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GESTURE'S ROLE IN BRIDGING SYMBOLIC AND NONSYMBOLIC REPRESENTATIONS OF NUMBER

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ABSTRACT

How do children transition from preverbal conceptions of numerical quantity to a full understanding of symbolic number (e.g. number words: one, two, three. etc.)? This is an important question in developmental psychology with serious implications for early childhood education. A surprisingly unspecified aspect of early number development is children's use of cardinal number gestures (e.g. holding up three fingers to indicate "three"). Although it is widely assumed that number gestures play some role in children's early number development (e.g. Gelman & Gallistel, 1978; Fuson, 1988), the specifics of this role are not well understood. In three studies, I establish the relevance of number gestures to the acquisition of number words and examine children's knowledge of number gestures in relation to their developing understanding of number words.

Study 1 examined cases in which children's number gestures do not match their spoken number words when labeling sets of items (e.g. a child holds up three fingers and says "two" in reference to a set of three items). Not only are children's number gestures typically more accurate than their speech during these gesture-speech mismatches, children who produced gesture-speech mismatchers are more likely to learn new number words from rich number input than children who did not produce gesture-speech mismatches. Studies 2 and 3 investigated whether children appreciate the symbolic properties of number gestures. Specifically, Study 2 found that children form precise mappings between number gestures and number words, even before demonstrating a comprehension of number words on traditional number measures. Study 3 found that children conceive of at least some number gestures as number symbols (like number words) and not merely item-based representations of number (such as arrays of dots). The results

of these three studies combined with previous research suggest that number gestures could serve as a bridge between nonsymbolic and symbolic representations of number.

1. CHAPTER ONE: Introduction

Learning to represent numbers using symbols (e.g. "one", "two", "three" or 1, 2, 3) is a major achievement in both the history of human civilization and the lives of individual children. Although humans (as well as other animals) possess innate abilities to perceive and reason about quantity (Feigenson, Dehaene & Spelke, 2004), these preverbal number systems fall short of the power and flexibility of symbolic number. Most notably, beginning in infancy children can make precise distinctions between small numbers of objects (e.g. 2 vs. 3 objects; Feigenson & Carey, 2003; Feigenson, Carey & Hauser, 2002) and approximate judgments about large quantities (e.g. 8 vs. 16 objects; Brannon, Abbot, & Lutz, 2004; Xu & Spelke, 2000). However, without a system for representing large, exact quantities such as counting, humans have difficulty making precise distinctions between larger quantities (e.g. 15 vs. 16 objects; Frank, Everett, Fedorenko, Gibson, 2008).

In contrast, number words represent exact quantities by mapping quantities to arbitrary symbols, which are related through the count list. Unfortunately, learning which number words refer to which quantities and how numbers are related through counting is not a quick or simple task for young children (Barner & Bachrach, 2010; Carey, 2009; Wynn, 1990; 1992). Substantial evidence suggests that children learn the meanings of number words through a series slow and piecemeal stages (e.g. Lee & Sarnecka, 2010; Sarnecka & Carey, 2008; Sarnecka & Lee, 2009; Wynn, 1990; 1992). By the time children enter school, there are already vast individual differences in their comprehension of symbolic number (e.g. Clements & Sarama, 2007; Dowker, 2008; Ginsburg & Russell, 1981; Klibanoff, Levine, Huttenlocher, Vasilyeva & Hedges, 2006; Starkey, Klein & Wakeley, 2004; West, Denton & Germino-Hausken, 2000), and these differences predict future academic success (Duncan et al., 2007) as well as other important life outcomes (Murnane, Willet, & Levy, 1995; Rivera-Batiz, 1992; Reyna, Nelson, Han & Dieckmann, 2009).

The contrast between children's early developing proficiency with approximate quantities and their difficulty learning the meanings of number words highlights the fact that numbers exist in several distinct codes (Dehaene, 1992). Specifically, Dehaene (1992) suggested that numbers are mentally manipulated in either a nonsymbolic, analogical code (i.e. numerical quantities) or one of two types of symbolic codes, an "Arabic" code (i.e. the Arabic Numerals) or a verbal code (i.e. number words). Accordingly, although infants are capable of forming analogical representations of numerical quantity shortly after birth, they must learn to represent number using symbolic number systems.

However, in addition to preverbal, analogical number systems and symbolic number words, children also have access to another code for representing numbers: number gestures (e.g. holding up five fingers to indicate 'five'). Importantly, number gestures share some properties of both the nonsymbolic and symbolic number codes. For instance, unlike number words, the relation between the form of number gestures and their meaning is not arbitrary. Rather, number gestures are iconic, item-based representations of number (the number of fingers displayed in a gesture corresponds exactly to the number of items the gesture is meant to describe). Early theories of symbolic development suggest iconic representations are easier to learn than arbitrary symbols (Piaget, 1962; Werner & Kaplan, 1963). More recent research suggests this may be particularly true for children around two years of age (Namy, Campbell & Tomasello, 2004), which is around the age when children begin to learn the meanings of number words. Accordingly, previous researchers have argued that number gestures and other iconic number systems are easier for children to learn than the purely symbolic systems, like number words (Wiese, 2003).

Additionally, number gestures have important similarities to symbolic number codes, such as number words. Number gestures can be used as symbols to reference specific quantities. They often become conventionalized, such that certain numbers are preferably created by holding up particular configurations of fingers (Di Luca & Pesenti, 2010; Noël, 2005). Moreover, at least by adulthood, many people in numerate societies appear to treat number gestures as symbols (Di Luca &Pesenti, 2008). Given the unique affordances of number gestures to act as symbols that specify particular quantities (like number words) and also map directly to collections of things via one-to-one correspondence (like nonsymbolic item-based representations), number gestures could be a useful tool in the development of symbolic number. In fact, there is some historical evidence that number words emerged from finger counting systems and other iconic number systems such as body counting and tally systems (Hawke, 2008; Ifrah 2000; Menninger, 1969; Winter, 1992).

Still, although many developmental theories assume number gestures play some role in the development of symbolic number understanding (e.g. Alibali & DiRusso, 1999; Di Luca & Pesenti, 2011; Gelman & Gallistel, 1978; Fischer, Kaufman & Domhas, 2012; Fuson, 1988), there is wide disagreement about what this role might be. Serious questions remain regarding the extent to which children's use and understanding of number gestures impact their developing understanding of number words and if so, through what mechanisms. In the present thesis, I will begin to tackle these questions. Chapter 1 will review children's nonsymbolic number systems, symbolic number systems, and the existing literature on where number gestures might fit in between the two. Chapter 2 will present preliminary evidence that number gestures do play some role in the acquisition of number words. Finally, in Chapters 3 and 4, I will explore what this role might be by probing the relation between number gestures and clear number symbols, number words. Ultimately, I conclude that although more research is needed, the present set of experiments combined with previous research suggests that children's knowledge of number gestures is extensive and that number gestures could play a significant supportive role in the acquisition of number words.

1.1. Preverbal, Nonsymbolic Number Systems

Prior to any formal training in mathematics, infants are capable of representing certain aspects of numerical quantity using two distinct systems: the Parallel Individuation System and the Approximate Number System (ANS) (e.g. Carey, 2009; Feigenson, Dehaene, & Spelke, 2004; Spelke & Kinzler, 2007). Both systems are available beginning in infancy prior to learning any language but are marked by important limitations.

The ANS enables children to represent the approximate number of items in a set, but these representations are noisy and marked by increasing variability as the magnitude of the set increases. Evidence of the existence of the ANS has been found in nonhuman animals (Church & Meck, 1984; Platt & Johnson, 1971), preverbal infants (e.g. Barth, La Mont, Lipton, & Spelke, 2005; Brannon, 2002; Brannon, Abbot, & Lutz, 2004; Lipton & Spelke, 2003,2004; Xu & Spelke, 2000; Xu, Spelke & Goddard, 2005), and adults who either never learned a count list (Frank et al., 2008; Gordon, 2004; Pica et al., 2004; Spaepen et al., 2011) or who are prevented from counting (Barth, Kanwisher & Spelke, 2003; Halberda & Feigenson, 2008; Whalen, Gallistel & Gelman; 1999). In each case, the ANS adheres to Weber's law, which states that the discriminability of two quantities is inversely proportional to the magnitude of the stimuli. For instance, when rats are trained to press a lever a certain number of times (4, 8, 16, or 24) the variability of the actual number of times they press the lever increases with the target number (Platt & Johnson, 1971).

Likewise, 6-month-olds who are habituated to displays of 8 dots recover interest and look longer at test display of 16 dots than at novel test displays of 8 dots (Xu & Spelke, 2000). In contrast, subsequent experiments revealed that 6-month-olds fail to discriminate between displays of 8 vs. 12 dots (a 2:3 ratio). As children age, the acuity of the ANS continues to develop, such that 9-month-olds can typically discriminate between quantities along a 2:3 ratio (e.g. 8 vs. 12 dots) and adults can generally discriminate between quantities along a 9:10 or 10:11 ratio (e.g. Lipton & Spelke, 2003; Halberda & Feigenson, 2008). Similar patterns of numerical approximation have been observed among members of Amazonian groups who speak languages that lack a formal count list (Frank et al., 2008; Gordon, 2004; Pica et al., 2004) as well as Deaf homesigners who live in numerate societies but lack access to a spoken or signed language (Spaepen et al., 2011). Together, these studies suggest that the ANS is present early in development, is not dependent on language, and continues to be used by adults whether or not they learn a formal count list.

Unlike the large, approximate representations of the ANS, the Parallel Individuation system enables children to represent small groups of items precisely. Specifically, children can track up to three individual items at a time, hold representations of those items in working memory, and make precise distinctions between 1, 2, and 3 items (e.g., Feigenson et al., 2004; Feigenson & Carey, 2003; Feigenson, Carey & Hauser, 2002; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Wynn, 1992). For instance, in one study 10- to 12-month olds were shown different numbers of crackers placed into two opaque buckets and then allowed to crawl to one of the two buckets. When children were tested on 1 vs. 2 crackers, 1 vs. 3 crackers, or 2 vs. 3 crackers, they correctly crawled to the bucket with more crackers. However, when they were tested on 3 vs. 4, 2 vs. 4, or even 1 vs. 4, children selected the bucket with more crackers at chance (50%) (Feigenson, Carey & Hauser, 2002). This same 3 item limit on children's Parallel Individuation system has been observed using a variety of tasks (e.g. Feigenson & Carey, 2003; Starkey & Cooper, 1980), although there is evidence that adults can track up to 4 items in parallel (Cowan, 2001).

In summary, preverbal number systems enable humans to make precise distinctions between 1, 2, 3, and sometimes 4 items, and approximate distinctions between larger sets. Importantly, neither system is capable of representing large, exact quantities, like 17 or 543. To go beyond the limits of our preverbal number systems, humans must develop symbolic number systems. This is perhaps most strikingly demonstrated by peoples who lack a formal count list. Groups like the Pirahã, Munduruku, and Nicaraguan homesigners (among others) are able to precisely label quantities up to about three or four but can only approximately label quantities beyond four (Coppola, Spaepen & Goldin-Meadow, 2013; Frank et al., 2008; Gordon, 2004; Pica et al., 2004; Spaepen, Coppola, Spelke, Carey & Goldin-Meadow, 2011; Spaepen, Flaherty, Coppola, Coppola, Spelke & Goldin-Meadow, 2013). However, even many systems capable of representing exact quantities show evidence of the limits of humans' ability to perceive large exact quantities. In the next section, I will take a brief historical and cross-cultural look at number symbols before turning to the development of symbolic number in children.

1.2. Symbolic Number Systems

1.2.1. Historical and Cross-Cultural Perspective on Symbolic Number Systems

Just as children are not born knowing how to count, humans have not always had symbolic count lists (Ifrah, 2000). In fact, Menninger (1969) suggests that truly symbolic numeral systems, like the Arabic numerals we use today, are a somewhat rare invention, and are often imported from other cultures. The earliest versions of the numeral system that we use today, which expresses every number through different combinations of a set of ten symbols originated in India sometime before the sixth century CE (Ifrah, 2000).

However, most cultures do find ways of tracking and communicating precise quantities. Some of the simplest and most common ways are through various tally systems (See Figure 1). Such systems take many forms, such as notches on a stick, knots in a rope, dashes or dots on paper, and so on. What these systems typically have in common, at least at first, is that the number of dashes, dots, or notches can be placed in one-to-one correspondence with the objects they are tracking. Another feature that these systems generally have in common is that they almost all look for ways of accommodating our limited capacity to represent exact sets above 4. For example, between the 5th and 3rd centuries BCE, Aramaic systems in Egypt grouped strokes into sets of 3 (See Figure 1A; Ifrah, 2000). In the tally system that we are most familiar with, 4 vertical strokes are crossed with a single horizontal stroke to indicate 5.

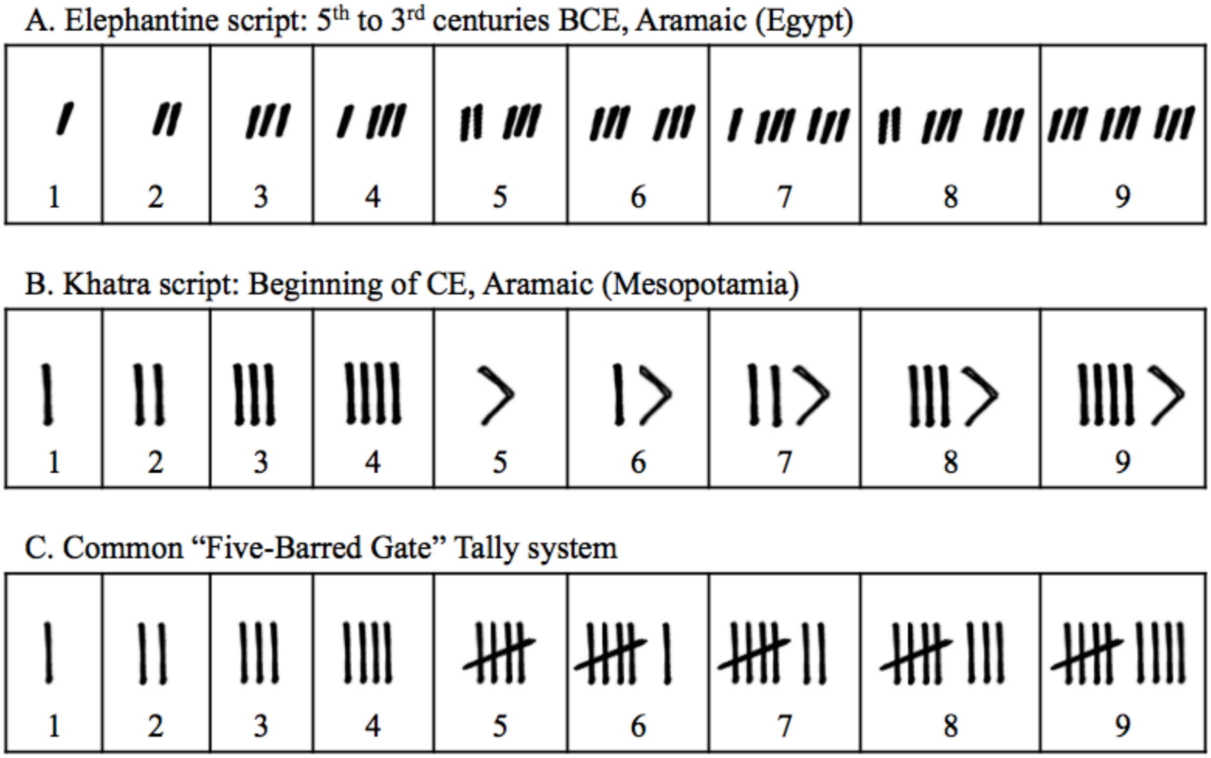


Figure 1. Historical and modern tally systems.

One of the most common (and perhaps the earliest) tally systems is counting on one's fingers. As I will discuss later in the chapter, using one's fingers to track exact quantities of objects is still a very common supplement to our symbolic number systems of words and numerals (Bender & Beller, 2012). Throughout history, finger counting systems have been widely used and developed to express numbers well beyond ten (Ifrah, 2000; Menninger, 1958). The ancient Romans used a form of finger counting which could represent numbers from 1 to 10,000 (Menninger, 1969). Other body counting systems are still used by several groups of people in Papua New Guinea (Saxe, 1981). In one system, 1 is represented by the right pinky, and each successive finger represents an additional item up until 5. At this point, the count continues to wrap around the body from the thumb (5), to the wrist (6), to the forearm (7), to the elbow (8), and so on, leading to a full count of 28 (or more if the lower half of the body and toes are used; Ifrah, 2000; Saxe, 1981).

Importantly, although I described the corresponding quantities of each position using numerals these body positions are not necessarily symbolic of these corresponding quantities. Rather positions may be used as tally marks, mapping in one-to-one correspondence with the items to be counted. Nonetheless, several researchers have suggested that symbolic counting systems as we know them were historically born out of tally systems such as these (Barner, 2017; Ifrah, 2000; Menninger, 1969). Ifrah (2000) proposes three stages of the evolution of counting systems. In the first stage, people are limited to their nonsymbolic preverbal number systems. In order to express exact quantities above four, they develop systems such as finger counting, body counting, or other tally systems that all function through one-to-one correspondence with the items they represent. In the second stage, the names for the body parts that are used in these one-to-one correspondence systems take on a more abstract meaning and become increasingly mapped directly to the quantities they represent. This brings people to the third stage in which the intermediary body counting is dropped and people are left with fully symbolic names for numbers.

In support of this, verbal counting systems sometimes contain vestigial characteristics of their past links to body counting systems (Ifrah, 2000). For instance, Hawtrey (1901) observed that the word that the Lengua people of Paraguay used for ‘five’ translated to “one hand”. In fact, some of the number words we use in English, as well as other European languages, may stem from words referring to our hands (Hawke, 2008; Winter, 1992). In English and many other languages the word for “five” is believed to stem from the root of the Proto-Indo-European word for “fist” and “finger” and there is some evidence to suggest that “ten” comes from a contraction of the Proto-Indo-European words for “two hands” (Winter, 1992). Likewise, we still call numerals and fingers “digits”. It has even been suggested that the reason base-ten number systems are so much more common than any other base counting system is that we have ten fingers (Andres, Di Luca & Pesenti, 2008; Ifrah, 2000).

Thus, history provides us with at least one mechanism through which number gestures might aid in the transition from nonsymbolic to symbolic representations of number. First, number gestures are mapped to precise quantities via one-to-one correspondence. Next, particular number gestures are given names. Finally, these names become associated with the quantities themselves rather than the gestures. The extent to which children follow a similar developmental trajectory on a vastly reduced timespan remains to be determined. Although cardinal number gestures are ubiquitous (Bender & Beller, 2012), most theories of number development do not include them as a necessary step in the acquisition of number words (e.g. Carey, 2009; Barner, 2017; Spelke & Tsivkin, 2001). However, many researchers have suggested that the ontogenetic development of numbers may be similar to the historical invention of numbers (e.g. Barner, 2017; Carey, 2001; 2004; 2009, Dehaene, 1992; 1997). Therefore, we should seriously consider the possibility that gesture could play a similar function in children's acquisition of number words. Even if number gestures are not a necessary step for children who are learning an existing symbolic number system, they could still support the acquisition of number words through a mechanism that is largely the same as their historical role – namely, as a bridge between nonsymbolic and symbolic number systems.

1.2.2. Development of Symbolic Number in Children

Decades of research indicate children learn the meanings of number words through a series of lengthy stages (e.g. Lee & Sarnecka, 2010; Sarnecka & Carey, 2008; Sarnecka & Lee, 2009; Wynn, 1990; 1992). Around the age of two, children begin to recite a portion of the count list (e.g. the number words "one" through "ten") but do not initially know what these words mean (e.g. Wynn, 1990). Next, children learn the actual meanings of the first few number words – "one", "two", "three", and sometimes "four" – through a series of prolonged stages (e.g., Sarnecka & Lee, 2009; Wynn, 1990, 1992). Children proceed through these stages sequentially, first learning the meaning of "one" and then spending several months as "one-knowers" before learning the meaning of two (thus, becoming "two" knowers"). Likewise, children spend several more months as two-knowers before learning the meaning of three. Finally after becoming three- and sometimes four-knowers children learn the cardinal principle, that the last number reached when counting a set represents the cardinal value of that set. This typically occurs around the age of four, roughly two years after first learning to recite the count list (Sarnecka & Lee, 2009; Wynn, 1990, 1992).

