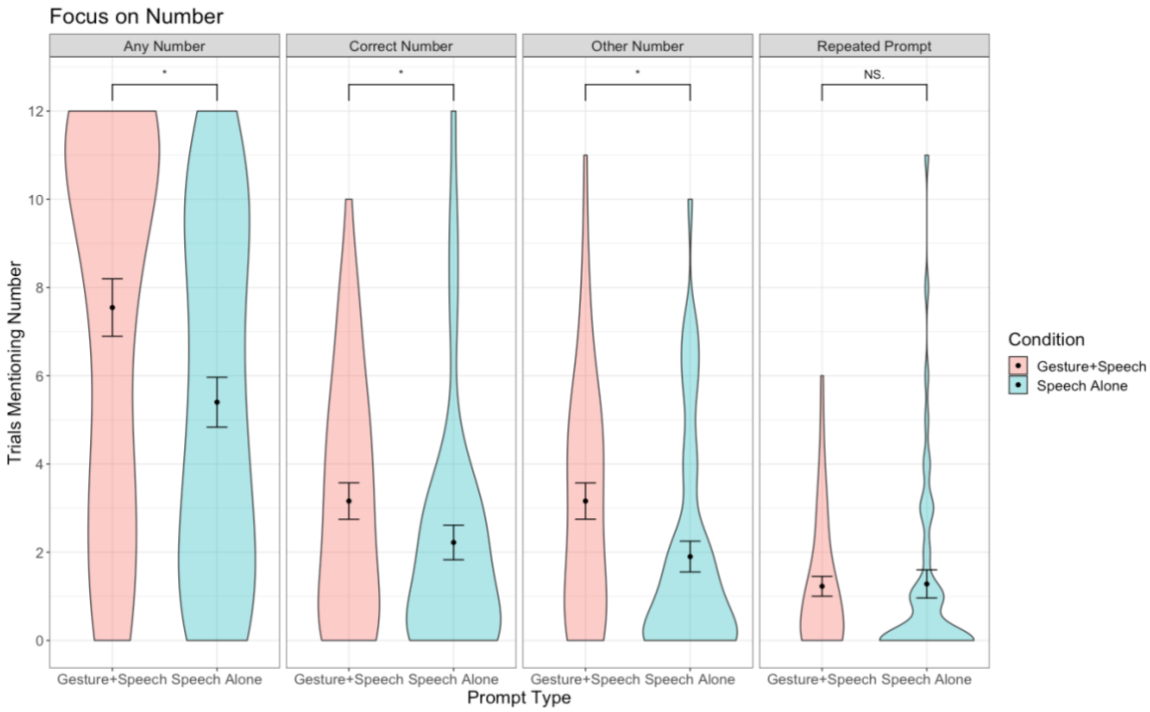


Figure 11. Children's numerical responses on the Primed WOC Task

4.3.2 Role of Set size

We next explore whether the role of gesture in facilitating children's number responses differed by set size. Children were exposed to sets of 2, 3, 4, and 6 items. We predicted that children would be more accurate at correctly labeling the smaller set sizes than the larger set sizes. We did not have specific predictions of the relationship between set size and children's mention of *any* number. Table 12 describes the means of numerical response types per set size by condition.

Overall, children in both conditions did perform differentially for different set sizes. Correct number responses were negatively correlated with set size, $r(379)$ -0.26, $p < 0.001$, whereas other-number responses were positively correlated with set size, $r(379) = 0.13$, $p < 0.001$.

A 2x2 ANOVA predicting mentioning any number reveals a main effect of condition $F(1, 376) = 21.16$, $p < 0.01$, and set size $F(1, 376) = 6.34$, $p < 0.05$; however, there was no interaction between condition and set size $F(1, 376) = 0.12$, p=0.72. Likewise, a 2x2 ANOVA predicting correct number responses reveals a main effect of condition $F(1, 376) = 9.3$, $p < 0.01$ and set size $F(1, 376) = 66.36$, $p < 0.01$ and no interaction between condition and set size $F(1, 376) = 0.58$, $p = 0.45$. However, a 2x2 ANOVA predicting other number responses reveals a main effect of condition $F(1, 376) = 9.3$, $p < 0.01$ and set size $F(1, 376) = 66.36$, $p < 0.01$ and an interaction between condition and set size $F(1, 376) = 0.58$, $p = 0.45$. To summarize, mentions of any number, correct number, and other number are explained by condition and set size, but only mentions of other number can also be explained by an interaction between condition and set size. A visual inspection of the means in Figure 12 appears as if children in the gesture condition provide more other-number responses as set sizes increase. Even though it appears as if children in the gesture+speech condition provide more correct responses for set sizes 3 and 4 than children in the speech-alone condition, they do not appear to differ from children for sets of 2 and 6.

CONDITION		**SET SIZE**			
		2	**3**	**4**	**6**
Gesture+Speech	Any Number	2.13 (1.04)	1.96 (1.19)	1.73 (1.25)	1.78 (1.22)
	Correct Number	1.47 (1.14)	0.96 (1.09)	0.58 (0.89)	0.29 (0.55)
	Other Number	0.31 (0.56)	0.67 (0.95)	0.93 (1.05)	1.18 (1.11)
	Repeat Prompt	0.35 (0.61)	0.33 (0.60)	0.22 (0.56)	0.31 (0.6)
Speech-alone	Any Number	1.86 (1.8)	1.16 (1.06)	1.1 (1.23)	1.26 (1.14)
	Correct Number	1.26 (1.17)	0.48 (0.87)	0.2 (0.64)	0.2 (0.57)
	Other Number	0.24 (0.59)	0.54 (0.86)	0.6 (0.95)	0.56 (0.79)
	Repeat Prompt	0.36 (0.75)	0.14 (0.40)	0.3 (0.74)	0.5 (0.84)

Table 12 Mean number of trials (out of 3) mentioning any number and mentioning each number type for each set size.

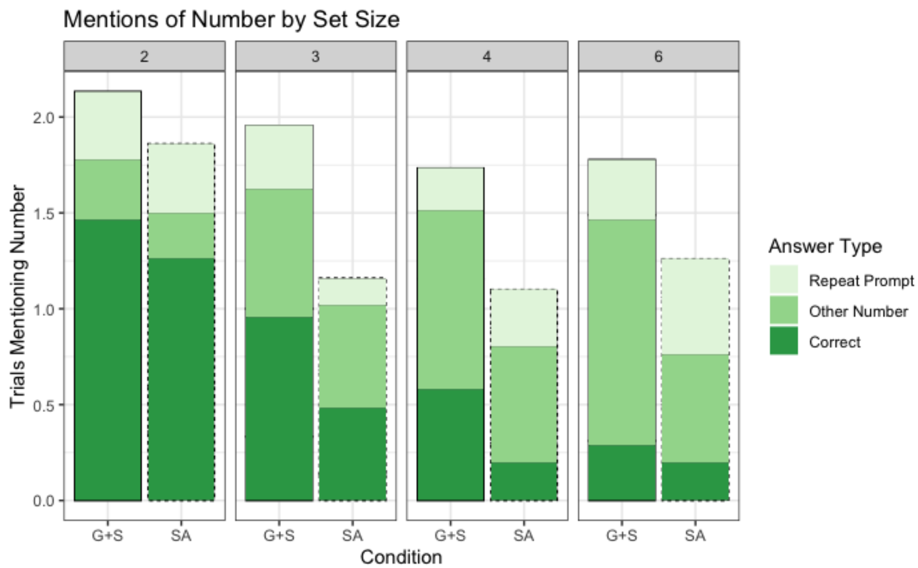


Figure 12. Response types by set size and condition

4.3.3 Block effects

Children in both conditions improved in their focus on numerical information and in their correct labeling of set sizes from the first block of 6 trials to the second block of 6 trials. While there was a significant influence of block on any number response, $F(1, 186) = 8.95$, $p < 0.05$, there was no interaction between the block and condition, $F(1, 186) = 0.01$, $p = 0.92$. Likewise for correct response, we found a significant influence of block, $F(1, 186) = 8.65$, $p < 0.05$, but no interaction between block and condition, $F(1, 186) = 0.09$, $p = 0.77$. There was no effect of block on children's other number responses, $F(1, 186) = 0.69$, $p = 0.4$. Thus, children mention correct numerical information, and numerical information in general, more in the 2nd half of the experiment regardless of the prompt type.

4.3.4 Relation between Prompted WOC and Which-is-X

3 of the 95 children became too fussy during the Which-is-X task to continue participating; thus we exclude them from these analyses.

While we included the Which-is-X task as a measure of children's cardinal number knowledge, we did not want to have children complete the task prior to the primed WOC task. Which-is-X explicitly asks children to pay attention to numerical information and thus may have dampened the effect of the gesture prime by inflating all children's attention to number regardless of condition. In having this task come second, we run the risk of the Primed WOC condition differentially affecting children's performance on Which-is-X. However, this does not appear to be the case. There were no differences in the number of correct answers on the Which-is-X task between children in the Gesture+Speech condition M = 12.98 (SD = 3.07) and those in the Speech-Alone condition M=12.96 (SD = 3.1), $t(94) = -1.23$, $p = 0.22$.

We hypothesized that children's performance on Which-is-X would interact with condition in predicting children's numerically relevant responses on the Primed WOC task such that children with lower cardinal number knowledge would benefit more from the Gesture+Speech prime than those with higher cardinal number knowledge. However, in a linear regression, there was not an interaction between condition and Which-is-X score in predicting children's mention of any number on Primed WOC ($\beta = 0.22$, SE = 0.2, $t(88) = 1.09$, $p = 0.28$), nor in predicting correct number mentions ($\beta = -0.05$, SE = 0.14, $t(88) = -0.39$, $p = 0.7$), nor in predicting other number mentions ($\beta = 0.2$, SE = 0.11, $t(88) = 1.7$, $p = 0.09$).

We did detect a significant relationship between Which-is-X performance and mentioning correct number on Primed WOC for children in the Speech-Alone condition, $r(90) = 0.34$, $p < 0.05$, and a marginally significant relationship for children in the Gesture+Speech condition, $r(90) = 0.28$, $p = 0.08$ [Figure 13].

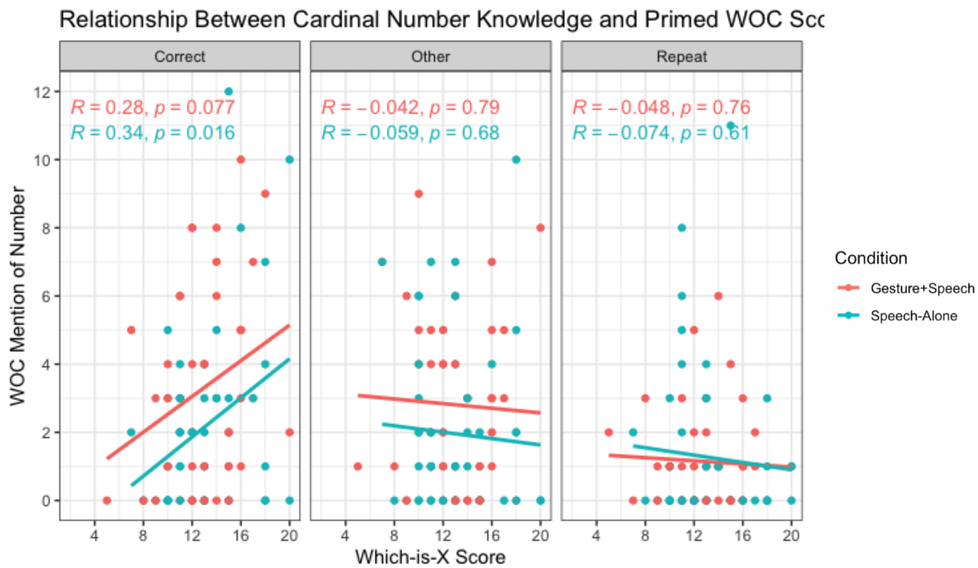


Figure 13. Relationship between Primed WOC and Which-is-X tasks

One reason we did not observe a correlation between Which-is-X and Primed WOC could be the validity of our Which-is-X task. Children appeared to have a side bias, being significantly more likely to answer "Elmo" than "Cookie Monster" t(90) = 3.65, $p < 0.001$.

4.3.5 Relation between Prompted WOC and Counting Skill

Count list fluency, as measured by how high children could count without making a mistake, showed a similar relationship to prompted WOC performance as Which-is-X did. Correct number mentions were positively correlated with children's highest count in both conditions, Gesture+Speech ($r(90) = 0.42$, $p < 0.01$) and Speech-Alone ($r(90) = 0.25$, $p < 0.05$) [see Figure 14]. However, we did not find any interactions between condition and highest count as they related to mentions of any number, correct number, nor other number.

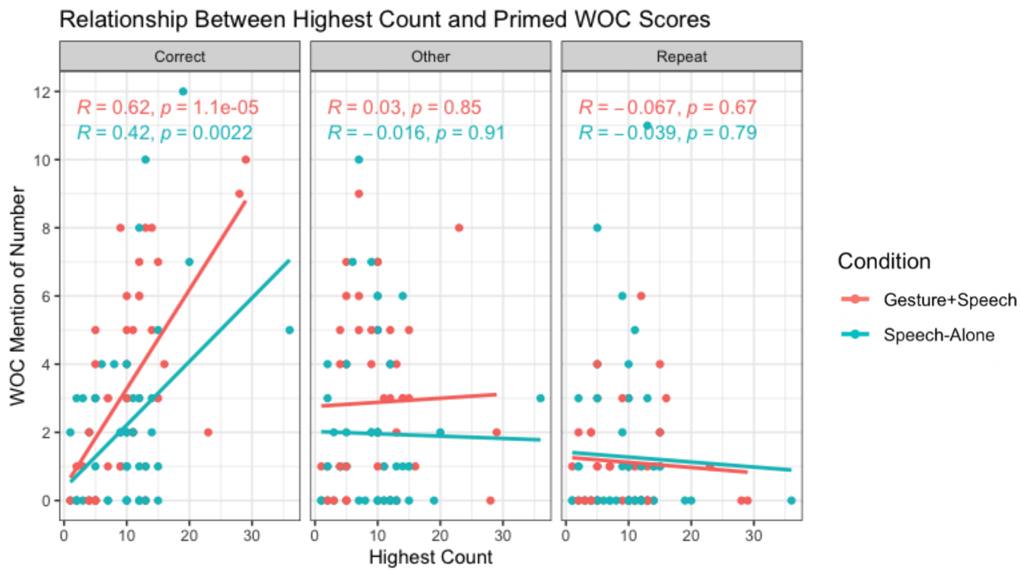


Figure 14. Relationship between Primed WOC and count list fluency

4.4 Discussion

In this study we asked how iconic number gestures help develop cardinal number knowledge by exploring whether they draw attention to numerical information as a relevant feature to label with a number word. We show that iconic number gestures accompanying number words encourage more focus on numerical information than number words alone. This is consistent with findings from our observational study (Chapter 3) in which parents' spontaneous iconic number gestures drew their children's attention to number more so than parents' number words alone. Furthermore, we demonstrate that an iconic number gesture does not need to match a visual set in magnitude to encourage children to focus on number.

As we hypothesized, children primed with an iconic number gesture and a number word mentioned number on more trials than children primed with a number word alone. When children didn't mention number they were, for the most part, providing a bare noun (e.g., "Fish"). It seems that children in the speech-alone condition did benefit from multiple trials of number word primes as mentions of number increased from the first block of trials to the second block. However, they still did not perform as well as children who got the additional support of gesture in either block. Thus, while number word input is helpful for children, number can be made even more salient with the addition of a gesture.

The iconic gesture prime also caused children to label the set size correctly more than the speech-alone prime. This is interesting because the prime was designed to not match the target set in magnitude, such that children viewing a set of 2 would never be prompted with “two”. This effect seemed to be mostly driven by set sizes 3 and 4. Sets of 2 were relatively easy for children at this age to accurately quantify resulting in little room for a gesture to boost attention. At the other extreme, children in both conditions found it difficult to accurately label sets of 6 and as such gestures did not seem to boost this understanding. This is unsurprising as sets of 6 are outside of the subitizable range and thus require children to deploy a counting strategy to figure out the exact quantity. Given most participants’ performance on Which-is-X, it is doubtful that the majority of them had the knowledge of how counting can be used to find cardinal labels (Wynn, 1992). However, for larger set sizes (4 and 6) children did provide more incorrect number when prompted with a gesture than speech alone, indicating that the gestures caused them to realize that they should say a number, but they did not have the ability to figure out which number to say.

We also demonstrate that an iconic number gesture does not need to match a set in magnitude for it to help children focus on numerical information. When children mentioned number, they rarely repeated the prompt’s number word, instead they attempted to quantify the set of objects they saw, even if their answers were inaccurate. This suggests that children at this age appreciate iconic number gestures as part of a set of gestures that all describe number—not necessarily that they communicate anything specific about what they are seeing. Thus seeing an iconic number gesture puts them in a ‘number head space’ such that they can lexically access other number words or pay attention to other numerical information. This result provides an important extension to previous work showing that iconic gestures draw attention to relevant features (McNeil et al., 2000; Mumford & Kita, 2014). The iconic gestures may not need to be the exact mapping to the relevant feature to encourage focus as long as they still evoke the category of the feature (e.g., number as opposed to physical size).

This study included two prompt types: iconic number gesture plus speech and speech alone. The design was intended to mirror the input types analysed in study 2, providing an experimentally controlled look at the impact iconic number gestures have on attention to number. However, this design also means we cannot entirely rule out the possibility that *any* gesture would have encouraged children to focus on numerical information. Indeed, deictic gestures do encourage focus on visual stimuli (Rohlfing et al., 2017). Future work should compare children's attention to number when they are primed with an iconic number gesture to those primed with other gestures such as deictic or iconic gestures which describe another feature of the depicted items such as size.