These stages indicate several important characteristics of how children acquire the meanings of number words. First, children generally learn to recite the count list prior to learning the meanings of the number words. Various researchers have likened this to the tally systems discussed in the previous chapter (Weise, 2003; Barner, 2017). Prior to learning the cardinal principle, children can generally learn to recite at least the first ten or so numbers of the count list in order and even correctly count each item in a set only once. However, prior to learning the cardinal principle, when asked how many items in a set after a child finishes counting them, they very often respond by repeatedly counting, beginning at "one" again, rather than repeating the last number they reached. Thus, there clearly exists a period when children can match items to a tally (i.e. a count list) before learning that specific quantities can be labeled using summary symbols.

Another notable characteristic of the knower-level trajectory is the clear divide between numbers that children learn prior to grasping the logic of the counting system (1, 2, 3, and often

4) and numbers that are learned as a consequence of the cardinal principle (numbers above 4; Although in my own studies, there are rare cases of 5-knowers). Most researchers interpret this divide as evidence that the parallel individuation system plays a role in children's early number development (Barner, 2017; Carey, 2009; Le Corre & Carey, 2007; Spelke & Tsivkin, 2001). However, it is important to note that there is disagreement about the exact role that the PI system plays, whether early meanings of number words are mapped directly to representations from the PI system (Carey, 2009; Le Corre & Carey, 2007) or merely constrained by the limits of the PI system (Barner, 2017). In either case, further evidence that the PI system is involved in children's acquisition of "one", "two", and "three" comes from the fact that children rarely count when asked to make these sets (Wynn, 1990; 1992). Furthermore, studies of children's ability to approximate the number of items in a set suggest that children form mappings between number words and approximate magnitudes relatively late in the process of number development, often after learning the cardinal principle (Le Corre & Carey, 2007; Lipton & Spelke, 2005; but see Gunderson et al., 2015, Wagner & Johnson, 2011 and Odic, Le Corre & Halberda, 2015 for some evidence that subset knowers do map number words to approximate magnitudes).

Furthermore, an important feature of the knower-level trajectory is how long it takes children to learn the meanings of each of the first several number words. Several researchers have proposed explanations of why children take so long to learn the meaning of each word. On one account, children are not born with innate concepts of ONE, TWO, and THREE and must construct these by enriching PI representations with set representations like those found in natural language (Carey, 2009; Le Corre & Carey, 2007) or by combining PI representations with ANS representations (Spelke & Tsivkin, 2001). In another view, the difficulty of learning the first three number words stems from the more general problem of mapping words to concepts

(Barner, 2017). To learn the meaning of any word children must figure out which aspect of the world that word is meant to label (Quine, 1960). This might be particularly difficult in the case of numbers, since number words, unlike other common words in children's vocabularies (e.g. nouns or adjectives), do not describe individual objects or even properties of objects but rather they describe properties of sets of objects (Bloom & Wynn, 1997). In support of this latter view, a study of bilingual children found that comprehension of a number word in one language did not predict comprehension of the corresponding number word in bilinguals' second language (as one would expect if the major barrier to learning the meaning of a number word was constructing the underlying number concept; Wagner, Kimura, Cheung & Barner, 2015). Still other researchers have even suggested that children have an innate understanding of both small numbers and the counting principles and number development is a process of mapping language to innate concepts (Leslie, Gelman & Gallistel, 2008).

Whether or not children initially possess the concepts underlying small number meanings, it is clear that the meanings of small number words are not immediately obvious to children and must be learned from extensive input (Levine et al., 2010; Gunderson & Levine, 2011). As subset-knowers children make frequent and often systematic errors when labeling sets or responding to a request for a certain number of items. For instance, there is evidence that children sometimes struggle to realize that the meanings of numbers are independent of the types of object in a set. At early stages of number development children, sometimes successfully learn the meaning of a number word within a limited context (e.g. two shoes) but fail to generalize their understanding of that number to all sets of equal size (Huang et al., 2010; Mix, Huttenlocher & Levine, 2002). For instance, children might learn to successfully point out sets of two dogs after training but be unable to point out sets of two that are made up of other objects.

Moreover, beyond learning that numbers describe quantities and not other features of objects, children must learn which exact quantity number words represent (Barner & Bachrach, 2010). Barner and Bachrach (2010) suggest that children do this by learning the meanings of number words in sequence. For instance, after learning the meaning of 'one' children know that 'two' has a lower-bound of one, but when asked for two items they often respond with more than two items suggesting they do not know the upper bound of 'two'. By gaining a partial understanding of 'three' (i.e. the lower bound of 'three'), children learn that 'two' refers to exactly two items.

The next aspect of the knower-levels trajectory that deserves attention is the transition from comprehending a subset of number words to fully grasping the cardinal principle. Again, there is disagreement concerning the significance of this transition in terms of children's representation of numbers and the counting system. In one account, acquiring the cardinal principle represents a major shift in children's understanding of numbers and the count list. For example, one proposal suggests that children grasp the cardinal principle through an induction of the successor function, the idea that each number n has a successor $n+1$ (Sarnecka & Carey, 2008; Carey, 2009). However, more recent research suggests that many cardinal principle knowers actually lack a complete understanding of the successor function (Davidson, Eng & Barner, 2012; Wagner et al., 2015) and that children may not fully understand the successor function until around the age of six, long after learning the cardinal principle (Cheung Rubenson & Barner, 2017). Therefore, in another view children first learn the cardinal principle as a simple procedural rule and then slowly acquire an understanding of the successor function through additional experience with the count list and sets of varying sizes (Barner, 2017).

Absent from many of the theories described above is a clear picture of how gesture may play a role in children's number development. However, given these various stages of number development, there are several possible points at which gestures could impact children's acquisition of symbolic number language. First, number gestures may serve as a tool for recognizing the abstract nature of small number words and helping children to remember the precise quantities they represent. As described above, children often struggle to recognize that number words describe abstract quantities. By giving children an iconic representation of numbers that they can take with them and reference, number gestures could support the learning of even the most basic number meanings.

Second, by giving children a way to communicate about precise quantities above 4, number gestures may help children recognize that exact quantities extend past the small number range. Barner (2017) draws the comparison between number development in children and the historical invention of number and suggests that humans developed counting systems to fill an 'explanatory gap' between our fuzzy, approximate representations of large numbers and our intuition that exact numbers extend beyond the small number range. By providing children with a way to represent exact quantities above 3 or 4, number gestures may bolster children's intuition that there are exact quantities beyond the limits of their perception. This could increase the salience of the 'explanatory gap' described by Barner and prompt children to develop the cardinal principle. Alternatively or in addition, precise mappings between number words and cardinal number gestures could help children notice the successor relation, at least within the 1-10 range. In the next section, I will review the existing literature on children's use of number gestures and the current evidence that number gestures could serve as a bridge between nonsymbolic and symbolic representations of number.

1.3. Role of Gestures in Number Development

Gestures are a useful tool for communicating numerical information and are frequently employed by children and their parents (Goldin-Meadow, Levine & Jacobs, 2014; Fuson, 1988; Suriyakham, 2007). Finger counting is one of the most frequent strategies used by children during counting and arithmetic activities (Fuson, 1982; Siegler & Shrager, 1984). Many theories suggest that number gestures play a role in the development of verbal number knowledge and counting principles (e.g. Butterworth, 1999, 2005; Gelman & Gallistel, 1978; Gracia-Bafully & Noël, 2008; Fuson et al., 1982; Fuson, 1988). However, despite the ubiquity of number gestures, there is surprisingly little agreement concerning the precise role that gestures play (or do not play) in number development.

Many of the proposed uses of number gestures revolve around children's comprehension and implementation of the counting principles (Alibali & DiRusso, 1999; Di Luca & Pesenti, 2008; Fuson, 1988; Gelman & Gallistel, 1978; Graham, 1999; Potter & Levy, 1968; Saxe, 1977; Saxe & Kaplan, 1981). Counting gestures, such as pointing to objects while counting and raising fingers while reciting the count list, are used by children as young as the age of two (Fuson et al. 1982; Gelman & Gallistel, 1978). Children use counting gestures to keep track of the number words while reciting the count list and to help maintain the stable order of the numbers in the count list (Fuson, 1982; Wiese, 2003). Pointing while counting also appears to be particularly useful for understanding and implementing the one-to-one correspondence principle by helping children map a single number word to each item being counted (Alibali & DiRusso, 1999). In fact, 3 to 4 year old children who watched an experimenter count, believed a count was incorrect if the experimenter pointed to one object twice even if the experimenter used the correct order and number of number words when counting (Briars & Siegler, 1984). By 4 years, children almost always point to each object when successfully implementing one-to-one correspondence during counting (Saxe, 1977).

Additional research has highlighted the connection between number processing and finger representation (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Moeller et al., 2012). Children's ability to represent their fingers mentally and discriminate between their fingers is correlated with math ability (Fayol, Barrouillet, & Marinthe, 1998; Noël, 2005). Number gestures have also been linked to numerical cognition by studies demonstrating common neuroanatomical substrates of finger representation and number processing (Pesenti et al., 2000; Piazza et al., 2002; Pinel et al., 2004).

1.3.1. Adults and Older Children's Understanding of Cardinal Number Gestures

Although cardinal number gestures are common across cultures (Bender & Beller, 2012), previous research has largely focused on adults' understanding of cardinal number gestures (e.g., Di Luca, Lefèvre, & Pesenti, 2010; Di Luca & Pesenti, 2008; Spaepen, Coppola, Flaherty, Spelke, & Goldin-Meadow, 2013; Spaepen, Coppola, Spelke, Carey, & Goldin-Meadow, 2011; Suriyakham, 2007). However, such adult research can provide insight into the different ways that children may be interpreting number gestures. In particular, to what extent are number gestures symbolic representations of the quantities they refer to (like number words) and to what extent are number gestures nonsymbolic, item-based representations of number (like tally systems)?

There is evidence that aspects of a person's experience may play an important role in whether they view number gestures as summary symbols or item-based representations (Spaepen et al., 2013; Spaepen et al., 2011). Deaf adults who do not have access to a sign-language or spoken language (and thus never learned a symbolic count list) and who have instead learned to communicate with homemade "homesigns" use cardinal number gestures to communicate about set sizes size (Spaepen et al., 2011; Coppola, Spaepen & Goldin-Meadow, 2013). However, homesigners' use of cardinal number gestures seems to reflect the same nonsymbolic number systems that support children's reasoning about number prior to learning symbolic number (ANS and Parallel Individuation system). Specifically, when asked to use gestures to label a set of items, homesigners are accurate when labeling sets up to 3 items, but only respond approximately when asked to label sets above 3.

Further evidence that homesigners represent cardinal number gestures as item-based rather than summary symbols comes from asking homesigners to recall sequences of cardinal number gestures. When tasked with recalling sequences involving high number gestures (e.g. 4, 5, 4) homesigners make more errors than when tasked with recalling sequences within the small number range (e.g. 2, 3, 2). The greater difficulty of large number sequences suggests that homesigners may be forming item based representations of these gestures (e.g. ONE ONE ONE ONE) which may be a heavier load on working memory than a single summary symbol (e.g. "four"). In contrast, Deaf adults who use American Sign Language and thus learned a symbolic count list, perform equally on small and large number sequences, suggesting they represent the cardinal number gestures in both sequences as summary symbols.

Additional evidence that numerate adults represent number gestures as summary symbols comes from comparisons of canonical number gestures (e.g. index and middle finger to mean "two") and noncanonical number gestures (e.g., an index and pinky finger raised to mean "two"). Adults, as well as second graders, are faster to name canonical number gestures than noncanonical number gestures (Di Luca &Pesenti, 2008; Noël, 2005). Similarly, in adults, canonical number gestures but not noncanonical number gestures prime nearby numbers in the count list in the same way that Arabic numerals do (Di Luca et al., 2010). The fact that the configuration of number gestures impacts the ease with which numerate adults and older children can interpret them suggests that the canonical form of cardinal number gestures might be symbolic of the meanings of these gestures (similar to number words), rather than linked only by the number of fingers raised.

1.3.2. Children's Understanding of Cardinal Number Gestures

The existing research on young children's understanding of cardinal number gestures has focused less on whether children view these as summary symbols or item-based representations and more on the extent to which young children can learn the meanings of these gestures at all. Unlike, number words, the mappings between number gestures and the quantities they represent are not arbitrary. Some have suggested that "iconic gestures" (gestures that resemble their referent), may be easier young children to learn than arbitrary symbols (Piaget, 1962; Namy et al., 2004) especially in an abstract domain like number (Wiese, 2003). However, young children also appear to be quite skilled at learning the arbitrary mappings between symbols and their referents (Bates, Benigni, Bretherton, Camaioni & Volterra, 1979; Westbury & Nicoladis, 1998). Therefore, the only way to truly know if children learn number gestures before number words is to test it directly.

In one study, Nicoladis and colleagues (2010) compared children's understanding of number words to their understanding of number gestures on two tasks. In the first task, the give-a-number task, children were presented with a number word or number gesture (from 1-10) and asked to retrieve the corresponding number of toys. In the second task, the how-many task, children were presented with a set of toys and asked to label the set using a number word or number gesture. They looked at two groups of children 2- to 3-year-olds and 4- to 5- year olds. They found that 2- to 3-year olds performed equally poorly on both the gesture and verbal versions of the give-a-number task, while the 4- to 5-year-olds performed better on the verbal version than the gesture version of this task. On the how-many task, there was no interaction of age such that both groups of children performed better on the verbal version than the gesture version of the task. Nicoladis and colleagues concluded that children's knowledge of number words exceeds their knowledge of number gestures, and thus that there was no evidence to suggest children use their knowledge of number gestures to learn number words. Similarly, Crollen et al. (2011) interpreted these findings to mean that number gestures do not precede the acquisition of number words and thus that the acquisition of number words is not rooted in children's acquisition of cardinal number gestures.

However, in a more recent paper, my colleagues and I pointed to several aspects of these findings which suggest that the advantage of number words over number gestures may not be universal across children of all ages and stages of number development (Gunderson et al., 2015). First, the effects were mainly driven by the difference in accuracy on set sizes 6, 7, 8, and 9, which require children to form different handshapes with each hand, a difficult task for young children (although this would only explain differences on the production task). Second, the advantage of words over speech was strongest for the 4- to 5- year olds who were likely to have already learned the cardinal principle. Given their knowledge of the cardinal principle, these children were likely to be well-practiced using number words and at or near ceiling on tasks involving number words.

If children ever display greater proficiency using number gestures compared to number words, it likely occurs before children become skilled with number words. Research outside of the domain of number suggests that when children are on the cusp of new knowledge their gestures often contain different and often times more accurate information than their speech (e.g.

Iverson & Goldin-Meadow, 2005). Accordingly, we are most likely to observe an advantage of using gestures over speech when children are still subset-knowers, prior to learning the cardinal principle. To test this, we administered two “What’s on this Card “(WOC) tasks in which children were asked to label sets of items on a sheet of paper using number words (WOC-Speech) or number gestures (WOC-Gesture). In addition, we used the Give-N tasks to determine if children were already cardinal principle knowers or if they were at an earlier stage of number development.

Consistent with our interpretation of the Nicoladis et al. (2010) findings, subset knowers were significantly more accurate when labeling small sets in gesture compared to speech (Figure 2). As predicted, this effect appeared to be strongest for numbers immediately above children’s knower level. In contrast, cardinal principle knowers showed either no difference or a slight advantage for labeling sets in speech compared to gesture depending on the set size. We concluded that the ability to label small sets, like two or three, using number gestures preceded the ability to label those same sets using number words.

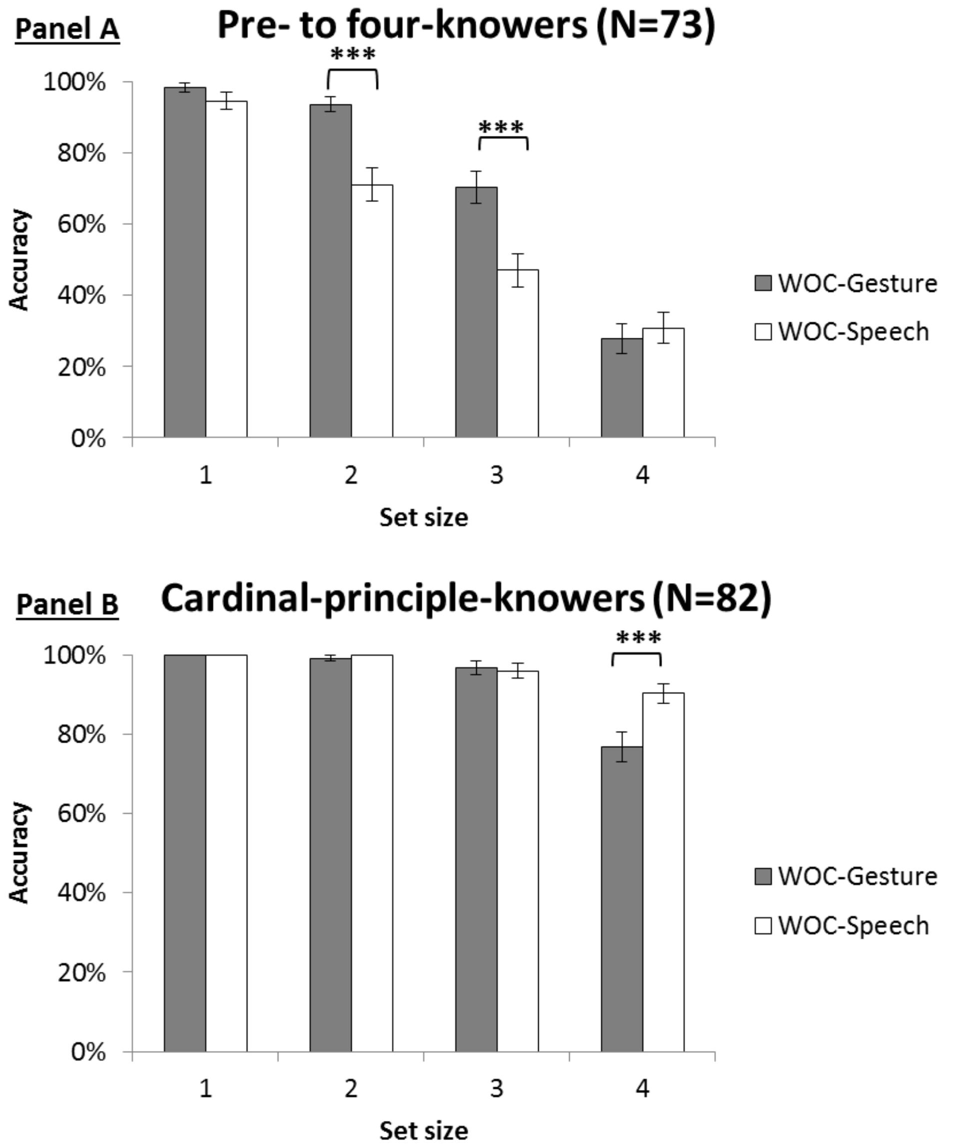


Figure 2. Accuracy on the WOC-Gesture and WOC-Speech tasks by set size. ***p<.001

We also looked at subset knowers' ability to approximate larger sets in gesture compared to speech (5 and 10 in gesture, 6 and 9 in speech), since subset knowers cannot accurately label set sizes above 4. Again, subset knowers were more accurate in approximating quantities using gestures than speech, as demonstrated by a positive slope between their gesture labels for 5 and 10 and a flat slope between their speech responses labels for 6 and 9 (Figure 3).

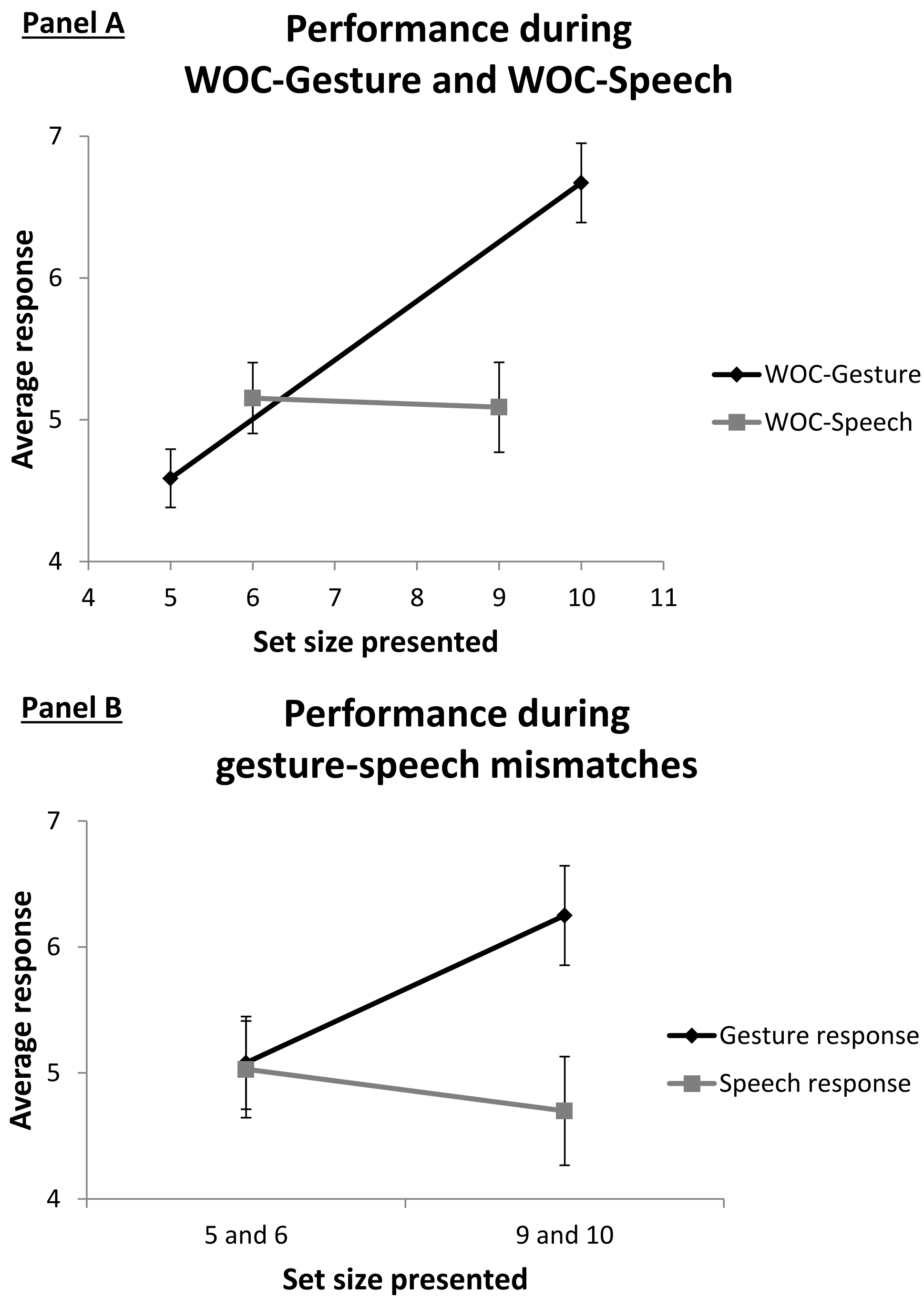


Figure 3. Subset-knowers' average responses to large set sizes (5-10) on the WOC-Gesture task and on the WOC-Speech task (Panel A) and on the gesture and speech components of the gesture-speech mismatches children produced on both tasks (Panel B).

Together, these findings show that prior to fully comprehending number words, children are more accurate when labeling both small and large sets using gestures compared to speech.

However, beyond demonstrating that children have some proficiency using number gestures, these data do not provide a clear picture of how children conceive of number gestures – whether they are simple item-based representations or mark the beginning of symbolic representations of number – and how they fit into the broader development of symbolic number knowledge. In the following section, I outline several questions aimed at gaining a better understanding of number gesture's place in number development more broadly.

1.4. Research Questions

Historically, number gestures may have served as a bridge between item-based representations of number and fully symbolic number systems (e.g. Ifrah, 2000; Menninger, 1969). Gunderson et al. (2015) suggested that number gestures could serve a similar purpose during children's acquisition symbolic number. The present thesis takes up that proposal by examining several implications of the bridge proposal.

Are children better at matching number gestures to nonsymbolic quantities than number words to nonsymbolic quantities?

In order for number gestures to serve as a bridge between preverbal item-based representations of number and symbolic representations (i.e. number words), children should find it easier to match number gestures to the quantities they represent than matching number words to their meanings. As argued by Nicoladis et al. (2010), the role that number gestures could play in the acquisition of number words would be limited if children learn the meanings of number gestures only after they learn the meanings number words. As reported above, we have already shown that prior to learning the meanings of small number words like two and three, children are more accurate when labeling sets of this size in gesture compared to speech

(Gunderson et al., 2015). These findings will be described further in Chapter 2 (Study 1) with a particular focus on children's simultaneous gestures and speech.

Are number gestures relevant to number word learning?

Although previous research has found a role for counting gestures in the development of symbolic number and the counting principles, there is little evidence to connect the development of cardinal number gestures to the acquisition of number words. Previous studies have found that gesture-speech mismatches, in which children's gestures convey more or different information than the accompanying speech, predict imminent learning in a variety of domains including math (e.g. Church & Goldin-Meadow, 1986; Iverson & Goldin-Meadow, 2005; Perry, Church, & Goldin-Meadow, 1988) Therefore, Study 1 explores whether gesture-speech mismatches when labeling the number of items in a set predicts who is likely to learn a new number word from number input.

Are children better able to match number words to number gestures than directly to nonsymbolic quantities?

The iconic nature of number gestures (i.e. fingers map via one-to-one correspondence to the items in a set) appears to help children make gesture-quantity mappings compared to number word-quantity mappings (Gunderson et al., 2015). However, in order for number gestures to serve as a bridge between preverbal item-based representations and symbolic representations of number (i.e. number words), children not only have to map number gestures to exact quantities but also map number gestures to number words. Here, the fact that number gestures number gestures share many properties of words (i.e. they may serve as summary symbols that refer to specific quantities) may help children learn the number words associated with them. Therefore, in Chapter 3 (Study 2), I look at whether children's ability to map number words to number gestures exceeds their ability to map number words to nonsymbolic representations of number (i.e. arrays of dots).

Are number gestures symbols?

A stronger version of the proposal in Study 2 is that number gestures are not only accurately mapped to number symbols (i.e. number words) but are in fact symbols themselves. Definitions of symbols used by previous researchers have distinguished symbols from iconic representations on the basis of symbols' arbitrary relation to their referent (Piaget, 1962; Vygotsky, 1962). More recent definitions have suggested that symbols need not be arbitrarily related to their referents (e.g. Namy & Waxman, 2012). In fact, newer theories have argued that iconicity can be useful for learning the mapping between a symbol and its referent (Namy et al., 2004). Nonetheless, in the case of number gestures, it is important to distinguish between item-based representations, in which each finger is represented separately (like representations of sets of objects) and summary representations in which the number gesture as a whole is linked to a particular quantity (like number words). For instance, adults and older children display an advantage when labeling canonical number gestures compared to non-canonical number gestures, suggesting children eventually map quantities to non-numerical features of number gestures (Di Luca & Pesenti, 2008; Noël, 2005). Thus, while it is not necessary that the mapping between gesture and quantity be arbitrary in order for it to be considered a symbol, attention to the configuration suggests that adults and older children do eventually treat number gestures as symbols. Likewise, if younger children attend to arbitrary, non-numerical features of gestures' configurations when matching them to their referents, it would suggest that children view number gestures as single symbols and not merely collections of items. If this is the case, number gestures may be some of the first number symbols that children learn, prior to learning number words. This would provide further evidence that number gestures can serve as a bridge between item-based representations and number words.

2. CHAPTER TWO Study 1: Number gestures predict learning of number words

2.1. Background

Decades of research have shown that learning the meanings of number words (one, two, three, etc.) is a protracted process that takes about two years (e.g., Carey, 2009; Sarnecka & Carey, 2008; Sarnecka & Lee, 2009; Wynn, 1990, 1992). These stages are remarkably consistent across different linguistic and cultural groups (Barner, Libenson, Cheung, & Takasaki, 2009; Li, Le Corre, Shui, Jia, & Carey, 2003; Piantadosi, Jara-Ettinger & Gibson, 2014; Sarnecka, Kamenskava, Yamana, Ogura, & Yudovina, 2007). However, the length of time that children spend in each stage, and the age at which they ultimately grasp the cardinal principle—that the last number reached when counting a set represents the cardinal value of that set (Gelman & Gallistel, 1978)—are far more variable (e.g. Lee & Sarnecka, 2010; Dowker, 2008). This variability is significant because the number knowledge that children have accrued by kindergarten entry predicts their future achievement in mathematics (Duncan et al., 2007).

Despite the importance of early number knowledge, little is known about the internal and external factors that propel children's progress through this developmental trajectory. Here we ask two interrelated questions. First, considering the gestures children produce in relation to their speech, can we identify children who are on the cusp of transitioning to the next stage of number knowledge? Specifically, do children's numerical gesture-speech mismatches (e.g., saying "three" while holding up two fingers) index their readiness to learn a new number word? Second, does the richness of the number input children receive influence whether children at the beginning of their number learning trajectory benefit from that input? Specifically, do these children learn more from number input that involves spatial alignment (e.g., seeing two beads next to three beads) and cardinal labeling than from counting alone (as has been shown for children on the cusp of learning the cardinal principle, Mix et al., 2012), and does this effect depend on the child's readiness to learn (i.e., whether the child has produced gesture-speech mismatches)?

Development of Number Word Knowledge

Beginning around two years of age, children learn to recite a portion of the count list, but without comprehending the meanings of these words (e.g., Carey, 2009; Wynn, 1990). Next, children slowly, and sequentially, learn the meanings of each of the first few number words – one, two, three, and four (e.g., Sarnecka & Lee, 2009; Wynn, 1990, 1992). Importantly, children spend several months as "one-knowers" before learning what "two" means, several more months as "two-knowers" before learning what "three" means, and so on, for "three" and "four". In total, 1 to 2 years pass between when children learn a partial count list (e.g. 1-10) and when they finally understand the meanings of number words beyond "three" or "four" that are within their count list, as demonstrated by knowledge of the cardinal principle (Le Corre & Carey, 2007; Sarnecka & Lee, 2009; Wynn, 1990, 1992).

There are many characteristics of number words that may explain why they are particularly challenging for young children to learn. First, numbers, unlike many nouns, which are learned quite easily by young children, do not describe a property of any single object but rather a property of a set of objects (Bloom, 2002; Bloom & Wynn, 1997). For example, in the phrase 'three ducks', 'three' refers to a feature of the set of ducks and does not apply to any individual duck. An extensive literature suggests that relational vocabulary of this sort, which requires children to focus on the relations between objects rather than on the objects themselves, is particularly difficult for young children to acquire (Gentner, 1982; Gentner & Borodistky, 2001; Gleitman, Cassidy, Nappa, Papafragou, & Trueswell, 2005).

Additionally, children must learn not only that numbers describe quantities in general, but also which particular quantity maps onto which particular number. Unlike other quantifiers, like "some," which can refer to a range of sets, "three" refers to exactly three items and children must learn to distinguish three from nearby quantities, such as two and four (Barner & Bachrach, 2010). A deeper look into the early stages of number development suggests that this knowledge comes piecemeal, with children first learning that "two" does not describe one object and only later learning that "two" does not describe three objects (Barner & Bachrach, 2010; Barner, 2012).

How children overcome these challenges and ultimately learn the meanings of number words remains an open question. At the same time that children are learning the meanings of number words, they commonly learn how to gesture about numbers (e.g., hold up three fingers to indicate "three"), and there is evidence that labeling sets with number gestures may be easier for children than labeling the same sets with number words (Gunderson, Spaepen, Gibson, Goldin-Meadow & Levine, 2015). Accordingly, a growing body of research is focused on how such number gestures may be related to children's acquisition of symbolic number language (for reviews, see Di Luca &Pesenti, 2011; Goldin-Meadow, Levine & Jacobs, 2014).

Development of Number Gestures

Gestures are common among both children and their parents when counting and communicating about numbers (Goldin-Meadow et al., 2014; Fuson, 1988; Suriyakham, 2007), and it is widely believed that gestures play a role in the development of verbal number knowledge and counting skills (e.g. Butterworth, 1999, 2005; Gelman & Gallistel, 1978; Gracia-Bafully & Noël, 2008; Fuson et al., 1982; Fuson, 1988). However, little is known about what exactly this role is, and whether certain types of gestures matter whereas others do not.

As reviewed above, research on children's use of number gestures has largely focused on gestures that are used while counting (i.e., raising one finger at a time or pointing to individual items in a set while counting) (Alibali & DiRusso, 1999; Di Luca & Pesenti, 2008; Fuson, 1988; Gelman & Gallistel, 1978; Graham, 1999; Potter & Levy, 1968; Saxe, 1977; Saxe & Kaplan, 1981). Children begin pointing while counting as early as two years of age (Gelman & Gallistel, 1978). Pointing to individual items while counting a set aids children's implementation of the counting principles, for instance, by helping them pair each object with a single number word and by helping them keep track of the objects they have already counted (Alibali & DiRusso, 1999). In this way, counting gestures can be related to children's understanding of one-to-one correspondence, a key feature of the counting routine and symbolic number.

Less is known about how the use of cardinal number gestures (i.e., holding up a certain number of fingers to indicate the number of items in a set) relates to children's acquisition of number language. Such gestures are used by both children and their parents, albeit less frequently than counting gestures (Goldin-Meadow et al., 2014; Suriyakham et al., 2007). They are also prevalent across cultures (Bender & Beller, 2012). In certain populations that lack a formal number system, such as deaf homesigners (individuals whose hearing losses prevent them from using the spoken language that surrounds them, and who have no access to sign language, Goldin-Meadow, 2003a), number gestures are used as a substitute (albeit an imperfect one) for precise number labels (Spaepen, Coppola, Spelke, Carey, & Goldin-Meadow, 2011; Coppola, Spaepen, & Goldin-Meadow, 2013; Spaepen, Coppola, Flaherty, Spelke, & Goldin-Meadow, 2013).

Like number words, number gestures can be used to convey the number of items in a set (at least up to ten). Yet, unlike number words, which are arbitrarily related to the number of items they represent, the form of a number gesture (i.e., the number of fingers that are held up) is directly related to the number of items in the set. This transparency could make number gestures easier to learn than number words. If so, number gestures have the potential to serve as a bridge towards the acquisition of symbolic number language (Gunderson et al., 2015).

Currently, there is no empirical evidence that cardinal number gestures play a role in children's acquisition of number words. In fact, previous research has dismissed the role that cardinal number gestures can play in the acquisition of verbal number words on the grounds that children as young as four are more accurate when labeling sets using number words than number gestures (Nicoladis, Pika & Marentette, 2010). However, this study did not distinguish between children who had already mastered the ability to label sets using number words and those who were still in the process of learning the meanings of number words.

However, as detailed in Chapter 1, more recent research has found that children who know the meanings of only a subset of the number words (subset-knowers) are more accurate when labeling unknown numbers up to 3 in gesture than in speech (Gunderson et al., 2015). In other words, the ability to label sets using gestures may precede the ability to label the same sets using number words. The advantage of gesture labels over verbal labels was observed not only when children's explicitly elicited verbal labels were compared to their gestural labels, but also when children's mismatching gestures were compared to the words they accompanied.

Such gesture-speech mismatches—utterances in which speakers convey different information in speech than in the gesture that accompanies that speech (Goldin-Meadow, 2003b)—are particularly interesting given evidence that gesture-speech mismatches predict imminent change in language (Iverson & Goldin-Meadow, 2005) and cognition (Church & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988). For example, 5- to 8-year-old children whose gestures and speech mismatch when explaining their responses to a classic conservation task (e.g., their gestures indicate the container's width while they are speaking about its height) are more likely to benefit from instruction on the task than children whose gestures match their speech (Church & Goldin-Meadow, 1986). Gesture-speech mismatch has also been found to predict readiness to learn on math tasks (e.g., problems such as 5 + 4 + 3 = ___ +3) in 9- to 10- year-olds (Perry et al., 1988). Even 10- to 24-month-olds use gesture-speech combinations in which gesture conveys different information from the accompanying speech (e.g., pointing to a cup while saying "daddy" to indicate "daddy's cup") when they are on the cusp of learning to use two-word utterances (e.g., "daddy's cup") (Iverson & Goldin-Meadow, 2005).

Gesture-speech mismatching thus appears to be a reliable marker of readiness-to-learn in a variety of concepts and in learners of all ages (including adults, see Ping et al., under review). Since young children who are in the process of learning number words frequently use number gestures, we hypothesized that, in line with previous studies of gesture-speech mismatch, children who produce such mismatches when labeling the numerosity of sets will be more likely to profit from number-word instruction than children who produce gestures that match their speech or who do not gesture while speaking.

Given that children are able to label sets accurately in gesture before they are able to label the sets accurately in words, their number gestures *per se* may also indicate a readiness to learn a new number word. However, since the advantages of gesture over speech in conveying numerical information are evident only for numbers up to 3 (Gunderson et al., 2015), number gesturing may be more likely to predict small number learning than large number learning or acquisition of the cardinal principle. Given this finding, we focus on "one-knowers" and "two-knowers" in the current study, asking whether their gesture-speech mismatches index their ability to learn the meaning of the next numbers in their count list ("two" and "three" for one-knowers, and "three" and "four" for two-knowers).

Variation in Number Input

Although individual differences in children's use of number gestures may help explain who is likely to benefit from number input, we cannot ignore the fact that children receive vastly different amounts of number input (Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006; Levine, Suriyakham, Rowe, Huttenlocher, & Gunderson, 2010). Importantly, these differences in number input predict children's number knowledge (Klibanoff et al., 2006; Levine et al., 2010). Children's developing number knowledge has been linked to the sheer quantity of number words parents use with their children (Levine et al., 2010), whether parent number talk involves a range of number words or is limited to just the first few numbers (Gunderson & Levine, 2011), whether parents use numbers to label sets of present objects (e.g., three cows in a picture, Gunderson & Levine, 2011), and how parents use grammatical devices to mark number (Almoammer et al., 2013; Barner et al., 2009; Li et al., 2003; Sarnecka et al., 2007). Together, these findings suggest that children's rate of number concept acquisition is related to the quantity and quality of parental input.

Given the wealth of data on the role of input in children's numerical development in naturalistic studies, experimental intervention studies designed to accelerate children's learning of number words or the cardinal principle often have a surprisingly limited impact. This unexpected finding may reflect the difficulty of providing enough input to make a difference, the fact that the input may not be optimal, or the fact that many children are simply not ready to learn the next number word. Previous intervention studies have often led to improved performance on tasks that closely resemble instruction rather than significant changes in children's knower-level, as determined by the Give-N task. (Huang, Snedeker & Spelke, 2010; Ramscar, Dye, Popick & O'Donnell-McCarthy, 2011). Moreover, children's gains on these tasks are often modest. For instance, children often fail to extend newly learned numbers to new contexts (e.g., sets made up of untrained objects) or they overextend numbers to neighboring quantities (e.g., mistaking sets of 5 for sets of 4) (Huang, Snedeker & Spelke, 2010).

Despite the mixed effectiveness of experimental studies in moving children along their number learning trajectories, some studies have found gains on the Give-N task after experimentally manipulated instruction. For example, Mix and colleagues (2012) found greater improvement in number knowledge as measured by the Give-N task after children received training involving both counting and cardinal labeling, compared to training on counting alone. However, the children in the study had already mastered the small numbers and thus showed posttest improvement only on the larger numbers (6 and 10). It is not yet clear whether instruction that combines counting and cardinal labeling (as opposed to counting alone) is needed to teach children the meanings of the first few number words. The present study was designed to understand how children learn the meanings of the small number words (i.e., "one," "two," and "three").

One characteristic of number instruction that has been relatively unexplored, and may be particularly useful for learning the meaning of the first few number words, is the degree to which key similarities and differences between sets are explicitly aligned. Previous research has found that aligning multiple concrete examples to highlight similarities and differences between the examples can help children learn a variety of concepts (Gentner & Namy, 2004; Gentner & Gunn, 2001). Comparing and contrasting aligned examples seems to be particularly helpful in tasks that require looking past the characteristics of individual objects and focusing on the relations between objects (Christie & Gentner, 2010), as is the case for number.

To understand how the quality of number input affects children's number learning, the present study compared two different types of number instruction: one that resembles a particularly common form of input (i.e., counting alone; Mix et al., 2012), and one that incorporates counting, cardinal labeling, and aligned comparison and contrast techniques.

The Present Study

The present study aimed to answer three questions: (1) What effect does the quality of number instruction—either sparse counting-only input or enriched number input involving cardinal labeling and clear alignment—have on children's learning of small number words? (2) What impact does a key individual characteristic of the learner—producing gesture-speech mismatches when communicating about number—have on their learning from number instruction? (3) How do these two factors interact?

To test these questions, we gave 47 one- and two-knowers a pretest, four training sessions, and a posttest. We focused on one- and two-knowers because we were particularly interested in teaching children the cardinal meanings of the small number words (rather than the cardinal principle itself), and these children have at least one number word to learn before being ready to learn the cardinal principle.

During the pretest, children were asked to label the number of items in a set; we used the labels they produced in gesture-speech combinations to determine whether the child produced gesture-speech mismatches (one number in speech and a different number in gesture). We also measured children's rote counting ability and used it as an index of their rote verbal numerical skills. Most studies of early number development report that children learn to recite the count list, albeit as a meaningless series, prior to learning that “one” refers to one thing or “two” refers to two things (Sarnecka & Carey, 2008; Sarnecka & Lee, 2009; Wynn, 1990, 1992). Moreover, there is some evidence that more proficient counters acquire the meanings of even small number words like “two” at an earlier age than less proficient counters (Almoammer et al., 2013).