We did not find evidence to support our second hypothesis that prompt type would interact with children's' cardinal number knowledge in predicting focus on number. We had suspected that children low on cardinal number knowledge, as measured by the Which-is-X task, would benefit most from the iconic number gesture prompt as children who had high cardinal number knowledge would notice number on most trials of Prompted-WOC and thus not need additional support. This was not the case. We can only speculate as to why there was no relationship. Firstly, our sample consisted mostly of children who did not have a firm grasp of the cardinal principle so all might stand to benefit from iconic number gestures. Only 9 children (10% of the sample) scored 18 or higher out of 20 on Which-is-X, and even still those children showed variability in their performance on Prompted-WOC.

Secondly, Which-is-X may not have been the ideal task. Which-is-X, and its variants, have fallen out of favour as a measure of cardinal number knowledge. We would have preferred to use Give-a-Number (Give-N) (Le Corre et al., 2006; Wynn, 1992) as it is common in the literature and can assess children's knower-level. However, due to the COVID-19 pandemic, data could not be collected in-person; Give-N requires children to generate sets with manipulatives, such as toy fish, and at the time of design there was no reliable version of Give-N for use in online data collection. Along these lines, the apparent side bias in our task indicates that the task might not be a valid measure of children's cardinal number knowledge. The classic version of Which-is-X has children point to the correct answer (Wynn, 1992). Because data was collected online, children had to verbally indicate the side the correct answer was on, increasing task demands. We regrettably chose familiar characters to indicate sides not realizing that one of the characters would be more preferred than the other. However, this second explanation does seem less likely as a cause for the lack of predicted interaction due to the similar lack of interaction between condition count list fluency in predicting primed WOC performance. Count list fluency is correlated with cardinal number knowledge (Wagner et al., 2015) so this finding (more appropriately, lack of finding) further implies that our prediction was not supported.

The findings of this study have implications for children's early math learning. The ability to notice number despite other competing features is predictive of later math outcomes (Hannula-Sormunen et al., 2015; Rathé et al., 2021). Thus, providing tools that better enable children to do so at an early age could improve children's early math ability.

5. CHAPTER FIVE: General Discussion

Understanding the meanings of number words is an important skill for young children, predicting later academic outcomes in both math and reading (Duncan et al., 2007; Geary et al., 2018). However, children's acquisition of these words can take months to years, and there are wide variations in when children understand and use these words (Clements & Sarama, 2007; Geary et al., 2018; Klibanoff et al., 2006; Levine et al., 2010; Starkey et al., 2004). While the quantity and quality of the number words and conversations children are exposed to appear to play a role in this acquisition, number gestures, and iconic number gestures in particular, could also play a role in children's number word learning (B. Butterworth, 1999; Di Luca & Pesenti, 2011; Fuson, 1988; Gelman & Gallistel, 1978; Goldin-Meadow et al., 2014). Previous research describes potential roles iconic number gestures play in highly specific laboratory contexts. Children who have not yet mastered the cardinal principle use iconic number gestures more accurately than number words, and can use number words to accurately label gestures before they can label sets of dots (Gibson, 2017; Gunderson, Spaepen, Gibson, et al., 2015). However, it has remained unclear if this is reflective of how children use number gestures and view others using them in naturalistic contexts. Moreover, few studies to date have explored the impact of iconic number gestures on cardinal number learning, and little is known about the mechanisms by which such gestures are beneficial. The three studies described in this dissertation addressed these questions.

Study 1, which involved observing and coding spontaneous iconic number gestures produced by parents and their young children in a naturalistic environment, provides an in-depth description of the contexts in which iconic number gestures as compared to number words without gestures are used by children and their caregivers, to determine if they play a unique role in communication about quantity. Observing and coding spontaneous iconic number gestures also holds potential for evaluating the cumulative effect of using and viewing iconic number gestures on children's long-term cardinal number learning. Studies 2 and 3 focus on the immediate, short-term impact of viewing iconic number gestures through observing and coding children's responses to parents' number words with and without gesture (Study 2). Finally, Study 3 follows up on Study 2 through an experiment comparing the responses of children to following a number word prime that did or did not include an iconic number gestures. Using complementary methods, studies 2 and 3 investigate one potential mechanism by which gestures could improve cardinal number understanding, by focusing attention on numerical information a feature to be labeled with a number word. In this final chapter, I summarize the key findings of studies 1-3, identify important avenues for further research, and consider the theoretical and practical implications of my work.

5.1 Summary of Results

Study 1 provides a descriptive examination of parents' and their 14- to 58-month-old children's spontaneous iconic number gestures. We found that iconic number gestures are infrequent, compared to number words. When they are used, they most often accompany a number word, label cardinal sets rather than count items, refer to magnitudes of 1 and 2, and refer to non-visible entities. The latter discovery is in contrast to how most number words (without gestures) are used, indicating that both parents and children selectively employ gestures as stand-ins when physical objects cannot be used.

Study 1 also explored the relationship between parents' gesture input and children's gesturing, number word use, and cardinal number knowledge. While parents' and children's iconic gesture use was related, we found no evidence that parents' number gesture use from when children were 14- to 42-months-of-age impacted children's number word production after 42-months-of-age, nor their cardinal number knowledge at 46-months-of-age. We speculate that this lack of relationship could be due to the low frequency of iconic gestures. Across 18 hours of observation, parents produced approximately 3 iconic number gestures on average, compared to approximately

190 number words. Either the small sample size made a relationship impossible to detect, or the true infrequency of iconic number gestures means there were limited opportunities for the gestures to have an impact on children's number knowledge.

Study 2 examined the impact of parents' gestures on children's number word production by narrowing the time scale of analysis. Instead of looking at cumulative impact of parent gestures over many months, we looked at the effect of parents' gestures on children's immediate responses, i.e., within the same conversation. As iconic gestures in other domains, such as verb learning, help children focus on relevant information, we speculated that iconic number gestures would increase children's focus on numerical information. Our hypothesis was proven true. When parents used an iconic number gesture in conversation, children provided more numerically relevant responses, mostly via number words but occasionally using iconic number gestures themselves, than when the same parents used a number word alone. Interestingly, in our data set, children of parents who never used any iconic number gestures also showed fewer verbal number responses to number words alone. Because this was an observational study, we could not control for many variables that may have also focused children's attention on number, such as the type of entities parents were quantifying (e.g., objects vs non-objects), the magnitude of the number (e.g., one vs ten), or the prosody of the parents' speech. However, the results suggest that iconic number gestures play a role as an attentional focuser on the referent of the number word, or a disambiguator or speech. In other words, iconic number gestures provide a clue for children to solve the "gavagai problem" of what aspect of the world a number word is referring to. Iconic number gestures focus attention on numerical information rather than another aspect of the environment. To rule out the role of extraneous variables, we followed up with a controlled experiment (Study 3) exploring this same hypothesis.

In Study 3 we controlled for referent type, set size, sentence type, and conversation context, by holding them constant while varying whether or not children saw an iconic number gesture accompanying a number word. Our data align with the results of Study 2. Specifically, that iconic number gestures serve as a disambiguator, focusing children on numerical information even when not explicitly asked to. Not only did viewing an iconic number gesture result in children correctly quantifying the set more so than hearing a number word alone, but it led children to mention number, albeit not always the correct number. Furthermore, the results show that iconic number gestures do not need to match a visible array in magnitude to be useful in drawing children's attention to number in a visual representation they are looking at. Even iconic number gestures that do not match the target number in the child's array can get children to focus on number as a relevant feature to describe in speech.

5.2 Limitations and Future Directions

Discovering ways to enrich children's number knowledge is important to closing the achievement gap already present at school entry (Clements & Sarama, 2007; Geary et al., 2018; Klibanoff et al., 2006; Starkey et al., 2004). Future work should investigate the long-term impact iconic number gestures can have on children's learning about cardinal number. Although the naturalistic data analyzed in Study 1 do not show this relationship, Study 1 shows that when parents produce more number gestures, their children produce more number gestures, which is possibly a stepping-stone that increases their cardinal number knowledge. Moreover, the immediate impact of viewing an iconic number gestures on children's attention to number found in Studies 2 & 3 increases the likelihood that iconic number gestures could have a long-term impact on children's number knowledge. It could be that, potentially due to the low number of observed iconic number gestures, we did not detect a relationship that was truly there (Type 2 error). Observations of rare behaviours are noisy, even the parents who we classified as 'Never-Gesturers' maybe have been producing gestures when the cameras where not around, but we had just happened to catch them at a time when they were choosing to do other activities. For example, for the majority of one session, participant 89's caregiver was busy cooking dinner and not able to give him her undivided attention, let alone have her hands available to gesture. Conversely, participant 66's older sister wanted to play an addition-based board game during a session, resulting in a great deal of finger counting by the participant and her caregiver. To give participants a fair chance of demonstrating their gestures, future work should observe parents and children in contexts where iconic number gestures may be more likely to occur, such as when doing math specific activities, to get a better understanding of the true frequency of their use in children's lives and the impact they have on cardinal number knowledge. Alternatively, perhaps parents' infrequent use of number gestures means that there is little opportunity for gestures to have a substantial impact. It could thus be the case that increasing children's exposure to iconic number gestures via an intervention would benefit them. My colleagues and I are currently testing this hypothesis using a parent-delivered book intervention that encourages parents and children to use iconic number gestures.