Following the pretest, children were randomly assigned to one of two training conditions. The first training condition provided children with basic number input, involving counting sets of objects while the experimenter pointed to each object, and was designed to mimic common unstructured number input (Counting Condition). The second training condition provided richer number input by contrasting sets of different sizes (to demonstrate that numbers refer to exact quantities), presenting different instances of the same set size (to demonstrate that numbers are generalizable to sets of any item), as well as counting objects while the experimenter pointed to each object and labeled the set size (Enriched Number Talk Condition).

Pursuing questions about characteristics of the learner alongside questions about input has several advantages. Given the mixed success of previous experimental number training studies, our approach allows us to explore why some children learn and some children do not, even from well-designed, research-supported instruction. Moreover, in some domains (e.g., conservation tasks, Church & Goldin-Meadow, 1986), gesture-speech mismatch predicts subsequent learning after a relatively sparse intervention involving manipulating the objects; however, in other domains (e.g., the balance scale, Pine, Lufkin & Messer, 2004), gesture-speech mismatch predicts subsequent learning only after rich instruction, suggesting that quality of instruction may interact with the child’s readiness to learn. Finally, children who mismatch when labeling set sizes are particularly interesting because they often skillfully align their gestures with the number of items in a set while, at the same time, failing to align their spoken number labels with their number gestures and thus with the number of items in the set (Gunderson et al., 2015). Accordingly, the Enriched Number Talk condition, which clearly aligns sets of the same and different sizes with their corresponding labels, may address some of the unique learning needs of mismatchers.

2.2. Method

Participants

Forty-seven children (25 female) participated in the study. The mean age was 4.15 years (SD=0.58, range=3.01 to 5.28 years). Participants were recruited through urban public and private preschools and were tested if their parents completed and returned a consent form that was sent home with information about the study. An earlier report described the spoken and gestured number labels used by these participants in the pretest of the current study (Gunderson et al., 2015). Here we extend these findings by exploring whether individual differences in children's simultaneous use of spoken and gestured number labels observed at pretest predict which children are likely to benefit from number instruction.

Participants were selected for the current study from a larger sample of preschool students who participated in a number battery, previously reported by Gunderson and colleagues (2015); 275 children completed the consent process, and only those who were one-knowers or two-knowers were included in this study (n=59). Pre-knowers (who had not yet begun learning the meanings of number words) were dropped from the study completely and did not receive training or a posttest. Three-, four-, and CP-knowers were entered into a separate experiment and given a different type of training, which was designed to train children on the successor function (Gunderson et al., under review).

Of the 59 one- and two-knowers who were thus eligible for the present study, children were excluded if they dropped out before completing the training or posttest (N=6) or if they were unable to complete our study (e.g., due to a developmental delay, lack of understanding of English, or refusal to speak) (N=6).

Procedure: Pretest and Posttest

Our experiment consisted of six one-on-one sessions administered during a roughly three-week span (M=20.21 days SD=6.29 days): one pretest, four training sessions, and one posttest. The primary measures taken at pretest and posttest were Give-a-Number, What's on this Card-Gesture (WOC-Gesture), What's on this Card-Speech (WOC-Speech), and Highest Count. The Highest Count task was presented first, followed by the Give-a-Number task. Next, children were given the WOC-Gesture and WOC-Speech Task in that order to encourage children to simultaneously gesture and speak when responding in the WOC-Speech Task. In addition, several other number tasks were administered as part of a larger study of numerical development, but not included in the present study (see Gunderson et al., 2015; Gunderson, Spaepen & Levine, 2015). The pretest and posttest were identical in the two training conditions.

Highest Count. Children were asked to count as high as they could. Their highest count was considered the last number they reached when counting, allowing for one mistake.

Give-a-Number. The Give-a-Number task was used to determine each child's knower level, which specifies the highest number word for which children understand the cardinal value (Wynn, 1990). Children were presented with 15 plastic fish and asked to place a certain number of fish into a clear plastic bowl (called "the pond"). If a child gave the wrong number of fish, the experimenter gave the child an opportunity to correct the mistake by saying, "But I asked for N fish! Let's check. [Experimenter and child count fish.] Can you put N fish in the pond?"

Children's final answers were recorded. The experimenter always began by asking the child to place one fish in the pond. The experimenter then proceeded to increase the number requested by one fish every time the child answered correctly and decreased the number requested by one fish every time the child answered incorrectly, following the procedure in Wynn (1990). Children were considered N knowers when N was the highest number for which they responded correctly on two out of three requests for N fish, and gave the experimenter N fish less than half as often when asked for more than N fish than when asked for N fish. If children succeeded on all numbers up to 6, they were considered cardinal principle knowers. If they failed to meet the one-knower criteria, they were considered pre-knowers. Children who were one- or two-knowers on *Give-a-Number* were included in the present study.

What's on this Card-Gesture. The WOC-Gesture task consisted of a gesture familiarization phase, a practice block, and three test blocks. In the gesture familiarization phase, children were asked to copy an experimenter's gestures. This procedure was followed to ensure that each child was able to produce a numerically correct gesture for each of the numbers (1, 2, 3, 4, 5, and 10) presented in the practice and test blocks. If a child failed to correctly produce one of these gestures, the experimenter helped the child until he/she could produce a gesture for that number on his/her own.

Next, the child was given one block of six practice trials. The experimenter presented cards displaying sets of 1, 2, 3, 4, 5, and 10 frogs. The cards were displayed one at a time and in order. On each trial, the experimenter demonstrated the correct gesture and then asked the child to copy the gesture saying, "For this, I would do this [holds up index finger]. Can you do that?" The experimenter corrected the child if necessary and repeated the procedure for each of the six trials.

Following the practice block, children were given three test blocks. Again, each block consisted of six trials (set sizes 1, 2, 3, 4, 5, and 10) and each block displayed sets of a different type of object (birds, flowers, or boats). On the first test trial, the experimenter displayed the first card (5 birds) and said, “Now it’s your turn. What would you do for this card?” If the child did not respond, the experimenter asked, “Can you use your fingers to show me what’s on this card?” or referred to the first practice card (1 frog) and said, “Remember for this I would do this [*holds up 1 finger*]. What would you do for this card?” The number of fingers the child held up was recorded along with any verbal number labels that the child used. This procedure was repeated for each of the 18 test trials (3 blocks of 6 trials).

What’s on this Card-Speech. Similar to WOC-Gesture, WOC-Speech consisted of 3 blocks of 6 trials depicting sets of different sizes (1, 2, 3, 4, 6, and 9). In the first trial, the experimenter showed a picture of one soccer ball and asked, “What’s on this card?” Children’s responses, which were typically “ball” or “a ball” and, less commonly, “one ball”, were not recorded. Regardless of the response, the experimenter said, “That’s right, it’s ONE ball.” On each of the remaining 17 trials, the experimenter asked, “What’s on this card?” If the child failed to give a verbal response, the experimenter asked, “Can you use your words to tell me what’s on here?” If the child counted but did not provide a cardinal label, the experimenter asked, “So, what’s on this card?” If a child still did not provide a cardinal number label, the experimenter asked, “What else can you tell me?” “Can you take a guess?” or referred to the first trial and said, “Remember, this was ONE ball. So what’s on this card?” Children’s cardinal number responses and any number gestures were recorded.

Procedure: Training

Children were randomly assigned to the Counting Condition or Enriched Number Talk Condition (see Figure 4 for example stimuli). Children in both conditions were trained on their lowest unknown number and the next number since there is some evidence that children must learn about the next number in order to learn the meaning of the number preceding it (Barner; 2012; Barner & Bachrach, 2010). In other words, one-knowers were trained on the meanings of “two” and “three,” and two-knowers were trained on the meanings of “three” and “four”.

Figure 4. Example stimuli used in Enriched Number Talk (left panel) and Counting Training conditions (right panel).

Counting Training. In the Counting condition, children were given practice counting to the two target numbers (two and three for one-knowers; three and four for two-knowers). They were asked to help a puppet get ready for school by counting to each number four times. They counted a set of dots on a card and then counted a set of beads three times (count beads on the table, count beads while putting them onto a stick, count beads after they are on the stick). The experimenter aided the child by pointing to each item as it was counted. No cardinal labels were used during the Counting training.

Enriched Number Talk Training. In the Enriched Number Talk condition, training was matched to the Counting condition in terms of the number of instances of counting and the number of objects the children counted. However, training in this condition was designed to provide richer number input than the Counting condition by emphasizing the cardinal value of each set, and by comparing the target sets to nearby sets. Children were told that one puppet "really liked" the first target number ("two" for one-knowers, "three" for two-knowers). The experimenter and child then compared sets of beads that made the puppet happy (i.e., the target number) and sets that did not make the puppet happy (one less than the target number). As in the Counting condition, the experimenter aided the child by pointing to each item as it was counted. The experimenter repeated this procedure with a new puppet that liked the next target number (three for one-knowers; four for two-knowers). The experimenter also drew attention to the relation between the two target numbers (e.g., that four is one more than three).

2.3. Results

The goals of the following analyses were to determine whether children benefit differentially from two types of number training—Counting Training and Enriched Number Talk training—and to determine whether the presence of gesture-speech mismatches in children's number labels could help explain who would benefit from each type of training.

Children were categorized as 'learners' if they improved in their knower level as measured by the Give-N task from pretest to posttest. At pretest, 11 participants were categorized as one-knowers (*Mean Age*= 3.93; *SD*=.41) and 36 participants were categorized as two-knowers

(*Mean Age*= 4.21; *SD*=.62). By posttest, 4 participants (36.36%) who were originally one-knowers improved at least one knower-level, and 12 participants (33.33%) who were originally two-knowers improved by at least one knower level. Table 1 displays the distribution of knower levels at pretest and posttest.

Table 1. Distribution of knower levels across pretest and posttest

Pretest Knower Level	**Posttest Knower Level** Pre-	One-	Two-	Three-	Four-	CP-
One-	1	6	3	1	0	0
Two-	0	2	22	6	5	1

Mismatching was determined on the basis of children's responses that contained speech and gesture on the WOC-Speech and WOC-Gesture tasks; if the number conveyed in gesture was different from the number conveyed in speech, the response was considered a mismatch. Children were categorized as 'mismatchers' if they produced at least one mismatch on either of the next two numbers above their knower-level (i.e., on 2 or 3 for one-knowers, and on 3 or 4 for two-knowers). Participants received three trials of each of the two quantities immediately above their knower level in both the WOC-Speech and WOC-Gesture tasks, resulting in twelve opportunities to mismatch, six per task.

Overall, 23 (out of 47) participants (48.94%) mismatched on at least one trial when labeling either of the two numbers immediately above their knower level and were therefore considered 'mismatchers'. Of the 22 participants randomly assigned to the Enriched Number Talk condition, 11 (50%) were mismatchers. Of the 25 participants randomly assigned to the Counting condition, 12 (48%) were mismatchers.

Participants who were categorized as mismatchers mismatched on an average of 3.30 trials (*SD*=2.12). Mismatching on the number immediately above one's knower level (n+1) was associated with mismatching on the next number (n+2), $\chi^2(1,47)=16.90$, $p<.001$.

Since previous research has found that mismatching is an important indicator of future learning regardless of whether the gesture is more accurate than speech (Church & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988), we considered a child to be a mismatcher even if the child's speech was correct and his gesture was incorrect. Twenty of the 23 participants who mismatched at least once were correct in the gesture they produced and incorrect in their speech on at least one trial. It was much less common for participants to be correct in speech and incorrect in gesture. Figure 5 displays children's speech and gesture accuracy in mismatches produced on the WOC-Gesture and WOC-Speech tasks, combined.

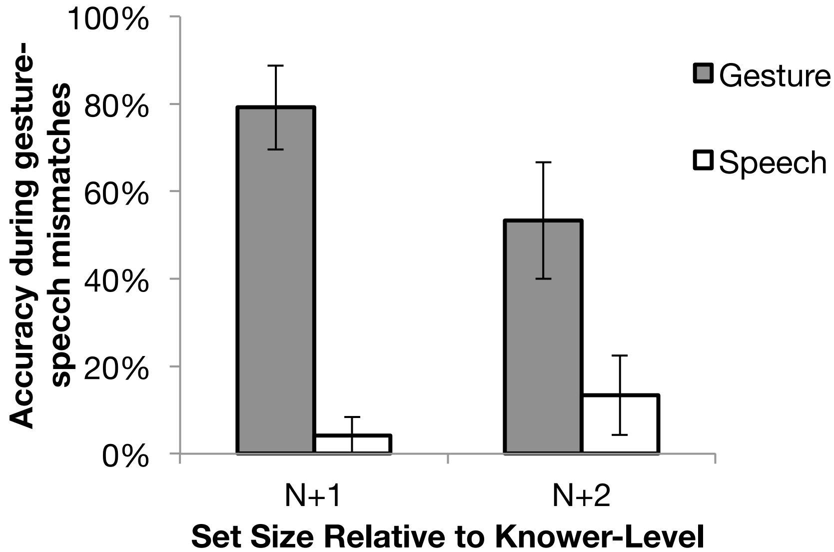


Figure 5. Accuracy of gesture and speech during mismatches.

We also measured counting ability as another factor that could influence whether a child improves in knower-level. Participants' highest count (allowing for one error) ranged from 4 to 39 (*Mean*=13.89; *SD*=5.94). We examined whether there were differences in participants' highest count between those in the Enriched Number Talk condition and those in the Counting condition, as well as between those who mismatched at pretest and those who did not mismatch. Participants in the Enriched Number Talk condition counted to between 4 and 25 (*Mean* = 13.32, *SD* = 4.80) and participants in the Counting condition counted to between 8 and 39 (*Mean* = 14.40, *SD* = 6.84). Participants who mismatched counted to between 4 and 30 (*Mean* = 13.22, *SD* = 5.17) and participants who did not mismatch counted to between 8 and 39 (*Mean* = 14.54, *SD*=6.63). A two-way Condition x Mismatching Status ANOVA revealed no significant differences in children's highest count based on Condition ($F(1,43) = .370$, p=.546) or Mismatching Status ($F(1,43) = .601$, $p = .442$), and no significant interaction of Condition and Mismatching Status ($F(1,43) = .375$, p =. 544).

Participants' age also did not significantly differ by Condition ($F(1,42)$=.825, p=.369), Mismatching Status ($F(1,42)$=1.364, p=.249), the interaction of Condition and Mismatching Status ($F(1,42)$=.116, p=.735), or Highest Count ($F(1,42)$=.287, p=.595). Participants in the Counting condition who mismatched were between 3.20 and 5.22 years old (*Mean*=4.15, *SD*=.55); participants in the Counting condition who did not mismatch were between 3.20 and 5.28 years old (*Mean*=4.30, *SD*=.65); participants in the Enriched Number Talk condition who mismatched were between 3.01 and 4.83 years old (*Mean*=3.92; *SD*=.59); participants in the Enriched Number Talk condition who did not mismatch were between 3.36 and 5.07 years old (*Mean*=4.20, *SD*=.56).

We next asked whether the two training conditions had different effects on learners and whether the child's status as a mismatcher affected the child's ability to profit from instruction. Figure 6 presents the data.

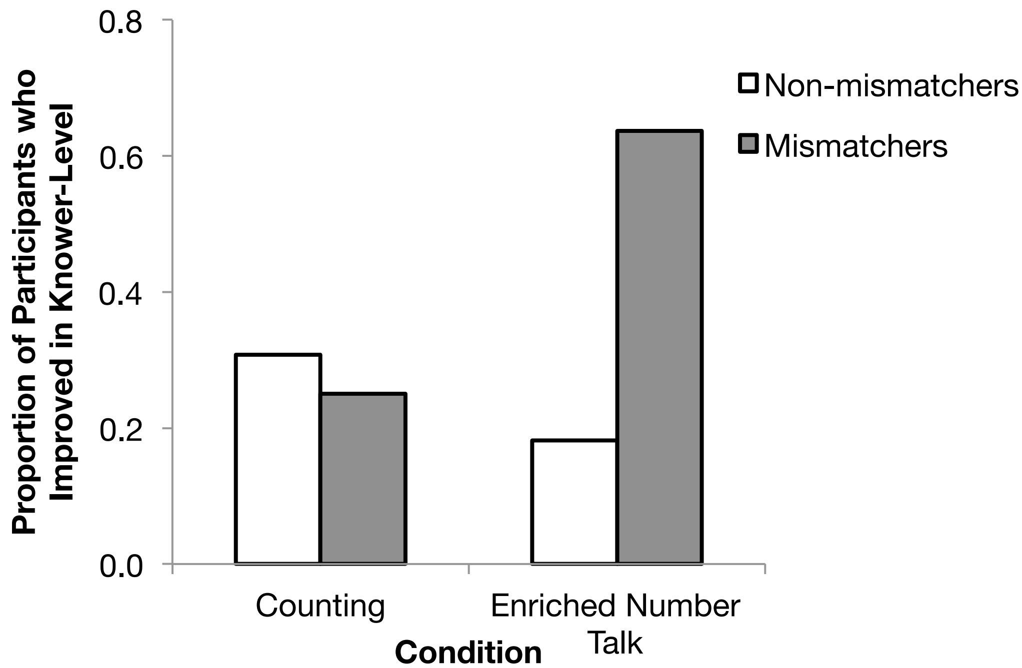


Figure 6. Proportion of children who improved in knower level by Condition and Mismatching Status.

We conducted a logistic regression to predict whether a child improved in knower-level from pretest to posttest based on Condition (Counting, Enriched Number Talk), Mismatching Status (Mismatcher, Non-mismatcher), Highest Count (as a continuous variable), Pretest Knower-Level (One-Knower, Two-Knower), and Condition x Mismatching Status interaction (see Table 2). There was no main effect of Condition (b=-.819, p=.455) or Mismatching Status (b=-.404, p=.693), but there was a significant Condition by Mismatching Status interaction (b=2.988, p=.050), as well as a main effect of Highest Count (the higher a child could count at pretest, the more likely the child was to profit from number instruction; b=.148, p=.039). To determine if ability to count at pretest interacted with Condition, we ran a second logistic regression replacing the Condition x Mismatching Status term with a Condition x Highest Count term. This analysis did not reveal a significant interaction between Condition and Highest Count (b=-.158, p=.303).

Table 2. Logistic regression model predicting whether or not participants improved in Knower-Level based on Condition, Mismatching Status, Highest Count, and Pretest Knower-Level.

Predictors	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**
Condition	-0.819	1.097	0.557	1	0.455	0.441
Mismatcher	-0.404	1.023	0.156	1	0.693	0.668
Condition * Mismatcher	2.988	1.521	3.858	1	0.0495	19.839
Highest Count	0.148	0.072	4.275	1	0.039	1.16
Pretest Knower Level	-0.184	0.866	0.045	1	0.832	0.832
Constant	-2.635	1.839	2.053	1	0.152	0.072

To further understand the interaction between Mismatching Status and Condition, we analyzed participants in each condition separately. Within participants in the Enriched Number Talk condition, there was a significant effect of Mismatching Status, controlling for Highest Count, (b=2.65; p<.021, see Table 3)—among participants in this condition, the odds of improving in knower-level for mismatchers was 14.09 times greater than the odds of improving for participants who did not mismatch. In contrast, there was no effect of Mismatching Status in the Counting condition (b=-0.73, p=0.38).

Table 3. Separate logistic regression models for the Counting and Enriched Number Talk conditions predicting whether or not participants improved in Knower-Level based on Mismatching Status, Highest Count, and Pretest Knower-Level.

Predictors	β	S.E.	Wald	df	Sig.	e^{β}
Counting Condition						
Mismatcher	-0.729	1.141	0.408	1	0.523	0.483
Highest Count	0.214	0.134	2.546	1	0.111	1.238
Pretest Knower Level	-0.926	1.125	0.678	1	0.410	0.396
Constant	-2.206	2.509	0.774	1	0.379	0.110
Enriched Number Talk Condition						
Mismatcher	2.645	1.150	5.293	1	0.021	14.088
Highest Count	0.033	0.123	0.074	1	0.785	1.034
Pretest Knower Level	1.609	1.612	0.996	1	0.318	4.995
Constant	-5.216	3.097	2.837	1	0.092	0.005

We also analyzed participants who mismatched and those who did not mismatch separately. Within the mismatchers, there was a significant effect of Condition, controlling for

Highest Count, (*b*=2.09; *p*=.047, see Table 4)—among mismatchers, the odds of improving in the Enriched Number Talk condition were 8.06 times the odds of improving in the Counting condition. In contrast, there was no effect of Condition amongst non-mismatchers (*b*=-0.65, p=0.59).

Table 4. Separate logistic regression models for Non-Mismatchers and Mismatchers predicting whether or not participants improved Knower-Level based on Condition, Highest Count, and Pretest Knower-Level.

Predictors	β	S.E.	Wald	df	Sig.	e^{β}
Non-Mismatchers						
Condition	-0.647	1.194	0.294	1	0.588	0.523
Highest Count	0.170	0.108	2.503	1	0.114	1.186
Pretest Knower Level	-1.140	1.549	0.542	1	0.461	0.320
Constant	-1.268	2.668	0.226	1	0.635	0.281
Mismatchers						
Condition	2.087	1.049	3.960	1	0.047	8.064
Highest Count	0.143	0.100	2.042	1	0.153	1.154
Pretest Knower Level	0.195	1.011	0.037	1	0.847	1.215
Constant	-3.541	2.311	2.348	1	0.125	0.029

2.4. Discussion

Our study provides the first empirical evidence that children who produce gesture-speech mismatches when labeling sets are more likely to learn new number words than children who do not produce mismatches if they are provided with rich number instruction. Although children gesture about numbers even before understanding the verbal labels for those numbers (Gunderson et al., 2015), children's cardinal number gestures have never before been shown to have relevance for their readiness to learn new number words. Our findings also extend prior research demonstrating the power of gesture-speech mismatch to predict learning (Church & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988; Pine et al., 2004) to the domain of early number development. The connection between gesture-speech mismatch and learning is particularly noteworthy in the case of number since gesturing about number is common among children and their parents (Suriyakham, 2007).

Turning to our question of whether children who received rich number instruction would be more likely to learn the next number words in their count list, we found that this was partially the case. Within the group of children who mismatched at pretest, children who received the Enriched Number instruction were significantly more likely to improve on the Give-N posttest than children who received the Counting instruction. Our findings thus extend previous work showing that cardinal and counting instruction can promote learning small number words, just as they promote learning larger number words and learning the cardinal principle (Mix et al., 2012). Moreover, we found our effects using a widely used measure of children's comprehension of number words—knower-level improvement—after a relatively brief intervention period—roughly three weeks.

Finally, we found a significant interaction between number instruction and child mismatching status: Mismatchers learned more from enriched instruction than did any of the other groups (they learned more than mismatchers in the Counting condition, and more than non-mismatchers in either condition). This interaction both complicates and provides insight into the possible mechanisms underlying our findings.

One possibility is that the Enriched Number Talk instruction addressed the unique learning needs of the mismatching children. Our Enriched Number instruction leveraged comparison and contrast and highlighted the alignment between the last number in the count list and the number of objects represented by that word. This focus on alignment may have been a particularly useful corrective to mismatching children, who spontaneously align their gestures with the number of objects in a set, but misalign their number words with both their number gestures and the number of objects in a set. Of course, Enriched Number Talk instruction is likely to be informative for all children learning their number words—cardinal labeling combined with counting is a key feature of quality number input at any stage of early number development, and aligned comparison and contrast has been shown to improve children's understanding of a variety of concepts, not just number (Christie& Gentner, 2010; Gentner & Namy, 2004; Gentner & Gunn, 2001). But, in our study, only those children who mismatched prior to instruction seemed to be ready to take advantage of the richness in the instruction and move onto the next knower-level. It is possible that extending our experiment to provide more instruction to all groups might reveal a condition difference even in children who did not mismatch at pretest (intensive enriched instruction could plunge them into a mismatching state, which would eventually make the children more susceptible to instruction, cf. Alibali & Goldin-Meadow, 1993), or could lead to improvements in number knowledge even without leading to mismatching.

Note that this account leaves open the question of why children who mismatched were more ready to move to the next knower-level (and thus required less input) than children who did not mismatch. Mismatchers may have greater latent knowledge of the numbers immediately above their knower-level than children who did not mismatch. When children's gestures and speech mismatched, their number gestures were more likely than their number words to be correct with respect to the target set size, suggesting that these children may know more about the numbers above their knower-level than their non-mismatching counterparts. Note, however, that mismatching children in the Counting condition were not likely to move onto the next knower-level, making it clear that even mismatchers require quality instruction to transform whatever partial knowledge they have into full comprehension.

Another important factor in predicting whether children were likely to improve from pretest to posttest was children's highest count at pretest. Previous research has suggested that the ability to count is an important prerequisite to understanding large, exact numbers (Gordon, 2004; Frank, Everett, Fedorenko, Gibson, 2008; Pica, Lemer, Izard & Dehaene, 2004; Spaepen et al., 2011). Moreover, a study on the number development of Slovenian children showed that understanding the meaning of "three" was associated with counting ability (Almoammer et al., 2013). However, our study is the first to show that children's highest count predicts their subsequent ability to learn the meaning of a new number word.

What drives the relation between the ability to count and the ability to learn number words is an open question. Since there was no interaction between highest count and type of instruction, it is difficult to determine whether counting higher is associated with an increased readiness to benefit from instruction, or whether higher counters were closer to the next knower-level stage than lower counters to begin with. It is possible that children's highest count is serving as an index of their familiarity with number words, or as an index of how much number input they received outside of the study. However, it is also possible that counting ability is playing a more direct causal role in children's acquisition of number meanings, although this mechanism would be surprising given that children in our study were still in the process of learning numbers within the subitizable range (numbers that do not require counting). Given other research demonstrating a relation between rote counting fluency and conceptual knowledge about the count list (e.g., the successor function, Davidson, Eng & Barner, 2012), the relation between individual differences in rote counting and the rate at which children learn the meanings of number words is worthy of further exploration.

How mismatching children are conceptualizing the next numbers in their count sequence is also an interesting question for future research. Although our study does not provide causal evidence for the role of number gestures in learning number words, our results do lead to the hypothesis that learning to gesture about numbers may affect the acquisition of verbal number labels. We speculated previously (Gunderson et al., 2015) that number gestures may be unique in supporting early number language acquisition as they possess some of the symbolic properties of number words, but retain one-to-one correspondences between the number of items in a set and the number of fingers in a gesture. To better understand the causal role that number gestures play in fostering verbal number knowledge, future research will need to encourage children to increase their overall use of number gestures during instruction, or instruct children in how to form number gestures, and then examine the extent to which these manipulations affect children's acquisition of number words.

Regardless of whether gestures play a causal role in number learning, having the ability to predict when a child is likely to move up in knower-level could enable educators to provide children with targeted numerical input. Given the limited timeline of this study, we do not know whether children who did not mismatch would also have improved in the Enriched Number Talk condition if we had continued providing training sessions even if they never mismatched, or whether these children would have benefited more from another type of training (e.g., training in number gestures that could then make them receptive to the enriched training). Nevertheless, having a more nuanced understanding of the individual differences between children within a knower-level will not only give researchers a way to explore the relative benefits of various types of instruction for children at particular stages of development, but also give practitioners a way to assess a child's readiness to profit from instruction.

In sum, our results not only support previous research demonstrating that quality number input matters in improving children's understanding of number words, but they also provide the first evidence of a connection between children's use of number gestures and their developing understanding of number words. Although we do not know how mismatching children are conceptualizing the numbers above their knower level, nor do we know how they are processing the number instruction they receive, our findings suggest that there are clear divisions among children at the same knower-level—divisions that can be detected and measured, and that have implications for subsequent growth and instruction. To better understand the role that number gestures play during the acquisition of number words, the following chapter will explore the relation between number gestures and number words.

3. CHAPTER THREE Study 2: Mapping Number Words to Number Gestures

3.1. Background

As discussed in Chapter 1, numbers take several forms. Numbers can take the form of nonsymbolic quantities (e.g. a collection of items), conventional symbols (e.g. “three” or “3”; Dehaene, 1992), and also number gestures (e.g. holding up three fingers to indicate three). Much of number development is learning to associate these various forms; for instance, learning that “three” refers to collections of exactly three items.

Thus far, there is evidence that children match number gestures to corresponding quantities (e.g. labeling two objects with two fingers) prior to matching number words to those same quantities (e.g. labeling two objects with the word “two”) (Gunderson et al., 2015). Moreover, the results of Study 1 suggest that these early uses of number gestures in tandem with number words have some relevance to the acquisition of number words. However, while these findings are encouraging of a possible link between number gestures and the acquisition of number words, they do not provide us with much insight into what this role might be.

One possibility is that number gestures serve as a bridge between nonsymbolic perceptual representations of quantity and purely symbolic systems of number (e.g. number words). In this account, children may first learn to associate particular gestures with the corresponding set sizes and then come to associate those gestures with the corresponding number words. The intermediary step of gesture, an item-based but conventional representation of number, could, therefore, serve as a bridge between nonsymbolic and symbolic number.

As discussed in the introduction, this pattern bears a striking resemblance to historical accounts of the cultural evolution of symbolic number (Ifrah, 2000; Menninger, 1969). Prior to developing fully symbolic systems of number, many groups of people invented ways to communicate about exact quantities using finger and body counting systems. Frequently, words are then used to label various gestures, rather than directly labeling quantities. Finally, these words become associated with the quantities themselves and the number gestures are dropped. This historical evidence, suggests that it may be easier to map number gestures to quantities and then map symbols (i.e. words) to number gestures rather than making the immediate direct mapping between exact quantities and number words, which are arbitrary symbols.

The results of Study 1 and Gunderson et al. (2015) support the first half of this proposal. Specifically, children's mappings between gestures and quantities were more accurate than their mapping between number words and quantities in the early stages of number development. This finding is in line with other studies showing children as well as non-numerate adults are capable of matching sets on the basis of one-to-one correspondence before learning the relevant number words (Huttenlocher, Jordan, & Levine, 1994; Izard, Streri & Spelke, 2014; Mix, 2008). However, Gunderson et al. (2015) did not provide evidence for the second part of the bridge proposal – that children should be better at mapping number words to number gestures than to other nonsymbolic quantities. In fact, the similarities between children's gesture-quantity mappings and other item-based mappings could suggest that gestures may function no differently than other item-based representations of number with respect to their associations with number words.

Therefore, in the present study, we examined children's associations between number gestures and number words and compared them to children's associations between nonsymbolic quantities and number words. Broadly, our goal was to find out if number gestures and number words have a special association in the minds of children or if they resemble any other association between number words and arrays of items. For greater clarity on the distinction between the present study and Gunderson et al. (2015) refer to Figure 7.

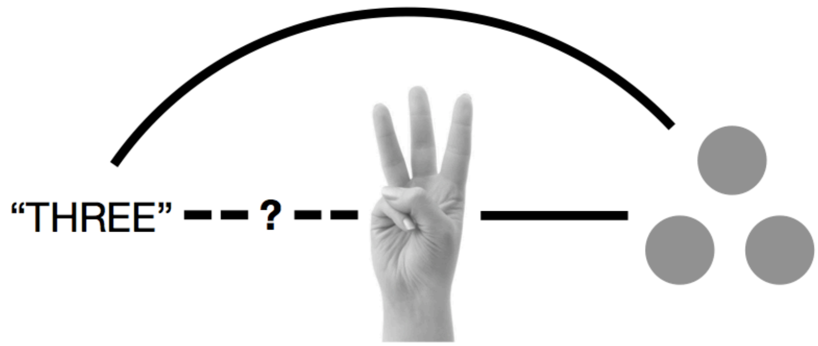


Figure 7. Interim diagram of number gesture as a bridge. Represented by the two solid lines, Gunderson et al. (2015) compared children's abilities to map number words and number gestures to nonsymbolic quantities. The present study seeks further evidence that number gestures may help bridge the gap between arbitrary number words and nonsymbolic quantities by investigating children's ability to map number words to number gestures (represented by the dotted line).

Mapping Between Symbolic and Nonsymbolic Representations of Number

Before learning to count, infants are capable of making precise discriminations between sets within the small number range (i.e. 1 to 3 or 4) and approximate discriminations between larger quantities (i.e. above 4) (e.g. Feigenson et al., 2004). In addition, children in numerate societies learn the meanings of number words through a protracted developmental trajectory. First they learn the meanings of the first few number words ("one", "two", "three", and possibly "four") through a series of lengthy stages before ultimately learning the cardinal principle (Le Corre et al., 2006; Sarnecka & Gelman, 2004; Wynn, 1990; 1992). Various accounts have been proposed concerning how and when symbolic and nonsymbolic representations of number become integrated in the minds of young children. In particular, although many agree that the parallel individuation plays some role from the beginning of learning the meanings of number words (Carey, 2009; Spelke & Tsivkin; see Barner, 2017 for a slightly different view) the extent to which the approximate number system plays a role in the development of symbolic number is a matter of some debate. Some have argued that mapping number words to ANS representations begins early in number development and is an important part of learning the meanings of number words and the cardinal principle (e.g. Gunderson, Spaepen, Goldin-Meadow, & Levine, 2015; Spelke & Tsivkin, 2001). Others have argued that children do not map number words to approximate representations of number until sometime after learning the cardinal principle and therefore that mappings between number words and ANS representations are not an important part of learning the cardinal principle or successor function (Carey; 2009; Le Corre & Carey, 2007). Still others have argued that mapping number words to approximate representations of number is not an important step towards learning the cardinal principle but is necessary for learning the successor function (Barner, 2017; Davidson et al., 2012)

There is substantial evidence that eventually people with access to a count list do learn to integrate the symbolic number system with their preverbal systems for representing quantities (e.g. Cordes & Gelman, 2005; Dehaene, 1997, Whalen et al., 1999). For example, when adults are asked to estimate the number of items in array without counting, their estimates display a hallmark characteristic of the ANS – scalar variability (e.g. Cordes, Gelman, Gallistel, & Whalen, 2001; Gallistel & Gelman, 2000; Gibbon, 1977; Moyer & Landauer, 1967; Whalen et al., 1999). Specifically, as the size of the set increases the variability around adults' mean estimate increases.

However, importantly, this only appears to be the case for larger numbers. Within the small number range, adults make "estimates" with near perfect accuracy and the variability in their responses does not increase across sets sizes of 1 to 4 (Choo & Franconeri, 2014; Kaufman et al., 1949). The ability to quickly and accurately label sets of 1-4 items has been labeled 'subitizing' and has been replicated in numerous studies (e.g. Kaufman et al., 1949, Mandler &

Shebo, 1982; Potter & Levy, 1968; Whalen, 2001). The discontinuity in performance between small and large sets has led several researchers to conclude that small sets are enumerated through a different mechanism (i.e. the PI system) than large sets (Chesney & Haladjian, 2011; Mandler & Shebo, 1982; Revkin, Piazza, Izard, Cohen, & Dehaene, 2008; but see Cordes et al., 2001 for a contrasting view).

Previous research has also addressed the extent to which young children make similar associations. Several studies suggest that children map number words to approximate magnitudes by the preschool years (Huntley-Fenner, 2001; Lipton & Spelke, 2005; Temple & Posner, 1998). Le Corre and Carey (2007) investigated when children first map number words to magnitudes by comparing the performance of subset knowers and cardinal principle knowers on a fast enumeration task that discouraged counting. They found that children begin to map number words to precise representations of small sets before learning the cardinal principle. Moreover, children's estimates of small sets did not show scalar variability, providing further evidence that the parallel individuation system is involved in children's enumeration of small sets. For larger numbers (i.e. 6 and 10), they found that many cardinal principle knowers gave larger estimates for larger set-sizes, suggesting they like adults and older children, had mapped number words to approximate magnitudes. However, this was not true for subset knowers and even some cardinal principle knowers, whom Le Corre and Carey labeled "CP-non-mappers". They concluded that children do not map number words to approximate magnitudes until roughly six months after learning the cardinal principle. Subsequent research has provided evidence that older subset knowers may also be capable of mapping number words to approximate magnitudes (Gunderson et al., 2015; but see Barner; 2017 for a different interpretation).

In addition to probing children's symbolic to nonsymbolic mappings, Hurst, Anderson and Cordes (2016), looked at children's ability to match two types of number symbols, number words and Arabic numerals. They found that 3 and 4 year old children were more accurate when matching Arabic numerals to number words (and vice versa) than when attempting to match Arabic numerals to nonsymbolic quantities of dots. Moreover, when mapping Arabic numerals to number words children did not display the same drop in accuracy for numbers above 3 that was observed in their attempts to match Arabic numerals to nonsymbolic quantities. Hurst and colleagues concluded that mappings between symbolic representations of number do not rely on the same preverbal number systems that are involved in children's mappings between symbols and nonsymbolic quantities.

Current Study

Previously, we showed that children are able to take advantage of the item-based nature of number gestures to more accurately label sets of objects using gestures compared to speech (Gunderson et al., 2015). An open question is whether children are also able to take advantage of the symbolic features of number gestures (i.e. their typical presentation in conventional forms) to more accurately match number words to number gestures than to nonsymbolic quantities. There is evidence that by adulthood children do process conventional number gestures in a way that is similar to how they process Arabic numerals (Di Luca & Pesenti, 2008; 2011; Roggerman, Verguts & Fias, 2007). Di Luca & Pesenti (2010) found that canonical number gestures, but not non-canonical number gestures, prime number words in the same way that Arabic numerals prime number words. Moreover, adults as well as second graders are faster to name canonical number gestures than non-canonical number gestures (Noël, 2005; Di Luca & Pesenti, 2008). However, these studies looked at adults and children well past the point at which they were still learning the meanings of number words. An open question is whether children accurately map number words to number gestures during periods when it might matter for symbolic number development i.e. when they are in the process of learning the cardinal principle or successor function.

Therefore, in the present study, we compared young children's associations between number words and nonsymbolic quantities to their associations between number words and number gestures. If children, conceive of number gestures merely as item-based representations, then word-quantity mappings should look very similar to word-gesture mappings. However, if number gestures have a special connection to number words, we would expect to see greater precision in children's word-gesture mappings compared to their word-quantity mappings. Likewise, if children map number words to number gestures in the same way that they map number words to other number symbols (i.e. Arabic numerals), then children should not exhibit the same decline in accuracy beyond the subitizable range at least within the one handed gestures (1-5) that is observed in children's ability to match number words to nonsymbolic quantities.

3.2. Experiment 1: Enumeration of Dots vs. Gestures

In our first test of children's associations between number gestures and number words, we focused on cardinal principle knowers. Previous studies have suggested that children do not map number words to approximate magnitudes until after learning the cardinal principle (e.g. Le Corre & Carey, 2007; but see Gunderson et al., 2015b). Therefore, young cardinal principle knowers provided a good initial test for whether children were more accurate when labeling number gestures with number words than when labeling nonsymbolic quantities. Although these children have already learned the basic meanings of number words, finding that young cardinal principle knowers are more accurate when labeling gestures compared to nonsymbolic quantities would be significant for several reasons. First, it has been hypothesized that mapping words to approximate magnitudes is an important step in learning the successor function after learning the cardinal principle (Barner, 2017; Davidson et al., 2012). In a similar vein, more accurate number gesture-number word mappings could have a positive impact on children's acquisition of the successor function. Additionally, as discussed above second graders are currently the children for which we have evidence of an advantage when labeling canonical number gestures. If much younger 3- to 6-year-olds do not show a similar advantage, it is unlikely that subset-knowers will display such an advantage.

3.2.1. Methods

Participants

Thirty-five children (20 female) participated in the study. The mean age was 4.55 years (SD = 0.75, Range = 3.35 – 6.20 years). Participants were recruited through urban preschools and daycares and were tested if their parents completed and returned a consent form that was sent home with information about the study. Participants came from a range of socioeconomic backgrounds. Family income ranged from less than $15,000 per year to more than $100,000 with the average family earning between $50,000 and $75,000.

Procedure

Participants were selected for the current study from a larger sample of preschool students who participated in a number battery and sorted into separate studies based on their knower-level. All participants were first asked to count as high as they could and then completed the Give-a-Number task (Wynn, 1990, 1992). Only children who successfully demonstrated knowledge of the cardinal principle were entered into the present study.

Give-a-Number. The Give-a-Number task was used to determine each child's knower level, which specifies the highest number word for which children understand the cardinal value (Wynn, 1990, 1992). Children were presented with 15 plastic fish and asked to place a certain number of fish into a clear plastic bowl (called "the pond"). If a child gave the wrong number of fish, the experimenter gave the child an opportunity to correct the mistake by saying, "But I asked for N fish! Let's check. [Experimenter and child count fish.] Can you put N fish in the pond?" Children's final answers were recorded. The experimenter always began by asking the child to place one fish in the pond. The experimenter then proceeded to increase the number requested by one fish every time the child answered correctly and decreased the number requested by one fish every time the child answered incorrectly, following the procedure in Wynn (1990). Children were considered N knowers when N was the highest number for which they responded correctly on two out of three requests for N fish, and gave the experimenter N fish less than half as often when asked for more than N fish than when asked for N fish. If children succeeded on all numbers up to 6, they were considered cardinal principle knowers. If they failed to meet the one-knower criteria, they were considered pre-knowers. Only children who successfully demonstrated knowledge of the cardinal principle were entered into the present study.