Studies 2 & 3 suggest that iconic number gestures help children to focus on numerical information in the moment. In study 3 this information was in the form of visually present sets. In study 2, the majority of iconic number referents were to non-visible entities whereas the number word alone referents were for the most part to visible entities. Other research, including study 1, shows that children are more likely to rely on iconic number gestures when quantifying non-visible items (Crollen & Noël, 2015), thus viewing iconic number gestures might be most beneficial for drawing attention to number when entities are not visible, e.g., measurement units like minutes, sounds. Future research should examine whether the benefit of iconic number gestures relative to number words alone depends on the visibility of the referent the child is meant to attend to. Children do not map number words onto non-visible entities as easily as visible entities; they do not initially realize that number words extend to entities beyond objects, and, even when they do, limits to working memory make it difficult to keep track of non-visual entities (Crollen & Noël, 2015; Gelman & Gallistel, 1978; Mix et al., 1996a). Determining whether iconic number gestures might help children in these cases could improve early math instruction.

Relatedly, there needs to be a more in-depth look at the mechanisms by which iconic number gestures allow children to focus on numerical information. While we did find in two different paradigms (studies 2 & 3) that observing an iconic number gesture engendered more numerically relevant verbal responses, there are a number of possible explanations for these results that do not implicate *iconic number* gestures specifically. It may be that the gestures serve as a general attention grabber, in which case we might expect children who view *any* gesture to pay more attention to numerical information. To address this, a third condition could be added to study 3 where the prompt includes a deictic gesture or a non-numeric iconic gesture such as a wave. Alternatively, a study similar to ours could have children judge the meaning of a novel word as either referring to numerosity or another attribute of a set, such as physical size. Children would either see an iconic number gesture or an iconic physical size gesture accompany the novel word. If children are appreciating the numerical information contained in the iconic number gesture, they should judge the novel word to refer to number only when viewing an iconic number gesture and judge the novel word to refer to physical size when viewing an iconic physical size gesture.

It could also be that having a double dose (i.e., two sources of the same information) of number is all that children need to focus on numerical information, in line with the dual coding theory (Clark & Paivio, 1991). In study 3, children in the speech-alone condition were primed with only one instance of numerical information per trial, whereas children in the gesture+speech condition received two instances of numerical information, in the form of a word and a gesture. We may have seen similar results if the number word was accompanied by an Arabic numeral, or a set of dots, or even if the number word was presented twice. Additional conditions could be added to rule out these possibilities.

Another reason why iconic gestures could increase children's focus on number is that speech tends to change when it is accompanied by gesture (Bernardis & Gentilucci, 2006; Krahmer & Swerts, 2007). In naturalistic contexts, the quality of speech that accompanies parents' iconic number gesture compared to the quality of speech when number words are used alone could explain why children are paying greater attention, rather than the gesture itself being the cue. For example, a parent may add more vocal emphasis to a number word when they use a number gesture. In other domains, adult speech is rated as more prosodically engaging when the speaker uses a gesture than when they don't (Krahmer & Swerts, 2007). There is also the possibility that parents use gestures when attempting to provide explicit pedagogical information, and thus use more prompting phrases designed to illicit numerical responses. We did not code for either of these factors in study 2 but could do so in the future. However, even if the contexts in which parents choose to use a gesture are more conducive to numerical responses (regardless of whether a cardinal number gesture was used or not), results of study 3 indicate that it is likely that the gesture is playing a unique role. Indeed, independent ratings of the prompts' prosodic quality in this study did not significantly differ between the gesture+speech and speech-alone conditions.

Lastly, this dissertation addressed one mechanism by which iconic gestures support cardinal number development: by focusing attention on number. It is also important to consider the other non-mutually exclusive possibilities outlined in Chapter 1. For instance, there are still outstanding questions concerning the bridge hypothesises. Iconic number gestures have the rare quality of representing both symbolic and non-symbolic information possibly serving as a bridge connecting symbolic number words to non-symbolic quantities (B. Butterworth, 1999; Di Luca & Pesenti, 2011; Gibson, 2017). Yet some have argued that children do not actually appreciate the iconic non-symbolic information contained in gesture (Nicoladis et al., 2018). Is it still possible that children can attend to the one-to-one correspondence between the fingers and the items in the referent set? There is anecdotal evidence that children do this when mimicking their parents' gesture using different fingers. For example, in study 1, while singing a song about different numbers of monkeys, one child's mother produced a canonical 3 gesture (index, middle, and ring finger raised). The child attempted to copy her mother's gesture but had difficulty maneuvering her fingers into the correct handshape, so she settled on raising her index, pinky, and thumb. While she did not produce exactly the same hand shape as her mother, she still produced the same number of fingers indicating she was matching her parent's gesture in a one-to-one manner. Exploration into evidence such as this and through more targeted experiments can help elucidate these remaining questions. Understanding which mechanisms are at play, and when, could give us insights into where children are in their math development or improve learning interventions. Iconic number gestures as an attention focuser would seem to be most useful when children are first learning to map number words to the feature of quantity, whereas gestures acting as a bridge between the symbolic and non-symbolic representations of numbers may be most helpful when children are learning the exact meanings of number words.

In sum, this dissertation provides novel information about the contexts in which cardinal number gestures are used, and how they affect children's focus on number. Although we did not find a direct relationship between observing or producing iconic number gestures over a two-year period (ages 14- to 42-months) on children's cardinal number knowledge at 46-months-of age, the limitations of the study design leave open the possibility that this relationship may still exist. A controlled experiment manipulating the amount of iconic number gestures children are exposed to could go a long way to answer this question more thoroughly.

This dissertation also provides at least a partial answer to the question 'why are iconic number gestures potentially beneficial to learning number word meanings?'. One way in which they help is by drawing children's attention to numerical information as a salient feature to verbally label. In so far as attention to number is related to children's cardinal number knowledge (Hannula-Sormunen et al., 2015; Rathé et al., 2021), we could assume that improving such attention via iconic number gestures can, in turn, improve children's understanding of number words. Our results do not rule out the possibility of other mechanisms through which iconic number gestures may impact math development. More work should examine if dual coding (having both visual and auditory information) or the bridge hypothesis (that children appreciate the non-symbolic one-to-one nature of gestures and use this to bridge symbolic and non-symbolic information) can explain why iconic number gestures might be beneficial.

5.3 Implications

The present studies make several important contributions to the existing literature. Study 1 provides the first detailed description of children and parents spontaneously using iconic number gestures across a broad time span and range of contexts. Prior research has only explored spontaneous gestures at one or two time points (J. Lee et al., 2015; Suriyakham, 2007) or in very specific contexts, such as when explicitly asking children to count items (Gunderson, Spaepen, Gibson, et al., 2015). Descriptions of how children and parents tend to use these gestures allows researchers to explore these usages in greater depth through targeted experiments. For example, such an experiment could explore the use of iconic number gestures when sets are and are not visible. Studies 2 and 3 rely on naturalistic and experimental data in just such a way. In Study 2, the naturalistic data showed that children were more likely to respond with a number word when their parent produced an iconic number gesture than when they produced a number word with no gesture. Consistent with this, the controlled experiment in study 3, revealed the same finding.

Studies 2 and 3 add support to the growing body of work in the gesture domain demonstrating the benefits of iconic number gestures on disambiguating word meanings (Mcgregor et al., 2009; McNeil et al., 2000; Mumford & Kita, 2014). Study 3 provides an important extension to such findings by showing that an iconic gesture does not necessarily need to be an exact match to the relevant set size a child is viewing to draw children's attention to it. In other words, iconic number gestures cue children that number is important within the context of the current conversation, even if the gesture does not match the numerosity of the set they are viewing.

This research also has practical implications for supporting children's early math development. For many years, children were discouraged from using their fingers to enumerate sets or perform calculations in school (Boaler & Chen, 2016; Phelps-Gregory et al., 2020). Work such as this suggests that this strategy was misguided, as gestures are powerful tools in the learning process. Children are better able to label gestures with a number word than sets of dots (Gibson, 2017) and sub-set knowers are more accurate at labeling sets with gestures than with words (Gunderson, Spaepen, Gibson, et al., 2015). Both these findings demonstrate that gestures may be better understood as symbols for quantity than number words in children's early years. However, study 1 shows that children receive relatively little number gesture input, compared to number words. This indicates that despite such differences in input, the meanings of number gestures are acquired more easily than the meaning of corresponding number words. Thus, even light touch interventions meant to get children to use gesture more may boost their number knowledge. As mentioned, we are already conducting a study to investigate this possibility.