Fast Dots. The Fast Dots task consisted of four blocks of seven trials (28 trials total) presented in a fixed, random order. In each block, children saw dots of different shapes and colors (triangles, squares, diamonds, plus-signs). The same seven set sizes were shown in each block (1, 2, 3, 4, 5, 10, 14). The task was displayed on a laptop. First, children were given instructions and familiarized to the task. They were told that some dots were going to flash up on the screen and that it would happen too quickly to count so their task was to try to guess how many dots they saw. Then, we familiarized them to the displays by showing them sets of 1-15 circles, labeling each set along with the child as they appeared. After this, the experimenter asked if the child was ready and then began the task. On each test trial, the dot array appeared on the screen for 1 second and then disappeared and the experimenter asked how many dots they saw? If the child was reluctant to answer, the experimenter prompted the child, "just make your best guess." If the child tried counting the experimenter reminded the child, "Remember it goes too fast to count, so just try to make your best guess – how many dots do you think you saw?" If the experimenter noticed that the child had looked away and missed the trial, the experimenter repeated the trial and recorded that the trial had been shown twice. If the child gave multiple responses, only the final response was included in the analyses.

Fast Gestures. The fast gesture task mirrored the Fast Dots task. Again, the task consisted of four blocks of seven trials (28 trials total) presented in a fixed, random order. In each block, children saw a different person's hands holding up various numbers of fingers. The same seven set sizes were shown in each block (1, 2, 3, 4, 5, 10, 14). For sets less than or equal to five, only one hand appeared, for the 10 finger trial, two hands appeared, and for the 14 finger trial, three hands appeared. The procedure of the fast gestures task was identical to that of the Fast-Dots task except gestures were used rather than sets of dots and children were asked to estimate how many fingers they saw. Children were given the same instructions and shown the same familiarization of gestures displaying 1-15 fingers.

3.2.2. Results

We predicted greater accuracy for number gestures, particularly on trials above the subitizable range. To test this hypothesis, we conducted a two-way repeated-measures ANOVA on accuracy with the Greenhouse–Geisser correction, with the within-subjects factors of task

(Fast Gestures vs. Fast Dots) and set size (1, 2, 3, 4, 5, 10 and 14). This showed a main effect of task (F(1,32)= 66.41, p<.001, η_p^2=.676), a main effect of set size (F(4.1, 129.8)=150.40, p<.001, η_p^2=.825), and a significant interaction of task and set size (F(3.8, 123) = 14.66, p<.001, η_p^2=.314). Accuracy by task and set size is depicted in Fig. 8.

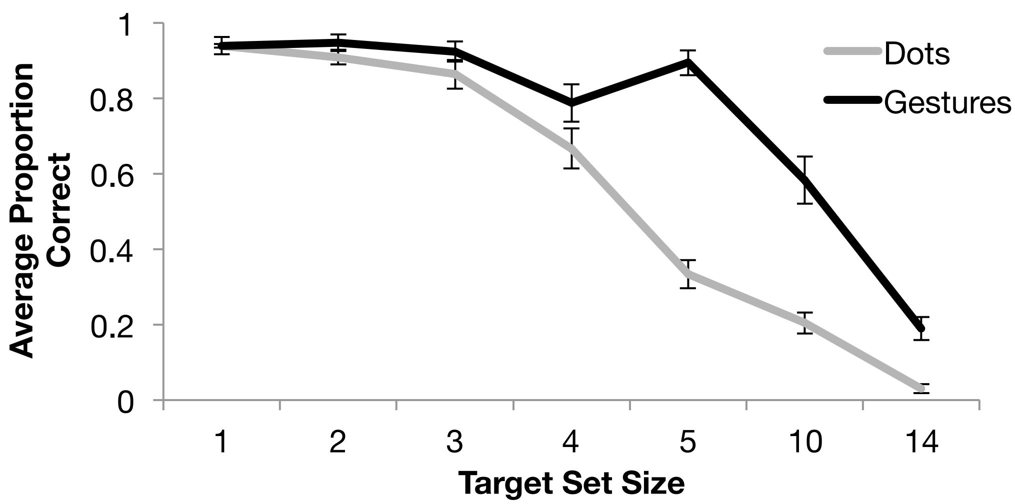


Figure 8. Accuracy on Fast Dots and Fast Gesture tasks by set size.

The greatest differences between the Fast Gesture and Fast Dots task were seen on set sizes 5 (t(33) = 10.29, p < .001, d = 1.79; sign test: Z = -5.20, p < .001) and 10 (t(33) = 5.02, p < .001, d = 0.86; sign test: Z = -3.08, p = .002). There were moderate differences in accuracy between the tasks on set sizes 4 (t(33) = 2.19, p =.036, d = 0.38 ; sign test: exact p = .043) and 14 (t(33) = 10.29, p < .001, d = 0.44; sign test: exact p = .039). There were no differences in accuracy on set sizes 1 (t(33) = 0, p < 1.000, d = 0; sign test: exact p = 1.000), 2 (t(33) = 1.15, p = .257, d = 0.20; sign test: exact p = .727), or 3 (t(33) = 1.14, p =.264, d = 0.20; sign test: exact p = .344) where children were close to ceiling on both tasks.

We also predicted that within the one handed gestures (1-5), there would not be the same decline in accuracy beyond the subitizable range (1 to 3) that is typically shown on tasks like our

Fast Dots task (e.g. Le Corre & Carey, 2007). To test this, we used a linear mixed model with subject as a random effect and Task (Dots vs. Gestures) and Set-Size (1-5; continuous) as fixed effects. We centered Set-Size at 3 in order to get an estimate of the main effect of task at the top of the subitizable range. The intercept was allowed to vary randomly. The results of this estimation are presented in Table 5.

Table 5. Predictors of Accuracy for set sizes 1 to 5

	b	**S.E.**	**df**	***t***	**Sig.**
Intercept	0.59	0.04	173.13	14.60	<.001
Task	0.16	0.02	314.64	7.36	<.001
Set Size	-0.27	0.02	310.60	-11.77	<.001
Task*Set Size	0.12	0.01	310.56	8.42	<.001

They indicate that there was a main effect of Task, whereby children were more accurate in the Fast Gestures task. There was also a main effect of Set Size, whereby accuracy decreased as the set size increase. Most importantly, there was a significant interaction between Task and Set size. The positive coefficient of the interaction terms suggests that as we predicted accuracy did not fall as steeply between set sizes 1 to 5 in the Fast Gestures task as it did in the Fast Dots task.

The results of these analyses clearly show that children were more accurate in the Fast Gestures task and there was not the same effect of set-size within the Fast Gestures task that is observed in the Fast Dots task. As a further illustration of these results, Figure 9 displays the distributions of children's responses for each set size and task.

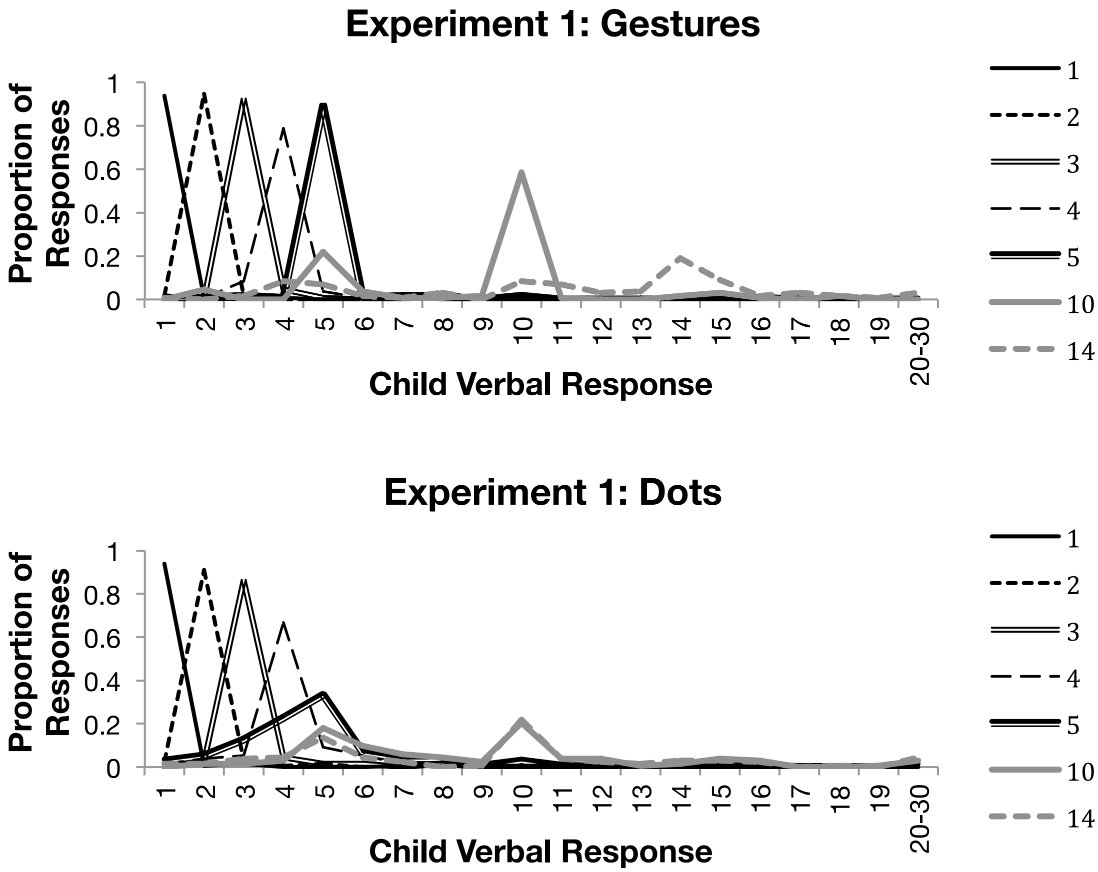


Figure 9. Distribution of responses for each set size (represented by individual lines) on the Fast Gestures task (top) and Fast Dots task (bottom)

3.2.3. Discussion

The results of Experiment 1 show that children were far more accurate at estimating the number of fingers in a gesture than at estimating the number of dots in an array. In particular, children showed an advantage when labeling gestures compared to dots for set sizes above 3. Moreover, the decline in performance across set sizes 1 to 5 was much smaller in the Fast Gestures task than the Fast Dice task. The steeper decline in performance from 1 to 5 items in the Fast Dots task likely reflects children's inability to subitize beyond 3 or 4 items, leading children to rely on fuzzier ANS representations.

There are several possible explanations for why we did not see this pattern on the Fast Gestures task and for why the overall performance on the Fast Gestures task differed from that on the Fast Dots task. First, adults and older children eventually come to think of canonical number gestures and map number words directly to conventional number gestures (Di Luca &Pesenti, 2008; Noël, 2005). It is possible that by the time they have learned the cardinal principle, 3- to 4-year olds have come to recognize the conventional form of number gestures and have made precise mappings between those gestures and the corresponding number words. In support of this, these results are strikingly similar to the pattern of children's responses when making symbol-to-symbol matches between number words and numerals (Hurst et al., 2016). Alternatively, visual features of number gestures could make them easier to enumerate than the arrays of dots use in this task. Gestures naturally organize fingers into sensible arrays, while the dots we presented children were randomly configured with no sensible organization. Moreover, although we used different hands to form the gestures in each block, the basic configuration of the gestures remained the same within each set-size, which was not the case for the dot arrays. Therefore, in Experiment 2, we tested the possibility that the organization of the arrays was driving the difference between Fast Gestures and Fast Dots.

3.3. Experiment 2: Enumeration of Dots vs. Dice vs. Gestures

To test the alternative explanation of the results of Experiment 1, we repeated the experiment and added a third task – Fast Dice. The Fast Dice task was identical to the other two tasks except the dots were organized into canonical dice configurations. We predicted that if the greater accuracy in the original Fast Gestures Task was due to the more organized configurations of gestures compared to random dot arrays, then children should also be more accurate when estimating the number of dots in a dice array compared to the number of dots in a random array (Fast Dots task). In addition, we sought to replicate the advantage of enumerating gestures over dots observed in experiment 1 and test whether it extended to the organized dot arrays in Experiment 2. If this is the case, it will suggest that the advantage of gestural representations of sets is not solely due to the organized nature of the input.

3.3.1. Methods

Participants

Fifty-one children (24 female) participated in the study. One additional participant was dropped because she failed to complete two our of the three enumeration tasks. Two other participants only completed two out of three enumeration tasks (one completed Fast Gestures and Fast Dice the other completed Fast Gestures and Fast Dots) and therefore were not included in analyses that compared performance on all three tasks. The mean age of the participants was 4.03 years (SD = 0.57, Range = 2.75 – 5.06 years). Participants were recruited through urban preschools and daycares and were tested if their parents completed and returned a consent form that was sent home with information about the study. Participants came from a range of socioeconomic backgrounds. Family income ranged from less than $15,000 per year to more than $100,000 with the average family earning between $50,000 and $75,000 per year.

Procedure

The procedure was identical to that of Experiment 1 except for the addition of the Fast Dice task. All participants received all three tasks and the order of the tasks was counterbalanced across participants. Again, participants received the Give-N task followed by the three enumeration tasks if they were cardinal principle knowers.

Give-N. Fast Dots. Fast Gestures. See Experiment 1.

Fast Dice. The Fast Dice task closely mirrored the other two enumeration tasks. Again, the task consisted of four blocks of seven trials (28 trials total) presented in a fixed, random order. In each block, children saw arrays made up of different basic shapes. The same seven set sizes were shown in each block (1, 2, 3, 4, 5, 10, 14). For sets less than or equal to five, the shapes were organized into configurations like those used on traditional six-sided dice. For set-size 10, two groups of five dots (each with the same configuration as the set size 5 trials) were displayed. For set size 14, two groups of 5 and one group of 4 were displayed. The procedure and instructions were the same as those used in the Fast Dots task (see Experiment 1).

3.3.2. Results

We conducted a repeated-measures ANOVA on accuracy with the Greenhouse–Geisser correction, with the within-subjects factors of task (Fast Gestures vs. Fast Dots vs. Fast Dice) and set size (1, 2, 3, 4, 5, 10 and 14). This showed a main effect of task ($F(1.4,69.2)= 52.86$, $p<.001$, $\eta_p^2=.524$), a main effect of set size ($F(3.7, 178.4)=274.50$, $p<.001$, $\eta_p^2=.851$), and a significant interaction of task and set size ($F(6.1, 293.4) = 25.48$, $p<.001$, $\eta_p^2=.347$). Accuracy by task and set size is depicted in Fig. 10 and the distribution of children's responses for each task and set size is displayed in Fig. 10.

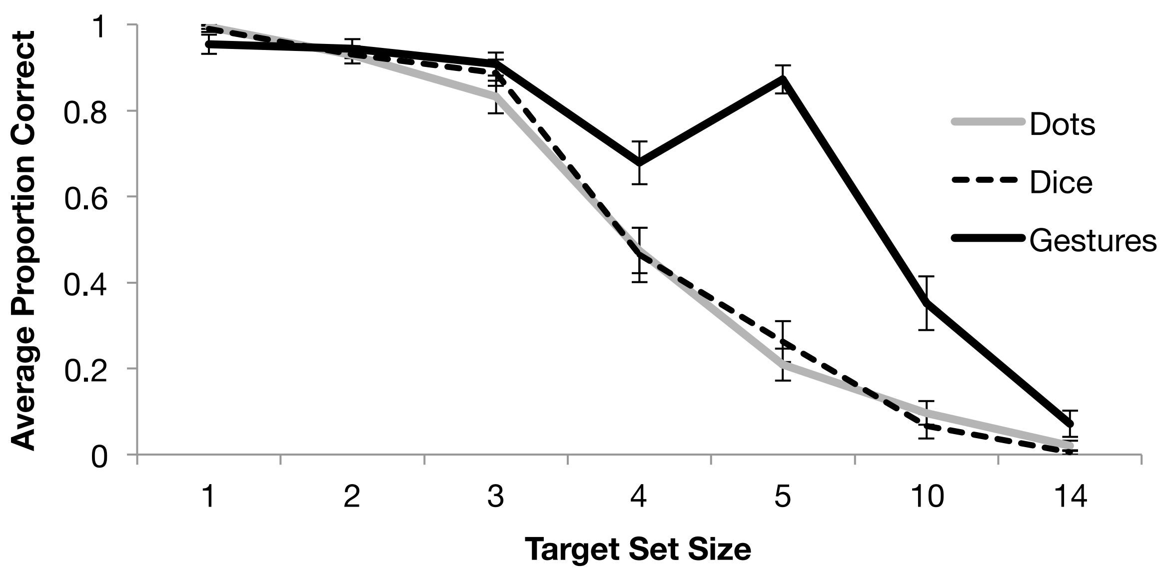


Figure 10. Accuracy on Fast Dots, Fast Dice and Fast Gesture tasks by set size.

To better understand these effects we ran separate ANOVAs comparing the two dots tasks (Fast Dots and Fast Dice) and each dots task to the Fast Gesture Task. First, we compared accuracy on the two types of Fast Dots tasks by running a 2 (Task: Fast Dots vs Fast Dice) by 7 (Set Size: 1, 2, 3, 4, 5, 10 and 14) repeated-measures. This revealed a main effect of set size (F(3, 143)vs.240.85, p<.001, η_p^2=.834, but no effect of task (F(1,48)= 0.31, p=.583, η_p^2=.006. Thus, we found no evidence that children benefited from the more organized configuration of the dots in the Fast Dice task compared to the Fast Dots task.

Next, we ran a 2 (Task: Fast Dice vs. Fast Gesture) by 7 (Set Size: 1, 2, 3, 4, 5, 10, 14) repeated measures ANOVA on accuracy with the Greenhouse–Geisser correction. There was a main effect of Task (F(1.0, 49.0)= 56.98, p<.001, η_p^2=.538), a main effect of set size (F(3.7, 181.7)= 229.11, p<.001, η_p^2=.824), and a significant interaction of task and set size (F(3.6, 176.3)= 29.48, p<.001, η_p^2=.376). Participants were more accurate on the Fast Gesture task than the Fast Dice task for set sizes 4 (t(49) = 2.78, p = .008, d = 0.39; sign test: Z = -1.78, p = .074), 5 ($t(49) = 12.57$, $p < .001$, $d = 1.78$; sign test: Z = -6.63, $p < .001$), and 10 ($t(49) = 5.33$, $p < .001$, $d = 0.75$; exact $p < .001$). There was a small difference in accuracy between the tasks on set size 14 ($t(49) = 2.10$, $p =.041$, $d = 0.30$; sign test: exact $p = .125$). There were no significant differences in accuracy on set sizes 1 ($t(49) = -1.55$, $p = .128$, $d = 0.22$; sign test: exact $p = .219$), 2 ($t(49) = 0.39$, $p = .7$, $d = 0.05$; sign test: exact $p = .791$), or 3 ($t(49) = 0.45$, $p =.652$, $d = 0.06$; sign test: exact $p = .815$).

As a direct replication of our results from Experiment 1, we ran a 2 (Task: Fast Dots vs. Fast Gesture) by 7 (Set Size: 1, 2, 3, 4, 5, 10, 14) repeated measures ANOVA on accuracy with the Greenhouse–Geisser correction. There was a main effect of Task ($F(1.0, 49.0)= 65.63$, $p<.001$, $\eta_p^2=.573$), a main effect of set size ($F(4.0, 198.1)= 225.60$, $p<.001$, $\eta_p^2=.822$), and a significant interaction of task and set size ($F(2.2, 192.6)= 29.48$, $p<.001$, $\eta_p^2=.423$). Participants were more accurate on the Fast Gesture task than the Fast Dots task for set sizes 4 ($t(49) = 3.47$, $p = .001$, $d = 0.49$; sign test: Z = -3.17, $p = .002$), set size 5 ($t(49) = 14.84$, $p < .001$, $d = 2.10$; sign test: Z = -6.65, $p < .001$), and set size 10 ($t(49) = 4.31$, $p < .001$, $d = 0.61$; sign test: Z = -3.33, $p = .001$). There was a small difference in accuracy between the tasks on set size 3 ($t(49) = 2.01$, $p =.050$, $d = 0.28$; sign test: exact $p = .064$). There were no significant differences in accuracy on set sizes 1 ($t(49) = -1.74$, $p < .088$, $d = 0.25$; sign test: exact $p = .125$), 2 ($t(49) = 0.57$, $p = .569$, $d = 0.08$; sign test: exact $p = .454$), or 14 ($t(49) = 1.75$, $p =.086$, $d = 0.25$; sign test: exact $p = .289$).