Acquiring number words is the earliest foundation of advanced mathematics. Early math skills are predictive of many later math, academic, and life outcomes (Claessens & Engel, 2013; Duncan et al., 2007; Geary et al., 2013; Jordan et al., 2009). Existing research has put forth ways of improving cardinal number knowledge, but none has experimentally tested how iconic gestures influence number word learning trajectories. Here I suggest iconic number gestures have an important role to play in children's numeracy environment. Number gestures are readily available, literally at one's fingertips, and do not require any specialized material. Thus, iconic number gestures may hold untapped potential for accelerating children's learning of a difficult and foundational mathematical concept, the cardinal principle. It is also possible that these gestures continue to play a role in children's mathematical development beyond this milestone. Children readily rely upon finger counting when learning addition (Jordan et al., 2008; Lafay et al., 2013); prior to this, children may be able to use the sequential raising of fingers, one-by-one, when finger counting to better understand the successor function (that for each number word representing a cardinal value, N, the next word in the count list represents the cardinal value N+1). Iconic number gestures could also elucidate the later-greater principle, that numbers later in the count list represent greater quantities, as the gestural symbols for later numbers are physically larger than those for earlier numbers (e.g., 5 vs 1). Future work in this area can illuminate iconic number gesture's role in children's understand of multiple important math concepts an inform practices to improve children's learning outcomes.

REFERENCES

Alibali, M. W., & DiRusso, A. A. (1999). The function of gesture in learning to count: More than keeping track. *Cognitive Development*, *14*(1), 37–56. https://doi.org/10.1016/S0885-2014(99)80017-3

Alibali, M. W., & Goldin-Meadow, S. (1993). Modeling learning using evidence from speech and gesture. *Proceedings of the Annual Conference of the Cognitive Science Society,* 203-208.

Alibali, M. W., & Kita, S. (2010). Gesture highlights perceptually present information for speakers. *Gesture*, *10*(1), 3–28. https://doi.org/10.1075/gest.10.1.02ali

Alibali, M. W., Kita, S., & Young, A. J. (2000). Gesture and the process of speech production: We think, therefore we gesture. *Language and Cognitive Processes*, *15*(6), 593–613. https://doi.org/10.1080/016909600750040571

Almoammer, A., Sullivan, J., Donlan, C., Marušič, F., Žaucer, R., O'Donnell, T., & Barner, D. (2013). Grammatical morphology as a source of early number word meanings. *Proceedings of the National Academy of Sciences*, *110*(46), 18448–18453.

Andres, M., Luca, S. D., & Pesenti, M. (2008). Finger counting: The missing tool? *Behavioral and Brain Sciences*, *31*(6), 642–643. https://doi.org/10.1017/S0140525X08005578

Austin, E. E., & Sweller, N. (2014). Presentation and production: The role of gesture in spatial communication. *Journal of Experimental Child Psychology*, *122*, 92–103. https://doi.org/10.1016/j.jecp.2013.12.008

Barner, D. (2017). Language, procedures, and the non-perceptual origin of number word meanings. *Journal of Child Language*, *44*(3), 553–590. https://doi.org/10.1017/S0305000917000058

Barner, D., & Bachrach, A. (2010). Inference and exact numerical representation in early language development. *Cognitive Psychology*, *60*(1), 40–62. https://doi.org/10.1016/j.cogpsych.2009.06.002

Batchelor, S., Inglis, M., & Gilmore, C. (2015). Spontaneous focusing on numerosity and the arithmetic advantage. *Learning and Instruction*, *40*, 79–88. https://doi.org/10.1016/j.learninstruc.2015.09.005

Bender, A., & Beller, S. (2012). Nature and culture of finger counting: Diversity and representational effects of an embodied cognitive tool. *Cognition*, *124*(2), 156–182. https://doi.org/10.1016/j.cognition.2012.05.005

Bernardis, P., & Gentilucci, M. (2006). Speech and gesture share the same communication system. *Neuropsychologia*, *44*(2), 178–190. https://doi.org/10.1016/j.neuropsychologia.2005.05.007

Berteletti, I., & Booth, J. R. (2015). Perceiving fingers in single-digit arithmetic problems. *Frontiers in Psychology*, *6*. https://www.frontiersin.org/article/10.3389/fpsyg.2015.00226

Bloom, L. (2000). The intentionality of word learning: How to learn a word, any word. In R. M. Golinkoff & K. Hirsh-Pasek (Eds.), *Becoming a word learning: A debate on lexical acquisition* (pp. 19-50). Oxford University Press.

Bloom, P., & Wynn, K. (1997). Linguistic cues in the acquisition of number words. *Journal of Child Language*, *24*(3), 511–533. https://doi.org/10.1017/S0305000997003188

Boaler, J., & Chen, L. (2016, April 13). *Using Fingers to Count in Math Class Is Not "Babyish."* The Atlantic. https://www.theatlantic.com/education/archive/2016/04/why-kids-should-use-their-fingers-in-math-class/478053/

Booth, A. E., McGregor, K. K., & Rohlfing, K. J. (2008). Socio-Pragmatics and Attention: Contributions to Gesturally Guided Word Learning in Toddlers. *Language Learning and Development*, *4*(3), 179–202. https://doi.org/10.1080/15475440802143091

Breckinridge Church, R., & Goldin-Meadow, S. (1986). The mismatch between gesture and speech as an index of transitional knowledge. *Cognition*, *23*(1), 43–71. https://doi.org/10.1016/0010-0277(86)90053-3

Butterworth, B. (1999). *What Counts: How the Brain is Hardwired for Math*. Free Press.

Butterworth, G. (2004). Joint visual attention in infancy. In G. Bremner & A. Slater (Eds.), *Theories of Infant Development* (pp. 317–354). Oxford: Blackwell.

Butterworth, G., Simion, F., & Butterworth, G. (2013). What is special about pointing in babies. *The Development of Sensory, Motor and Cognitive Capacities in Early Infancy: From Perception to Cognition*, 171–190.

Cannon, J., & Ginsburg, H. P. (2008). "Doing the Math": Maternal Beliefs About Early Mathematics Versus Language Learning. *Early Education & Development*, *19*(2), 238–260. https://doi.org/10.1080/10409280801963913

Cantrell, L., & Smith, L. B. (2013). Open questions and a proposal: A critical review of the evidence on infant numerical abilities. *Cognition*, *128*(3), 331–352. https://doi.org/10.1016/j.cognition.2013.04.008

Carey, S. (2009). *The Origin of Concepts*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195367638.001.0001

Carrazza, C., & Levine, S. C. (under review). *Less is not always more: Rich and meaningful counting books support preschool children's number learning.*

Chan, J. Y.-C., & Mazzocco, M. M. M. (2017). Competing features influence children's attention to number. *Journal of Experimental Child Psychology*, *156*, 62–81. https://doi.org/10.1016/j.jecp.2016.11.008

Cheung, P., Rubenson, M., & Barner, D. (2017). To infinity and beyond: Children generalize the successor function to all possible numbers years after learning to count. *Cognitive Psychology*, *92*, 22–36. https://doi.org/10.1016/j.cogpsych.2016.11.002

Chu, F. W., vanMarle, K., & Geary, D. C. (2016). Predicting Children's Reading and Mathematics Achievement from Early Quantitative Knowledge and Domain-General Cognitive Abilities. *Frontiers in Psychology*, *7*. https://www.frontiersin.org/article/10.3389/fpsyg.2016.00775

Church, R. B., Ayman-Nolley, S., & Mahootian, S. (2004). The Role of Gesture in Bilingual Education: Does Gesture Enhance Learning? *International Journal of Bilingual Education and Bilingualism*, *7*(4), 303–319. https://doi.org/10.1080/13670050408667815

Claessens, A., & Engel, M. (2013). How Important is Where you Start? Early Mathematics Knowledge and Later School Success. *Teachers College Record*, 29.

Clark, J. M., & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review*, *3*(3), 149–210. https://doi.org/10.1007/BF01320076

Clements, D. H., & Sarama, J. (2007). Effects of a Preschool Mathematics Curriculum: Summative Research on the Building Blocks Project. *Journal for Research in Mathematics Education*, *38*(2), 136–163. https://doi.org/10.2307/30034954

Cook, S. W. (2018). Chapter Four - Enhancing learning with hand gestures: Potential mechanisms. In K. D. Federmeier (Ed.), *Psychology of Learning and Motivation* (Vol. 69, pp. 107–133). Academic Press. https://doi.org/10.1016/bs.plm.2018.10.001

Cook, S. W., & Goldin-Meadow, S. (2006). The Role of Gesture in Learning: Do Children Use Their Hands to Change Their Minds? *Journal of Cognition and Development*, *7*(2), 211–232. https://doi.org/10.1207/s15327647jcd0702_4

Coolidge, F. L., & Overmann, K. A. (2012). Numerosity, Abstraction, and the Emergence of Symbolic Thinking. *Current Anthropology*, *53*(2), 204–225. https://doi.org/10.1086/664818

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

Crollen, V., Seron, X., & Noël, M.-P. (2011). Is Finger-counting Necessary for the Development of Arithmetic Abilities? *Frontiers in Psychology*, *2*. https://www.frontiersin.org/article/10.3389/fpsyg.2011.00242

Davidson, K., Eng, K., & Barner, D. (2012). Does learning to count involve a semantic induction? *Cognition*, *123*(1), 162–173. https://doi.org/10.1016/j.cognition.2011.12.013

de Chambrier, A.-F., Thevenot, C., Barrouillet, P., & Zesiger, P. (2018). Frequency of finger looking during finger counting is related to children's working memory capacities. *Journal of Cognitive Psychology*, *30*(5–6), 503–510.

Desrochers, S., Morissette, P., & Ricard, M. (1995). Two perspectives on pointing in infancy. *Joint Attention: Its Origins and Role in Development*, 85–101.

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

Di Luca, S., & Pesenti, M. (2011). Finger Numeral Representations: More than Just Another Symbolic Code. *Frontiers in Psychology*, *2*. https://doi.org/10.3389/fpsyg.2011.00272

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, *43*(6), 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428

Dupont-Boime, J., & Thevenot, C. (2018). High working memory capacity favours the use of finger counting in six-year-old children. *Journal of Cognitive Psychology*, *30*(1), 35–42.

Elliott, L., & Bachman, H. J. (2018). SES disparities in early math abilities: The contributions of parents' math cognitions, practices to support math, and math talk. *Developmental Review*, *49*, 1–15. https://doi.org/10.1016/j.dr.2018.08.001

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/bf03193146

Fayol, M. (1998). Predicting arithmetical achievement from neuro-psychological performance: A longitudinal study. *Cognition*, *68*(2), B63–B70. https://doi.org/10.1016/S0010-0277(98)00046-8

Feigenson, L., & Carey, S. (2005). On the limits of infants' quantification of small object arrays. *Cognition*, *97*(3), 295–313. https://doi.org/10.1016/j.cognition.2004.09.010

Feyereisen, P. (2006). Further investigation on the mnemonic effect of gestures: Their meaning matters. *European Journal of Cognitive Psychology*, *18*(2), 185–205. https://doi.org/10.1080/09541440540000158

Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex*, *44*(4), 386–392. https://doi.org/10.1016/j.cortex.2007.08.004

Fischer, U., Suggate, S. P., & Stoeger, H. (2020). The Implicit Contribution of Fine Motor Skills to Mathematical Insight in Early Childhood. *Frontiers in Psychology*, *11*, 1143. https://doi.org/10.3389/fpsyg.2020.01143

Franco, F., & Butterworth, G. (1996). Pointing and social awareness: Declaring and requesting in the second year*. *Journal of Child Language*, *23*(2), 307–336. https://doi.org/10.1017/S0305000900008813

Frye, D., Braisby, N., Lowe, J., Maroudas, C., & Nicholls, J. (1989). Young Children's Understanding of Counting and Cardinality. *Child Development*, *60*(5), 1158–1171. https://doi.org/10.2307/1130790

Fuson, K. C. (1988). *Children's Counting and Concepts of Number*. Springer-Verlag: New York.

Fuson, K. C., Pergament, G. G., Lyons, B. G., & Hall, J. W. (1985). Children's Conformity to the Cardinality Rule as a Function of Set Size and Counting Accuracy. *Child Development*, *56*(6), 1429–1436. https://doi.org/10.2307/1130462

Geary, D. C., Hoard, M. K., Nugent, L., & Bailey, D. H. (2013). Adolescents' Functional Numeracy Is Predicted by Their School Entry Number System Knowledge. *PLoS ONE*, *8*(1), e54651. https://doi.org/10.1371/journal.pone.0054651

Geary, D. C., vanMarle, K., Chu, F. W., Rouder, J., Hoard, M. K., & Nugent, L. (2018). Early Conceptual Understanding of Cardinality Predicts Superior School-Entry Number-System Knowledge. *Psychological Science*, *29*(2), 191–205. https://doi.org/10.1177/0956797617729817

Gelman, R., & Gallistel, C. R. (1978). *The Child's Understanding of Number*. Harvard University Press.

Gibson, D. J. (2017). *Gesture's Role in Bridging Symbolic and Nonsymbolic Representations of Number* [Doctoral Dissertation, The University of Chicago]. ProQuest Dissertations Publishing. https://www.proquest.com/docview/1957428410/abstract/749291BD046741A4PQ/1

Gibson, D. J., Gunderson, E. A., & Levine, S. C. (2020). Causal Effects of Parent Number Talk on Preschoolers' Number Knowledge. *Child Development*, *91*(6). https://doi.org/10.1111/cdev.13423

Gibson, D. J., Gunderson, E. A., Spaepen, E., Levine, S. C., & Goldin-Meadow, S. (2019). Number gestures predict learning of number words. *Developmental Science*, *22*(3). https://doi.org/10.1111/desc.12791

Goldin-Meadow, S. (2015). From action to abstraction: Gesture as a mechanism of change. *Developmental Review*, *38*, 167–184. https://doi.org/10.1016/j.dr.2015.07.007

Goldin-Meadow, S., Levine, S. C., & Jacobs, S. (2014). Gestures role in learning arithmetic. *Emerging Perspectives on Gesture and Embodiment in Mathematics*, 51–72.

Goldin-Meadow, S., Levine, S. C., Zinchenko, E., Yip, T. K., Hemani, N., & Factor, L. (2012). Doing gesture promotes learning a mental transformation task better than seeing gesture. *Developmental Science*, *15*(6), 876–884. https://doi.org/10.1111/j.1467-7687.2012.01185.x

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining Math: Gesturing Lightens the Load. *Psychological Science*, *12*(6), 516–522. https://doi.org/10.1111/1467-9280.00395

Goodrich, W., & Hudson Kam, C. L. (2009). Co-speech gesture as input in verb learning. *Developmental Science*, *12*(1), 81–87. https://doi.org/10.1111/j.1467-7687.2008.00735.x

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

Graham, T. A. (1999). The Role of Gesture in Children's Learning to Count. *Journal of Experimental Child Psychology*, *74*(4), 333–355. https://doi.org/10.1006/jecp.1999.2520

Guarino, K. F., Wakefield, E. M., Morrison, R. G., & Richland, L. E. (2021). Exploring how visual attention, inhibitory control, and co-speech gesture instruction contribute to children's analogical reasoning ability. *Cognitive Development*, *58*, 101040. https://doi.org/10.1016/j.cogdev.2021.101040

Guilbert, D., Sweller, N., & Van Bergen, P. (2021). Emotion and gesture effects on narrative recall in young children and adults. *Applied Cognitive Psychology*, *35*(4), 873–889. https://doi.org/10.1002/acp.3815

Gunderson, E. A., & Levine, S. C. (2011). Some types of parent number talk count more than others: Relations between parents' input and children's cardinal-number knowledge: Types of parent number talk. *Developmental Science*, *14*(5), 1021–1032. https://doi.org/10.1111/j.1467-7687.2011.01050.x

Gunderson, E. A., Spaepen, E., Gibson, D., Goldin-Meadow, S., & Levine, S. C. (2015). Gesture as a window onto children's number knowledge. *Cognition*, *144*, 14–28. https://doi.org/10.1016/j.cognition.2015.07.008

Gunderson, E. A., Spaepen, E., & Levine, S. C. (2015). Approximate number word knowledge before the cardinal principle. *Journal of Experimental Child Psychology*, *130*, 35–55. https://doi.org/10.1016/j.jecp.2014.09.008

Hannula, M. M., & Lehtinen, E. (2005). Spontaneous focusing on numerosity and mathematical skills of young children. *Learning and Instruction*, *15*(3), 237–256. https://doi.org/10.1016/j.learninstruc.2005.04.005

Hannula-Sormunen, M. M., Lehtinen, E., & Räsänen, P. (2015). Preschool Children's Spontaneous Focusing on Numerosity, Subitizing, and Counting Skills as Predictors of Their Mathematical Performance Seven Years Later at School. *Mathematical Thinking and Learning*, *17*(2–3), 155–177. https://doi.org/10.1080/10986065.2015.1016814

Huttenlocher, J., Waterfall, H., Vasilyeva, M., Vevea, J., & Hedges, L. V. (2010). Sources of variability in children's language growth. *Cognitive Psychology*, *61*(4), 343–365. https://doi.org/10.1016/j.cogpsych.2010.08.002

Ifrah, G. (2000). *The universal history of computing: From the abacus to quantum computing*. John Wiley & Sons, Inc.

Igualada, A., Esteve-Gibert, N., & Prieto, P. (2017). Beat gestures improve word recall in 3- to 5-year-old children. *Journal of Experimental Child Psychology*, *156*, 99–112. https://doi.org/10.1016/j.jecp.2016.11.017

Iverson, J. M., & Goldin-Meadow, S. (1998). Why people gesture when they speak. *Nature*, *396*(6708), 228–228.

Iverson, J. M., & Goldin-Meadow, S. (2001). The resilience of gesture in talk: Gesture in blind speakers and listeners. *Developmental Science*, *4*(4), 416–422.

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2008). Development of number combination skill in the early school years: When do fingers help? *Developmental Science*, *11*(5), 662–668. https://doi.org/10.1111/j.1467-7687.2008.00715.x

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early Math Matters: Kindergarten Number Competence and Later Mathematics Outcomes. *Developmental Psychology*, *45*(3), 850–867. https://doi.org/10.1037/a0014939

Kartalkanat, H., & Göksun, T. (2020). The effects of observing different gestures during storytelling on the recall of path and event information in 5-year-olds and adults. *Journal of Experimental Child Psychology*, *189*, 104725. https://doi.org/10.1016/j.jecp.2019.104725

Kaufmann, L., Vogel, S. E., Wood, G., Kremser, C., Schocke, M., Zimmerhackl, L.-B., & Koten, J. W. (2008). A developmental fMRI study of nonsymbolic numerical and spatial processing. *Cortex*, *44*(4), 376–385. https://doi.org/10.1016/j.cortex.2007.08.003

Kita, S. (2000). How representational gestures help speaking. In D. McNeill (Ed.), *Language and Gesture* (pp. 162-185). Cambridge University Press.