Like in Experiment 1, we also estimated a linear-mixed model to test whether the same decline in accuracy across set sizes 1 to 5 was observed regardless of configuration (Random or Dice) or Format (Dots vs. Gestures). The results of this estimation are presented in Table 6.

Table 6. Predictors of Accuracy for set sizes 1 to 5

	b	**S.E.**	**df**	***t***	**Sig.**
Intercept	0.76	0.02	50.31	43.29	<.001
Format	0.06	0.01	700.64	9.41	<.001
Configuration	0.01	0.01	703.38	1.00	.317
Set Size	-0.15	0.01	699.35	-23.63	<.001
Format*Set Size	0.05	0.00	699.35	11.90	<.001
Configuration*Set Size	0.01	0.01	699.35	0.73	.467

The results replicate those in Experiment 1. There were main effects of Format, such that participants were more accurate on the Fast Gesture task than the Fast Dots and Dice tasks, and a main effect Set Size, such that accuracy decreased with set size. Again, there was a significant interaction of Format and Set-Size. Participants' accuracy in the Fast Gestures task declined less rapidly across set sizes 1 to 5 than their performance on the Fast Dots and Dice task. However, we did not find any evidence that the configuration of the dots had an effect on children's accuracy, either overall (no significant main effect of Configuration) or in terms of how children's accuracy was affected by Set Size (no significant interaction of configuration and set size).

To further illustrate these findings, the figure below displays Figure 11 displays the distributions of children's responses for each set size and task.

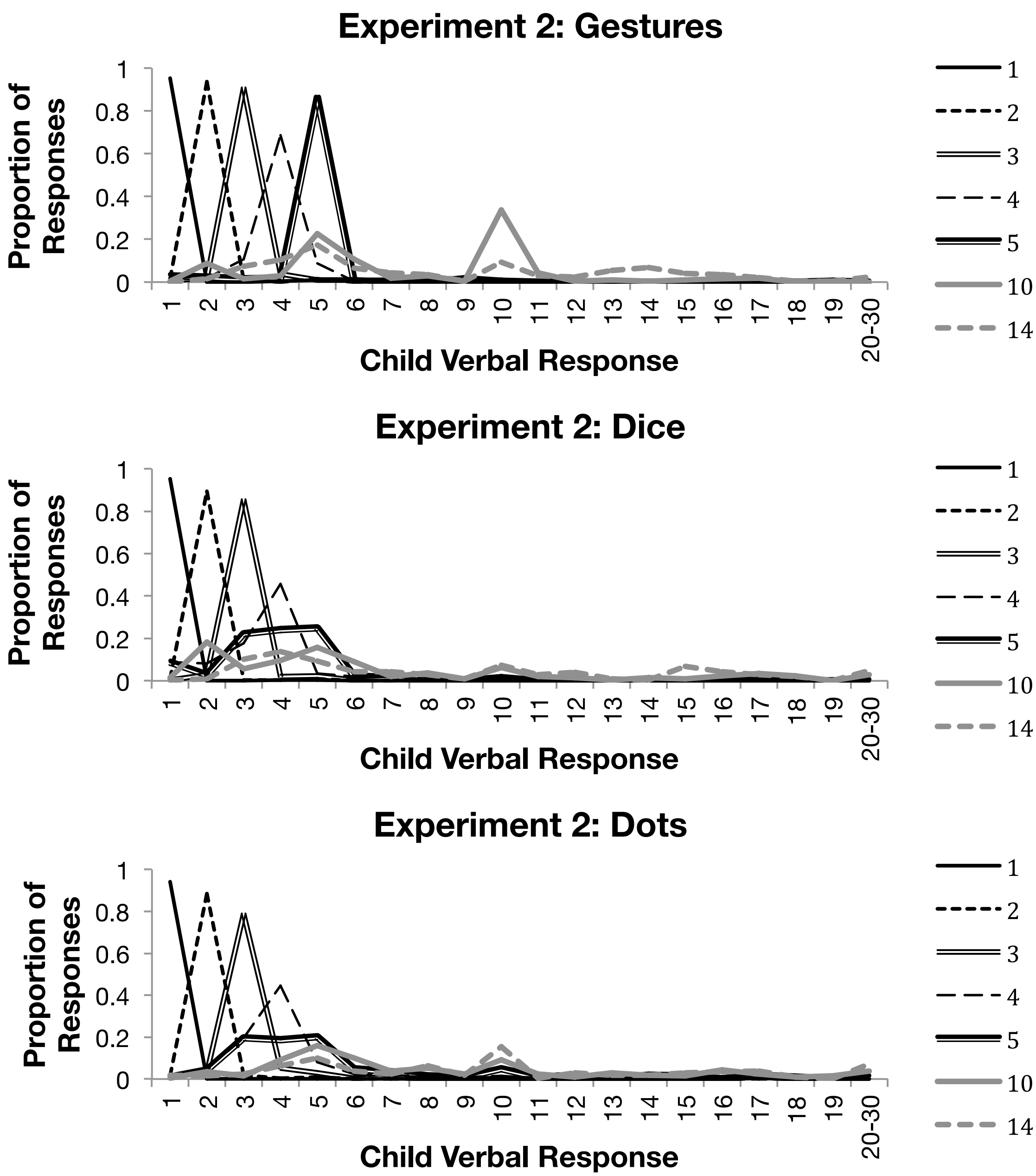


Figure 11. Distribution of responses for each set size (represented by individual lines) on the Fast Gestures task (top), Fast Dice task (middle) and Fast Dots task (bottom)

3.3.3. Discussion

In Experiment 2, we found no evidence to suggest that children benefitted from the greater visual organization of the arrays used in the Fast Dice tasks compared to the Fast Dots task. We also mostly replicated the advantage of enumerating gestures over enumerating dots from Experiment 1 and showed that this advantage extends to cases where dots are organized into groups. Unlike Experiment 1, there was not a significant difference in accuracy between the Fast Gestures and Fast Dots task for set size 14. However, this difference was significant, albeit small, in a comparison of the Fast Dots and Fast Gestures task. This slight departure from the findings of Experiment 1 is not extremely surprising given the relatively low performance on set-size 14 trials in both experiments.

The results of Experiment 2 suggest that children's greater accuracy on the Fast Gesture task compared to the Fast Dots likely does not stem from the greater organization of the items within the display. Therefore, it is more likely that children have learned the mappings between number words and conventional number gestures. Even when dots are presented in neatly organized arrays, there is a steep decline in performance across set sizes 1 through 5, reflecting children's inability to subitize quantities above 3 or 4. In contrast, there is relatively little decline in children's accuracy across gestures for 1 through 5. This pattern is reminiscent of the pattern of children's mappings between numerals and number words (two types of arbitrary symbols) (Hurst et al., 2015), suggesting that children at this stage of number development may already view number gestures as summary symbols and not merely item based representations.

3.4. Experiment 3: Subset Knowers, Dice vs. Gestures

The results of Experiment 1 and 2 reveal that soon after learning the cardinal principle most children can label the number gestures for 1 through 5 with fairly high accuracy without counting. This supports the possibility that number gestures could help bridge the gap between nonsymbolic quantities and number words. However, in order for this to have an impact on children's acquisition of the meanings of cardinal number words, there should be evidence that children begin mapping number gestures to number words prior to learning the cardinal principle. Therefore, in Experiment 3, we tested subset knowers' ability to label number gestures (Fast Gestures) and dot arrays (Fast Dice) using number words.

3.4.1. Methods

Participants

Twenty-one children (9 female) participated in the study. The mean age was 3.94 years (SD = 0.75, Range = 3.52 – 4.56 years). Participants were recruited through urban preschools and daycares and were tested if their parents completed and returned a consent form that was sent home with information about the study. Participants came from a range of socioeconomic backgrounds. Family income ranged from less than $15,000 per year to more than $100,000 with the average family earning between $15,000 and $35,000 per year.

Procedure

The procedure was identical to that of Experiments 1 and 2 with a few exceptions. First, participants completed the experiment only if they were subset-knowers rather than cardinal principle knowers as in the first two experiments. Second, participants only received the Fast Dice and Fast Gestures enumeration tasks, the order of which was counterbalanced across participants. Finally, participants were tested on set sizes 1, 2, 3, 4, 5, 6, and 10. For both the Fast Dice and Fast-Gestures Tasks, set size 6 was presented as groups of 5 and 1, separated by a space, to ensure the stimuli were comparable in both tasks.

3.4.2. Results

We determined participants' knower-levels using the Give-N task. This revealed that 3 participants were one-knowers, 5 participants were two-knowers, 9 participants were three-knowers, and 4 participants were four-knowers. Given our small sample size and our primary goal of understanding how children map number words to number gestures prior to learning the cardinal principle,

We conducted a two way repeated-measures ANOVA on accuracy with the Greenhouse–Geisser correction, with the within-subjects factors of task (Fast Gestures vs. Fast Dots vs. Fast Dice) and set size (1, 2, 3, 4, 5, 10 and 14). This showed a main effect of task ($F(1,20)= 38.38$, $p<.001$, $\eta_p^2=.657$), a main effect of set size ($F(3.34, 66.85)=98.75$, $p<.001$, $\eta_p^2=.832$), and a significant interaction of task and set size ($F(3.63, 72.55) = 19.55$, $p<.001$, $\eta_p^2=.494$). Accuracy by task and set size is depicted in Figure 12.

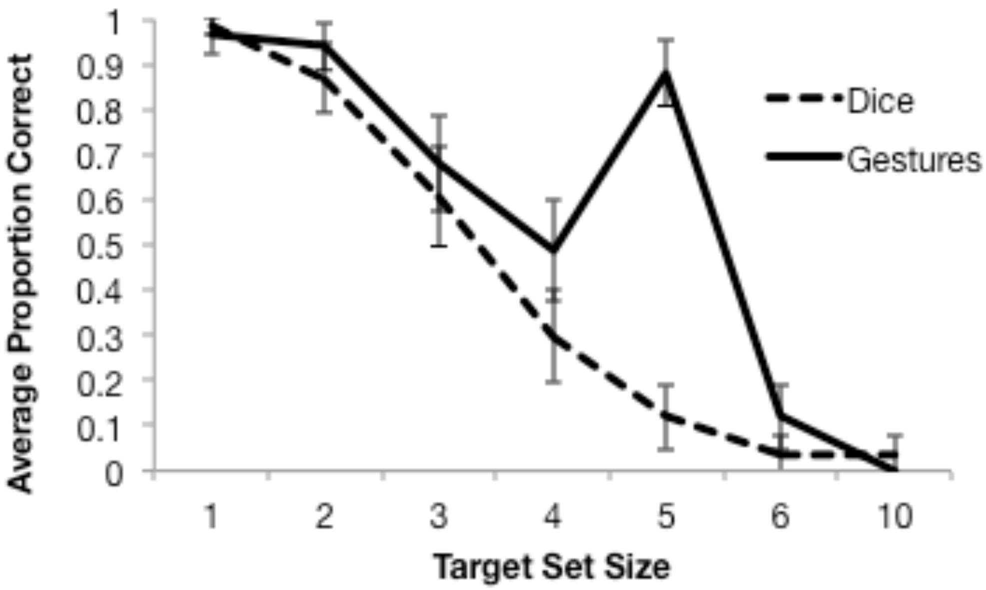


Figure 12. Accuracy on Fast Dots and Fast Gesture tasks by set size.

Overall, accuracy was greater on the Fast Gestures Task (*Mean*=.58; *SD*=.11) than the Fast Dice task (*Mean*=.42; *SD*=.10; $t(20)=6.20$, $p<.001$, $d=1.35$). However, broken down by target set size the difference between Fast Gestures and Fast Dice was only significant at set size 5 ($t(20)=11.61$, p<.001, $d = 2.53$; all other p's >.092). Although the difference between the two tasks at set size 4 was not significant, the size of the difference was comparable to that found in Experiments 1 and 2 for set size 4.

As in Experiment's 1 and 2, we estimated a linear-mixed model to test whether accuracy declined at the same rate between Set Size 1 to 5 in the two tasks. The results of this analysis are displayed in Table 7.

Table 7. Predictors of Accuracy for set sizes 1 to 5

	b	**S.E.**	**df**	***t***	**Sig.**
Intercept	0.36	0.06	193.67	5.94	<.001
Task	0.21	0.04	186.00	5.80	<.001
Set Size	-0.40	0.04	186.00	-9.68	<.001
Task*Set Size	0.17	0.03	186.00	6.47	<.001

In line with the Experiments on cardinal principle knowers, we found main effects of Task, such that participants were more accurate on the Fast Gesture task than the Fast Dots task, and a main effect Set Size, such that accuracy decreased with set size. Again, there was a significant interaction of Format and Set-Size, such that participants' accuracy in the Fast Gestures task declined less rapidly across set sizes 1 to 5 than their performance on the Fast Dots

These analyses suggest a very similar pattern of results in the subset knowers compared to the performance of the cardinal principle knowers, with some slight differences. While there was no difference in accuracy for many of the set sizes, the distribution of children's errors provides further evidence that they may be solving the Fast Gestures task differently than the Fast Dice task. Figure 13 shows the distribution of children's responses for each set size and task. For instance, when shown 10 fingers (two hands each displaying five fingers) children never correctly labeled the set "ten" however they frequently labeled this display "five". In fact, children labeled set size 10 as "five", on 69% of trials in the Fast Gestures tasks compared to only 18% of trials in the Fast Dice task. Likewise, the most common response on Fast Gestures for set size 6, was "one" (27% of trials), likely reflecting the fact that one of the hands was making the gesture for 1. Children also frequently responded with combinations of number words for set size 6 in the Fast Gesture task, such as "five and one". If we include correct combinations as correct responses, then children's average accuracy for set size six did differ significantly between the two tasks (*Mean Accuracy Gesture* = .39, *SD*=.38; *Mean Accuracy Dice* = .08, *SD*=.18; $t(20)=-4.02$, p=.001).

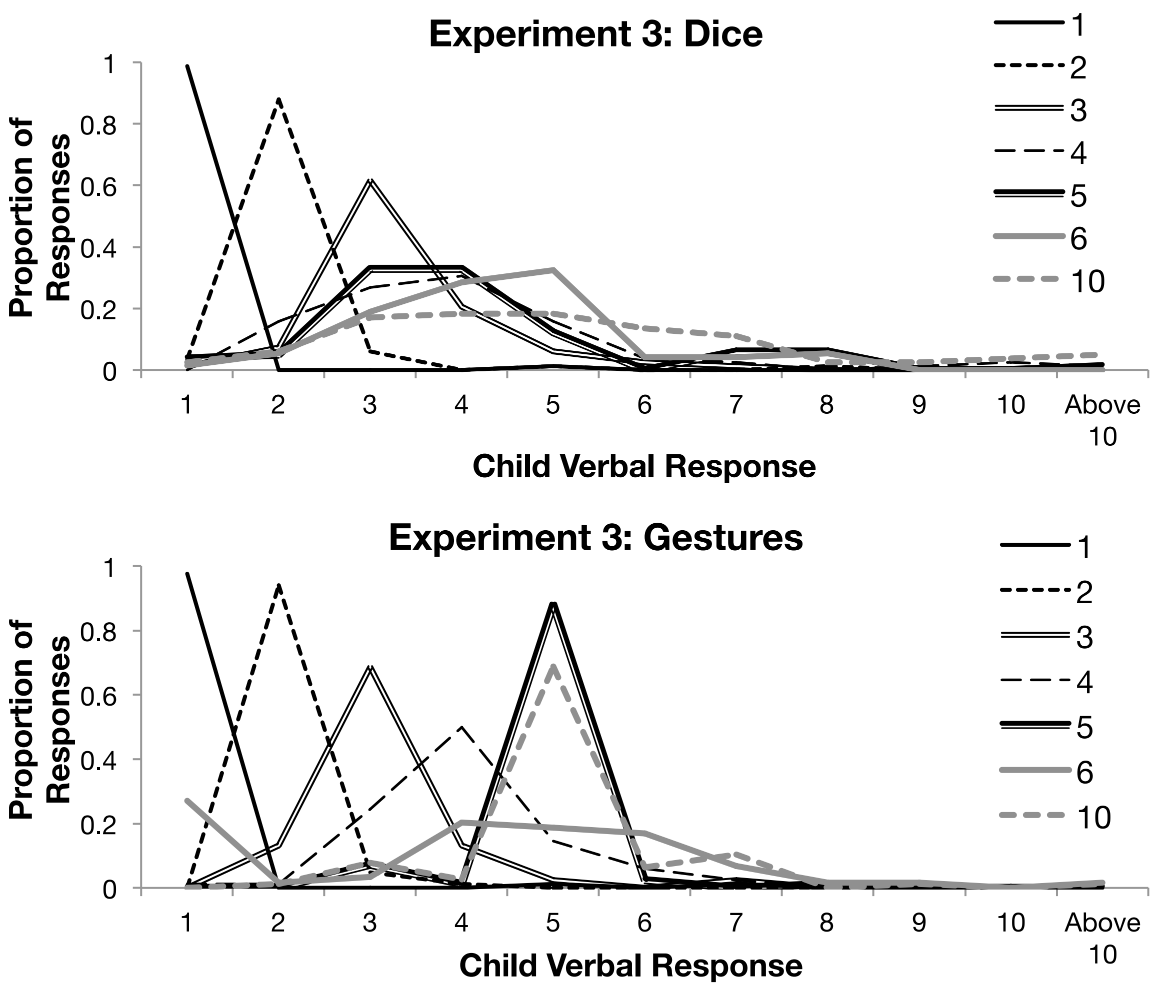


Figure 13. Distribution of responses for each set size (represented by individual lines) on the Fast Dice task (top) and Fast Gestures task (bottom)

3.4.2. Discussion

The results of Experiment 3 suggest that prior to learning the cardinal principle, children are already more accurate when labeling number gestures with number words than when labeling nonsymbolic quantities with number words. In addition to an overall advantage of labeling number gestures over dot arrays, the greatest difference in accuracy was observed on set size 5. Participants high accuracy when labeling the 5-gesture (nearly 90% of trials correct on average) is particularly surprising given that all participants in this experiment were subset knowers and could not yet demonstrate an understanding of the meaning of "five" on standard measures of number comprehension. I discuss the implications of this finding as well as the results of Experiments 1 and 2 in the General Discussion of Study 2 below.

3.5. General Discussion

The present study found that shortly after learning the cardinal principle and beginning even earlier, children are far more accurate when assigning number words to corresponding number gestures than to nonsymbolic quantities. There are several possible interpretations of these findings in regards to child's conception of number gestures. However, under any interpretation, these findings suggest that number gestures have a special association with number words. Parallel to previous findings showing children are initially better at mapping nonsymbolic quantities to number gestures than to number words (Study 1; Gunderson et al., 2015), the present findings show that children are also better at mapping number words to number gestures than to nonsymbolic quantities. In other words, children are more accurate when mapping number gestures to nonsymbolic quantities and to number words than they are at mapping nonsymbolic quantities directly to number words. This finding supports the possibility that number gestures could serve as a useful bridge between nonsymbolic quantities and number symbols (i.e number words).

In Experiments 1 and 2, we explored cardinal principle knowers' relative abilities to estimate the number of fingers in a gesture and the number of dots in an array. These experiments resulted in several key findings. First, in line with previous research (e.g. Le Corre & Carey, 2007), we found that children were quite accurate when estimating small sets of dots (i.e. 1-3) and increasingly inaccurate when estimating the number of dots in larger sets. Interestingly, this pattern did not differ based on whether the dots were organized into dice configurations or merely randomly scattered throughout the display. This contrasts with some previous work which suggests that children are more accurate, particularly for sets above the subitizing range (i.e. above 3), when dots are arranged into dice configurations (Jansen et al., 2014).

In contrast to children's performance on both versions of the dots tasks, children were very accurate estimating the number of fingers in gestures. Apart from a slight dip in accuracy on set-size 4, children's accuracy was remarkably consistent from set-size 1 to 5, suggesting children's estimates of number gestures were not as affected by the 3 item subitizing limit. We confirmed this by finding a significant interaction between set-size and the format of the task (dots vs. gesture) within the 1 to 5 range. Specifically, the decline in accuracy from 1 to 5 in the gesture task was much smaller than in the two dots tasks. This raises the important question of why there was not the same precipitous decline in accuracy beyond the subitizable range that is observed in estimates of the number of dots.

One possibility is that despite our best efforts to control for the inherent organization of the hand configuration by including the Fast Dice task, some visual feature of gestures may make them easier to enumerate. The fact that children continued to show a strong advantage when labeling gestures compared to dice is some evidence against this possibility. Moreover, at least one study that did find a benefit of configuration found that this benefit was specific to dice-like configurations as opposed to dots arranged in a line (Jansen et al, 2014). Given the fairly linear arrangement of fingers within a gesture, one might not expect this to be the ideal configuration. Nevertheless, children could be benefiting from some other aspect of gestures' configuration. For instance, the fact that children are more familiar with number gestures could enable them to take advantage of gestures' configuration to quickly enumerate them.