Klibanoff, R. S., Levine, S. C., Huttenlocher, J., Vasilyeva, M., & Hedges, L. V. (2006). Preschool children's mathematical knowledge: The effect of teacher "math talk." *Developmental Psychology*, *42*(1), 59–69. https://doi.org/10.1037/0012-1649.42.1.59

Kouider, S., Halberda, J., Wood, J., & Carey, S. (2006). Acquisition of English Number Marking: The Singular-Plural Distinction. *Language Learning and Development*, *2*(1), 1–25. https://doi.org/10.1207/s15473341lld0201_1

Krahmer, E., & Swerts, M. (2007). The effects of visual beats on prosodic prominence: Acoustic analyses, auditory perception and visual perception. *Journal of Memory and Language*, *57*(3), 396–414. https://doi.org/10.1016/j.jml.2007.06.005

Krauss, R. M. (1998). Why do we gesture when we speak? *Current Directions in Psychological Science*, *7*(2), 54–54.

Krauss, R. M., Chen, Y., & Gottesman, R. F. (2000). 13 Lexical gestures and lexical access: A process. *Language and Gesture*, *2*(261), 261–283.

Krauss, R. M., & Hadar, U. (1999). The role of speech-related arm/hand gestures in word retrieval. In R. Campbell & L. Messing (Eds.), *Gesture, Speech, and Sign* (pp. 93-116). Oxford University Press.

Krinzinger, H., Koten, J., Horoufchin, H., Kohn, N., Arndt, D., Sahr, K., Konrad, K., & Willmes, K. (2011). The Role of Finger Representations and Saccades for Number Processing: An fMRI Study in Children. *Frontiers in Psychology*, *2*, 373. https://doi.org/10.3389/fpsyg.2011.00373

Lafay, A., Thevenot, C., Castel, C., & Fayol, M. (2013). The role of fingers in number processing in young children. *Frontiers in Psychology*, *4*. https://www.frontiersin.org/article/10.3389/fpsyg.2013.00488

Le Corre, M., Van de Walle, G., Brannon, E. M., & Carey, S. (2006). Re-visiting the competence/performance debate in the acquisition of the counting principles. *Cognitive Psychology*, *52*(2), 130–169. https://doi.org/10.1016/j.cogpsych.2005.07.002

LeBarton, E. S., Goldin-Meadow, S., & Raudenbush, S. (2015). Experimentally Induced Increases in Early Gesture Lead to Increases in Spoken Vocabulary. *Journal of Cognition and Development*, *16*(2), 199–220. https://doi.org/10.1080/15248372.2013.858041

Lee, J., Kotsopoulos, D., Tumber, A., & Makosz, S. (2015). Gesturing about number sense. *Journal of Early Childhood Research*, *13*(3), 263–279. https://doi.org/10.1177/1476718X13510914

Lee, M. D., & Sarnecka, B. W. (2010). A Model of Knower-Level Behavior in Number Concept Development. *Cognitive Science*, *34*(1), 51–67. https://doi.org/10.1111/j.1551-6709.2009.01063.x

Leung, E. H., & Rheingold, H. L. (1981). Development of pointing as a social gesture. *Developmental Psychology*, *17*(2), 215–220. https://doi.org/10.1037/0012-1649.17.2.215

Levine, S. C., Jordan, N. C., & Huttenlocher, J. (1992). Development of calculation abilities in young children. *Journal of Experimental Child Psychology*, *53*(1), 72–103. https://doi.org/10.1016/S0022-0965(05)80005-0

Levine, S. C., Suriyakham, L. W., Rowe, M. L., Huttenlocher, J., & Gunderson, E. A. (2010). What counts in the development of young children's number knowledge? *Developmental Psychology*, *46*(5), 1309–1319. https://doi.org/10.1037/a0019671

Llanes-Coromina, J., Vilà-Giménez, I., Kushch, O., Borràs-Comes, J., & Prieto, P. (2018). Beat gestures help preschoolers recall and comprehend discourse information. *Journal of Experimental Child Psychology*, *172*, 168–188. https://doi.org/10.1016/j.jecp.2018.02.004

Lucca, K., & Wilbourn, M. P. (2019). The what and the how: Information-seeking pointing gestures facilitate learning labels and functions. *Journal of Experimental Child Psychology*, *178*, 417–436. https://doi.org/10.1016/j.jecp.2018.08.003

Marušič, F., Žaucer, R., Plesničar, V., Razboršek, T., Sullivan, J., & Barner, D. (2016). Does Grammatical Structure Accelerate Number Word Learning? Evidence from Learners of Dual and Non-Dual Dialects of Slovenian. *PLOS ONE*, *11*(8), e0159208. https://doi.org/10.1371/journal.pone.0159208

Mcgregor, K. K., Rohlfing, K. J., Bean, A., & Marschner, E. (2009). Gesture as a support for word learning: The case of *under*. *Journal of Child Language*, *36*(4), 807–828. https://doi.org/10.1017/S0305000908009173

McNeil, N. M., Alibali, M. W., & Evans, J. L. (2000). The role of gesture in children's comprehension of spoken language: Now they need it, now they don't. *Journal of Nonverbal Behavior*, *24*(2), 131–150.

Menninger, K. (1969). *Number words and number symbols: A cultural history of numbers.* M.I.T. Press.

Miller, H. E., Andrews, C. A., & Simmering, V. R. (2020). Speech and Gesture Production Provide Unique Insights Into Young Children's Spatial Reasoning. *Child Development*, *91*(6), 1934–1952. https://doi.org/10.1111/cdev.13396

Mix, K. S. (1999). Similarity and Numerical Equivalence. *Cognitive Development*, *14*(2), 269–297. https://doi.org/10.1016/S0885-2014(99)00005-2

Mix, K. S., Huttenlocher, J., & Levine, S. C. (1996a). Do Preschool Children Recognize Auditory-Visual Numerical Correspondences? *Child Development*, *67*(4), 1592–1608. https://doi.org/10.1111/j.1467-8624.1996.tb01816.x

Mix, K. S., Huttenlocher, J., & Levine, S. C. (1996b). Do Preschool Children Recognize Auditory-Visual Numerical Correspondences? *Child Development*, *67*(4), 1592. https://doi.org/10.2307/1131720

Moeller, K., Fischer, U., Link, T., Wasner, M., Huber, S., Cress, U., & Nuerk, H.-C. (2012). Learning and development of embodied numerosity. *Cognitive Processing*, *13*(1), 271–274. https://doi.org/10.1007/s10339-012-0457-9

Morsella, E., & Krauss, R. M. (2004). The role of gestures in spatial working memory and speech. *The American Journal of Psychology*, 411–424.

Mumford, K. H., & Kita, S. (2014). Children Use Gesture to Interpret Novel Verb Meanings. *Child Development*, *85*(3), 1181–1189. https://doi.org/10.1111/cdev.12188

Namy, L. L. (2008). Recognition of iconicity doesn't come for free. *Developmental Science*, *11*(6), 841–846. https://doi.org/10.1111/j.1467-7687.2008.00732.x

Namy, L. L., Campbell, A. L., & Tomasello, M. (2004). The Changing Role of Iconicity in Non-Verbal Symbol Learning: A U-Shaped Trajectory in the Acquisition of Arbitrary Gestures. *Journal of Cognition and Development*, *5*(1), 37–57. https://doi.org/10.1207/s15327647jcd0501_3

Namy, L. L., Vallas, R., & Knight-Schwarz, J. (2008). Linking parent input and child receptivity to symbolic gestures. *Gesture*, *8*(3), 302–324. https://doi.org/10.1075/gest.8.3.03nam

Napoli, A. R., & Purpura, D. J. (2018). The home literacy and numeracy environment in preschool: Cross-domain relations of parent–child practices and child outcomes. *Journal of Experimental Child Psychology*, *166*, 581–603. https://doi.org/10.1016/j.jecp.2017.10.002

Nicoladis, E., Marentette, P., Pika, S., & Barbosa, P. G. (2018). Young Children Show Little Sensitivity to the Iconicity in Number Gestures. *Language Learning and Development*, *14*(4), 297–319. https://doi.org/10.1080/15475441.2018.1444486

Nicoladis, E., Mayberry, R. I., & Genesee, F. (1999). Gesture and early bilingual development. *Developmental Psychology*, *35*(2), 514–526. https://doi.org/10.1037/0012-1649.35.2.514

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

Noël, M.-P., Seron, X., & Trovarelli, F. (2004). Working memory as a predictor of addition skills and addition strategies in children. *Cahiers de Psychologie Cognitive/Current Psychology of Cognition*, *22*(1), 3–25.

Novack, M., & Goldin-Meadow, S. (2015). Learning from Gesture: How Our Hands Change Our Minds. *Educational Psychology Review*, *27*(3), 405–412. https://doi.org/10.1007/s10648-015-9325-3

Phelps-Gregory, C. M., Frank, M., & Spitzer, S. M. (2020). Prospective Elementary Teachers' Beliefs About Mathematical Myths: A Historical and Qualitative Examination. *The Teacher Educator*, *55*(1), 6–27. https://doi.org/10.1080/08878730.2019.1618423

Ping, R., & Goldin-Meadow, S. (2008). Hands in the air. *Developmental Psychology*, *44*(5), 1277–1287. https://doi.org/10.1037/0012-1649.44.5.1277

Ping, R., & Goldin-Meadow, S. (2010). Gesturing Saves Cognitive Resources When Talking About Nonpresent Objects. *Cognitive Science*, *34*(4), 602–619. https://doi.org/10.1111/j.1551-6709.2010.01102.x

Pomiechowska, B., & Csibra, G. (2020). *Nonverbal action interpretation guides novel word disambiguation in 12-month-olds* [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/tkhsp

Pruden, S. M., Hirsh-Pasek, K., Golinkoff, R. M., & Hennon, E. A. (2006). The Birth of Words: Ten-Month-Olds Learn Words Through Perceptual Salience. *Child Development*, *77*(2), 266–280. https://doi.org/10.1111/j.1467-8624.2006.00869.x

Quine, W. V. O. (1960). *Word and Object, New Edition*. The MIT Press.

Rathé, S., Torbeyns, J., De Smedt, B., & Verschaffel, L. (2021). Longitudinal associations between spontaneous number focusing tendencies, numerical abilities, and mathematics achievement in 4- to 7-year-olds. *Journal of Educational Psychology*, *114*(1), 37–55. https://doi.org/10.1037/edu0000665

Rohlfing, K. J., Grimminger, A., & Lüke, C. (2017). An Interactive View on the Development of Deictic Pointing in Infancy. *Frontiers in Psychology*, *8*, 1319. https://doi.org/10.3389/fpsyg.2017.01319

Rohlfing, K. J., Longo, M. R., & Bertenthal, B. I. (2012). Dynamic pointing triggers shifts of visual attention in young infants. *Developmental Science*, *15*(3), 426–435. https://doi.org/10.1111/j.1467-7687.2012.01139.x

Rowe, M. L., & Goldin-Meadow, S. (2009a). Early gesture selectively predicts later language learning. *Developmental Science*, *12*(1), 182–187. https://doi.org/10.1111/j.1467-7687.2008.00764.x

Rowe, M. L., & Goldin-Meadow, S. (2009b). Differences in Early Gesture Explain SES Disparities in Child Vocabulary Size at School Entry. *Science*, *323*(5916), 951–953. https://doi.org/10.1126/science.1167025

Sarnecka, B. W., & Carey, S. (2008). How counting represents number: What children must learn and when they learn it. *Cognition*, *108*(3), 662–674. https://doi.org/10.1016/j.cognition.2008.05.007

Sarnecka, B. W., Kamenskaya, V. G., Yamana, Y., Ogura, T., & Yudovina, Yulia. B. (2007). From grammatical number to exact numbers: Early meanings of ‘one’, ‘two’, and ‘three’ in English, Russian, and Japanese. *Cognitive Psychology*, *55*(2), 136–168. https://doi.org/10.1016/j.cogpsych.2006.09.001

Sarnecka, B. W., & Lee, M. D. (2009). Levels of number knowledge during early childhood. *Journal of Experimental Child Psychology*, *103*(3), 325–337. https://doi.org/10.1016/j.jecp.2009.02.007

Saxe, G. B., & Kaplan, R. (1981). Gesture in Early Counting: A Developmental Analysis. *Perceptual and Motor Skills*, *53*(3), 851–854. https://doi.org/10.2466/pms.1981.53.3.851

Singer, M. A., & Goldin-Meadow, S. (2005). Children learn when their teacher’s gestures and speech differ. *Psychological Science*, *16*(2), 85–89.

Singleton, N. C., & Saks, J. (2015). Co-Speech Gesture Input as a Support for Language Learning in Children With and Without Early Language Delay. *Perspectives on Language Learning and Education*, *22*(2), 61–71. https://doi.org/10.1044/lle22.2.61

Snedeker, J., & Gleitman, L. (2004). Why it is hard to label our concepts. In D. G. Hall & S. R. Waxman (Eds.), *Weaving a Lexicon* (pp. 257-294). MIT Press.

So, W. C., Sim Chen-Hui, C., & Low Wei-Shan, J. (2012). Mnemonic effect of iconic gesture and beat gesture in adults and children: Is meaning in gesture important for memory recall? *Language and Cognitive Processes*, *27*(5), 665–681. https://doi.org/10.1080/01690965.2011.573220

Spaepen, E., Coppola, M., Flaherty, M., Spelke, E., & Goldin-Meadow, S. (2013). Generating a lexicon without a language model: Do words for number count? *Journal of Memory and Language*, *69*(4), 496–505. https://doi.org/10.1016/j.jml.2013.05.004

Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly*, *19*(1), 99–120. https://doi.org/10.1016/j.ecresq.2004.01.002

Suriyakham, L. W. (2007). *Input effects on the development of the cardinality principle: Does gesture count?* [Doctoral Dissertation, The University of Chicago]. ProQuest Dissertations Publishing. https://www.proquest.com/docview/304790374/abstract/51275C56318E4C63PQ/1

Syrett, K., Musolino, J., & Gelman, R. (2012). How Can Syntax Support Number Word Acquisition? *Language Learning and Development*, *8*(2), 146–176. https://doi.org/10.1080/15475441.2011.583900

Thompson, L. A., Driscoll, D., & Markson, L. (1998). Memory for Visual-Spoken Language in Children and Adults. *Journal of Nonverbal Behavior*, *22*(3), 167–187. https://doi.org/10.1023/A:1022914521401

Tomasello, M., Carpenter, M., & Liszkowski, U. (2007). A New Look at Infant Pointing. *Child Development*, *78*(3), 705–722. https://doi.org/10.1111/j.1467-8624.2007.01025.x

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

Valenzeno, L., Alibali, M. W., & Klatzky, R. (2003). Teachers' gestures facilitate students' learning: A lesson in symmetry. *Contemporary Educational Psychology*, *28*(2), 187–204. https://doi.org/10.1016/S0361-476X(02)00007-3

van Marle, K., Chu, F. W., Li, Y., & Geary, D. C. (2014). Acuity of the approximate number system and preschoolers' quantitative development. *Developmental Science*, *17*(4), 492–505. https://doi.org/10.1111/desc.12143

Van Rinsveld, A., Hornung, C., & Fayol, M. (2020). Finger Rapid Automatized Naming (RAN) predicts the development of numerical representations better than finger gnosis. *Cognitive Development*, *53*, 100842. https://doi.org/10.1016/j.cogdev.2019.100842

Wagner, K., Chu, J., & Barner, D. (2019). Do children's number words begin noisy? *Developmental Science*, *22*(1), e12752. https://doi.org/10.1111/desc.12752

Wagner, K., Kimura, K., Cheung, P., & Barner, D. (2015). Why is number word learning hard? Evidence from bilingual learners. *Cognitive Psychology*, *83*, 1–21. https://doi.org/10.1016/j.cogpsych.2015.08.006

Wakefield, E., Foley, A., Ping, R., Villarreal, J., Goldin-Meadow, S., & Levine, S. C. (2019). Breaking down gesture and action in mental rotation: Understanding the components of movement that promote learning. *Developmental Psychology*, *55*(5), 981–993. https://doi.org/10.1037/dev0000697

Wakefield, E., Novack, M., Congdon, E., Franconeri, S., & Goldin-Meadow, S. (2018). Gesture helps learners learn, but not merely by guiding their visual attention. *Developmental Science*, *21*(6), e12664. https://doi.org/10.1111/desc.12664

Wesp, R., Hesse, J., Keutmann, D., & Wheaton, K. (2001). Gestures maintain spatial imagery. *The American Journal of Psychology*, *114*(4), 591.

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

Winter, W. (1992). Some thoughts about Indo-European numerals. *Indo-European Numerals*, *57*, 11–28.

Wood, J. N., Kouider, S., & Carey, S. (2009). Acquisition of singular-plural morphology. *Developmental Psychology*, *45*(1), 202–206. https://doi.org/10.1037/a0014432

Wu, Z., & Gros-Louis, J. (2015). Caregivers provide more labeling responses to infants' pointing than to infants' object-directed vocalizations. *Journal of Child Language*, *42*(3), 538–561. https://doi.org/10.1017/S0305000914000221

Wynn, K. (1990). Children's understanding of counting. *Cognition*, *36*(2), 155–193. https://doi.org/10.1016/0010-0277(90)90003-3

Wynn, K. (1992). Children's acquisition of the number words and the counting system. *Cognitive Psychology*, *24*(2), 220–251. https://doi.org/10.1016/0010-0285(92)90008-P

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*(1), B1–B11. https://doi.org/10.1016/S0010-0277(99)00066-9

Zammit, M., & Schafer, G. (2011). Maternal label and gesture use affects acquisition of specific object names. *Journal of Child Language*, *38*(1), 201–221. https://doi.org/10.1017/S0305000909990328