Alternatively, it seems quite plausible from these findings that children have begun memorizing associations between number gestures and particular handshapes. For instance, children's high accuracy on set size five suggests they may have learned that when all fingers and thumb are extended, it means there are five fingers raised. All number gestures were presented using conventional American number gestures (e.g. index finger for 1, index and middle for two, etc.). Children might have learned the number words associated with these various configurations and therefore not need to enumerate the gestures at all beyond what is necessary for deciphering the configuration. In support of this possibility, children's gesture-number word mappings resemble the way they map number words to Arabic numerals (Hurst et al., 2016) in that there was little decline in performance between set sizes 1 to 5. This parallel, suggests that children might view number gestures as symbols, themselves. In order to distinguish between this possibility and the possibility that children are just better at quickly enumerating number gestures, I will return to the question of whether number gestures are symbols in Study 3.

The question of whether or not number gestures are interpreted as symbols by young children is also interesting to consider in light of subset-knowers' surprising accuracy on the Fast Gestures task. In addition to performing better on the Fast Gestures task overall than on the Fast Dice task, subset knowers correctly responded "five" on nearly ninety percent of 5-gesture trials. If number gestures are merely item-based representations (like dots) in the minds of these children, this finding is particularly surprising given participants' failure to demonstrate comprehension of numbers above four on the Give-N task. However, in light of this discrepancy, it is perhaps more likely that even subset-knowers recognize the conventional configuration of the 5-gesture, and may not even fully understand exactly how it relates to the number of fingers displayed in the gesture.

The particularly high accuracy on 5-gesture trials across the three experiments raises the question of whether this gesture may be driving some of the observed effects. Importantly, we also see an advantage of labeling gestures relative to labeling dots at set size 4, at least amongst CP knowers. Even amongst the subset knowers, there was a main effect of task, reflecting children's slightly higher performance on the Fast Gesture task than the Fast Dice task (though differences between the two tasks did not reach significance for set sizes other than 5). Given the similar albeit lesser advantages of labeling number gestures other than the 5-gesture (relative to dots), it seems likely that similar mechanisms underly children's performance on 5-gesture trials and lower number gestures.

We also found that the advantage of estimating gestures over dots extended to set size 10 and to a lesser extent set size 14 for cardinal principle knowers. There are two possible explanations for this finding. First, children could be familiar with these gestures in the same way that they may be familiar with gestures for smaller numbers. This is much more likely in the case of 10 since the 14-gesture required three hands. Alternatively, participants may recognize the gesture of each hand and then sum across the hands. If the latter is true, it might suggest that at least some cardinal principle knowers have fully integrated both symbolic features and cardinal value of number gestures. This contrasts with subset-knowers' responses on number gestures above 5. Subset knowers were rarely correct above 5. However, they did fairly frequently attempt to label these sets using combinations of number words such as "five and one" in response to a 6-gesture. This was uncommon on the Fast Dice task despite the fact that dot configurations above 5 were grouped into configurations of 5 and 1 (6 total) or 5 and 5 (10 total). In fact, when we included such combinations as correct responses, children's accuracy on the gesture task was significantly higher than their accuracy on the fast dice task for set size 6.

Although it is difficult to definitively conclude from these data whether or not children conceive of number gestures as symbols, it is clear that children are far better at mapping number words to number gestures than to nonsymbolic quantities, at least on a time limited task. Previous research has suggested a role for mapping number words to approximate magnitudes in children's development of an understanding of number and the counting system. Since children can learn the number words associated with number gestures to a high degree of accuracy (demonstrated by the current study) and have an early understanding of the approximate magnitude of number gestures (Gunderson et al., 2015), experience with number gestures could be particularly useful when integrating exact and approximate representations of number. For instance, Spelke & Tsivkin (2001) argued that children come to understand the meanings of number words by integrating their ANS representations with precise PI representations. Specifically, the ANS provides children with an understanding of the set-based and ever increasing nature of number words while the PI system enables children to think about quantities in terms of precision. Under this account, children's overlapping ANS and PI representations for small sets, combined with knowledge of the count list leads children to the insight that precise, set-based quantities continue to increase beyond the small number range. However, the extent to which ANS is actually involved in representations of sets below four is a matter of at least some debate (Clearfield & Mix, 2001; Xu, 2003; Xu, et al., 2005; Star, Libertus & Brannon, 2013). Therefore, number gestures could serve as an important link between these two systems, particularly above the small number range (e.g. the gesture for five).

Others have argued that ANS representations only become integrated with children's knowledge of number words after learning the cardinal principle, but are nonetheless important for acquiring the successor function (i.e. that each number *n* has a successor *n*+1; Barner, 2017; Davidson et al., 2012). Under this account, mapping number words to ANS representations helps children constrain the types of inductions they make about the structure of the counting sequence, leading them to an understanding of the successor function. Given the affordances of number gestures, they could certainly serve as a useful tool in this process. Moreover, previous research has highlighted the utility of number gestures for implementing the counting on procedure (i.e. representing a set with one gesture and then extending additional fingers to add additional items; Fuson, 1986; 1987) which is similar in many ways to the successor function

Future research should therefore explore the relations between children's use of number gestures and their acquisition of the cardinal principle and the successor function. Relatedly, a limitation of Experiment 3 was that we were unable to analyze children at individual knower-levels to see how their ability to map number words to number gestures might change over the course of number development. Understanding when and for which particular numbers children form strong associations between number words and number gestures would improve our understanding of how and when number gestures may be useful over the course of number development. In addition, further research is necessary to establish whether children, even at these early stages of number development, recognize the utility of number gestures as summary symbols in addition to item-based representations of quantity. The following study investigates this question.

4. CHAPTER FOUR Study 3: Are Number Gestures Symbols?

4.1. Background

Learning the arbtrary relation between number words and the exact quantities they represent is a major milestone in children's mathematical development. It typically takes children years to learn the meanings of all of the number words within their memorized count list (e.g. Lee & Sarnecka, 2010; Wynn, 1990; 1992) and children's number knowledge at the time they enter kindergarten is predictive of future academic success (Duncan et al., 2007). Previously, we have shown that children are able to accurately label small numbers of items using number gesture prior to accurately labeling those sets with number words (Gunderson et al., 2015). However, whether children conceive of these number gestures as summary symbols or merely item-based representations, like tallies or any other collection of item, is an open question. Historically, tally-based systems seem to precede fully symbolic number systems but are cumbersome when used to represent large, exact quantities (Ifrah, 2000).

Children's more accurate use of number gestures compared to number words likely stems from the fact that number gestures can be mapped via one-to-one correspondence to the quantities they represent. In line with this, there is evidence that the ability to match to quantities via one-to-one correspondence precedes the ability to label those sets using number words (e.g. Mix et al., 2002; Izard et al., 2014). Similarly, Nicaraguan homesigners who never learn a verbal count list can match gestures to numerical quantities on the basis of one-to-one correspondence and approximate quantity but appear to use number gestures as item-based representations, rather than symbols (Spaepen et al., 2011; Spaepen et al, 2013). Therefore, it is certainly possible that number gestures are initially item-based representations and do not function as summary symbols until later in development. Currently, there is evidence that children may come to think of canonical number gestures as symbolic of the quantities they represent by second grade (Noël, 2005), but this is well after children learn the meanings of number words and logic of the verbal counting system.

In Study 2, we showed that the mappings children make between number gestures and number words are more accurate than the mappings they make between number words and nonsymbolic quantities. One explanation of this is that children recognize number gestures as summary symbols rather than item-based representations. As discussed in Study 2, there are several reasons to favor this explanation. Most importantly, when labeling gestures, children do not exhibit the same subitizing limit of 3 to 4 objects that they display when estimating the number of dots in an array. Instead, there is relatively little decline in accuracy across the one handed gestures 1-5. This resembles children's attempts to match number words to Arabic numerals (two types of arbitrary number symbols) (Hurst et al., 2016).

Still, it is possible that frequent exposure to number gestures or the inherent organization of number gestures could lead children to become skilled at enumerating number gestures without necessarily viewing number gestures as summary symbols. Previous studies have found that both adults and children display an advantage when enumerating dots presented in a canonical array compared to random arrays (Jansen et al., 2014; Piazza, Mechelli, Butterworth & Price, 2001). Although we found no benefit of dots arranged into canonical dice arrays compared to random arrays, it is possible that children require experience with these sorts of canonical arrays before they become easier to enumerate.

In the present study, we conducted a more direct test of whether children view number gestures as symbols or item-based representations. Specifically, we tested whether children base their estimates on the actual number of fingers raised or the nonnumerical aspects of the configuration of the gesture. Although recent definitions of what it means for something to be a symbol do not necessarily require that there is an arbitrary relation between a symbol and its referent (e.g. Namy & Waxman, 2012), finding that children pay attention to the overall configuration rather than basing their judgments purely on the number of fingers raised would suggest that children conceive of number gestures as single items that convey meaning (like symbols) rather than collection of multiple individual items.

To test this, we showed children number gestures in which either the number of fingers was consistent with canonical configurations of the gesture (e.g. a 5 gesture in which all 4 fingers and thumb are extended into a canonical 5 gesture configuration) or in which the number of fingers was inconsistent with the configuration of the gesture (e.g. a canonical 5-gesture with all fingers and thumb extended but in which one finger had been digitally removed leaving only 4 extended fingers total; see Figure 14).

4.2. Methods

Participants

Thirty-four children (16 female) participated in the study. The mean age was 4.14 years (SD = 0.45, Range = 2.70 – 4.82 years). Participants were recruited through urban preschools and daycares and were tested if their parents completed and returned a consent form that was sent home with information about the study. Participants came from a range of socioeconomic backgrounds. Family income ranged from less than $15,000 per year to more than $100,000 with the average family earning between $50,000 and $75,000 per year.

One additional participant was excluded because she was not paying attention to the task. Moreover, this participant's responses were greater than ten standard deviations above the mean response of the other participants. Therefore, in order to get the most accurate estimates of children's responses, this outlying participant was excluded. However, the results of our main analyses remain significant with or without the inclusion of this participant.

Procedure

Participants in the current study were obtained from a larger sample of preschool students who participated in a number battery and sorted into separate studies based on their knower-level. All participants were first asked to count as high as they could and then completed the Give-a-Number task (Wynn, 1990, 1992). Only children who successfully demonstrated knowledge of the cardinal principle were entered into the present study.

Give-a-Number. The Give-a-Number task was used to determine each child's knower level, which specifies the highest number word for which children understand the cardinal value (Wynn, 1990, 1992). Children were presented with 15 plastic fish and asked to place a certain number of fish into a clear plastic bowl (called "the pond"). If a child gave the wrong number of fish, the experimenter gave the child an opportunity to correct the mistake by saying, "But I asked for N fish! Let's check. [Experimenter and child count fish.] Can you put N fish in the pond?" Children's final answers were recorded. The experimenter always began by asking the child to place one fish in the pond. The experimenter then proceeded to increase the number requested by one fish every time the child answered correctly and decreased the number requested by one fish every time the child answered incorrectly, following the procedure in Wynn (1990). Children were considered N knowers when N was the highest number for which they responded correctly on two out of three requests for N fish and gave the experimenter N fish less than half as often when asked for more than N fish than when asked for N fish. If children succeeded on all numbers up to 6, they were considered cardinal principle knowers. Only children who successfully demonstrated knowledge of the cardinal principle were entered into the present study.

(Modified) Fast Gestures Task. The Fast Gestures task consisted of a brief familiarization followed by a single block of test trials. During the familiarization, children were told they were going to see some number gestures and their task was to guess how many fingers they saw raised. They were then shown three examples – a gesture with one finger raised, a gesture with two fingers raised, and a gesture with three fingers raised. The experimenter labeled each gesture with the appropriate number words along with the child. During the test phase, participants were shown a combination of filler trials (canonically configured gestures for 1, 2, and 3), Consistent Configuration trials (canonically configured gestures for 4 and 5) and Inconsistent Configuration trials (4 and 5 gestures in which the configuration of the gesture and the number of fingers raised was reverse by digitally removing or adding a finger; see Figure 14). These trials were repeated three times (21 trials total), and within each grouping of 7 trials were presented in a random order.

On each test trial, the gesture appeared on the screen for 1 second and then disappeared and the experimenter asked how many fingers they saw? If the child was reluctant to answer, the experimenter prompted the child, "just make your best guess." If the child tried counting the experimenter reminded the child, "Remember it goes too fast to count, so just try to make your best guess – how many fingers do you think you saw?" If the experimenter noticed that the child had looked away and missed the trial, the experimenter repeated the trial and recorded that the trial had been shown twice. If the child gave multiple responses, only the final response was included in the analyses.

Figure 14. Example stimuli of Consistent Configuration trials (top row) and Inconsistent Configuration trials (bottom row).

4.3. Results

First, we looked at the average response children gave for the Consistent Configurations trials and the Inconsistent Configuration trials (5 configuration with 4 total fingers, and 4 configuration with 5 fingers extended and 6 fingers total). We ran a 2 (Configuration: Typical vs. Reversed) by 2 (Set Size: 4 vs. 5) ANOVA on participants' average number response. This revealed a main effect of set size ($F(1, 33)=7.43$, $p=.010$, $\eta_p^2=.184$), no effect of configuration ($F(1, 33)=.33$, $p=.571$, $\eta_p^2=.010$), and a significant set size by configuration interaction ($F(1, 33)=109.43$, $p<.001$, $\eta_p^2=.768$). The average response for each set size and type of configuration is depicted in Figure 15.

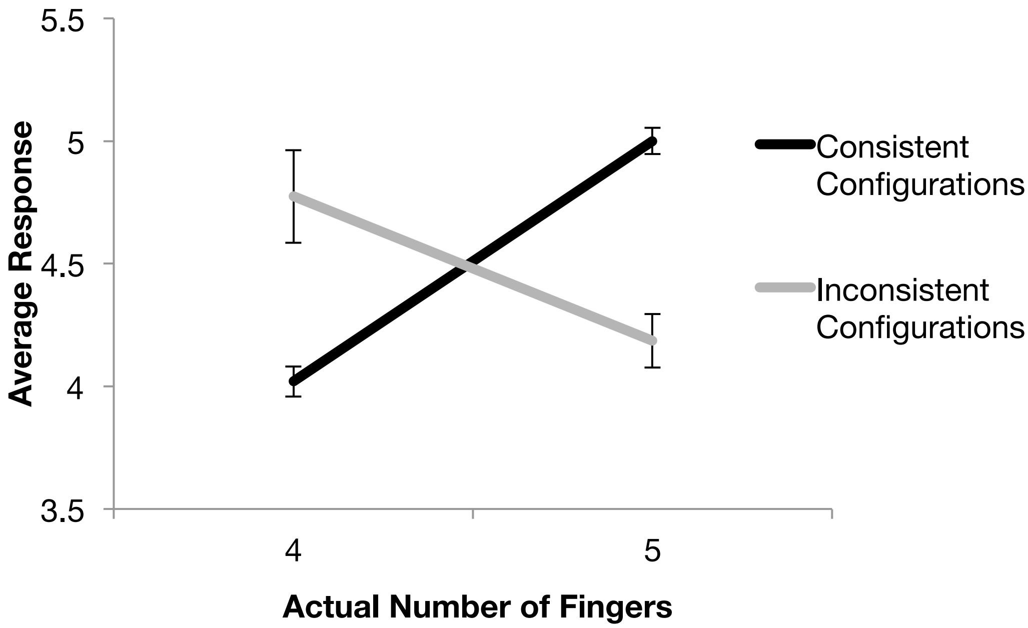
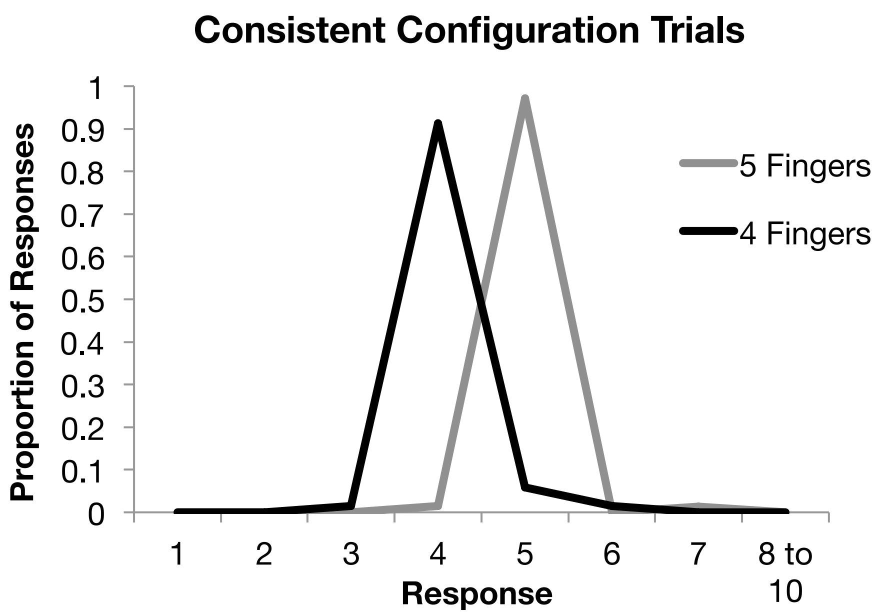


Figure 15. Average response by actual number of fingers raised and configuration type.

As expected, within the typical configurations, children's estimates for set size 5 were significantly higher than their estimates for set size 4 ($t(33) = 50.00$, $p < .001$, $d = 8.57$; sign test: Z = -5.66, $p < .001$). In contrast, within the inconsistent configurations, children's estimates for set size 5 were significantly lower than their estimates for set size 4 ($t(33) = -2.13$, $p = .041$, $d = .69$; sign test: Z = -3.83, $p < .001$). Additionally, children's esitmates for inconsistently configured set size 5 trials were significantly lower than their estimates for the consistently configured set size 5 $t(33) = -11.52$, $p < .001$, $d = 1.98$; sign test: Z = -4.87, $p < .001$, and the reverse pattern was found for the estimates of set size 4 ($t(33) = 7.03$, $p < .001$, $d = 1.20$; sign test: Z = -4.56, $p < .001$).

As a further test of this conclusion, we categorized children's responses on Inconsistent Configuration trials into three groups: responses that matched the configuration, responses that matched the actual number of fingers raised, and responses that matched neither the configuration or number of fingers. The distributions of children's actual responses are displayed in Figure 16. Across both types of Inconsistent Configuration trials (102 trials total) participants' responses matched the configuration on 165 trials (81%), matched the actual number of raised fingers on 26 trials (13%) and matched neither the configuration nor the number on 13 trials (6%).



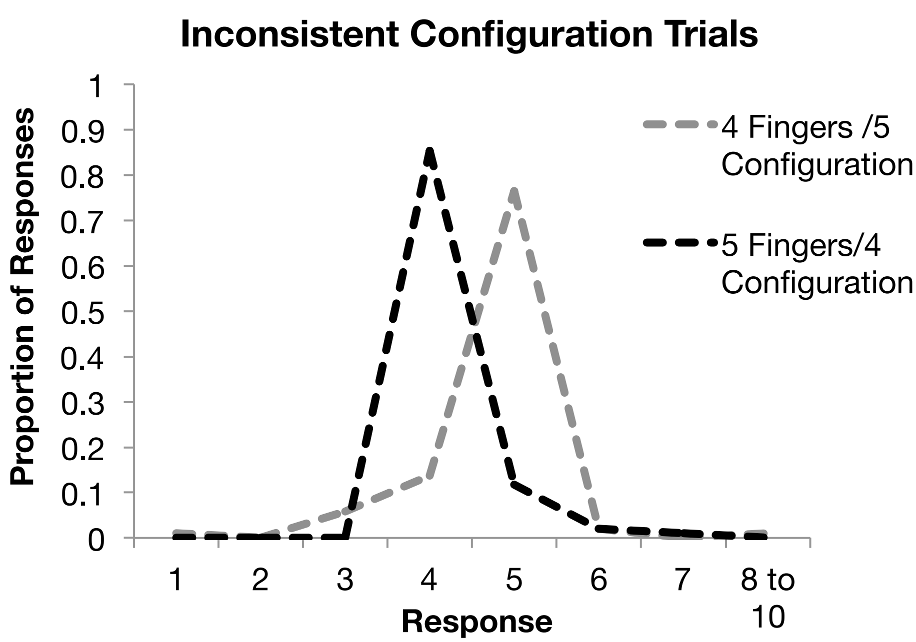


Figure 16. Distribution of responses for each set size (represented by individual lines) on Consistent Configuration trials (top) and Inconsistent Configuration trials (bottom)

A chi-square goodness-of-fit test confirmed that children's responses were not equally distributed amongst these three categories, X^2 (2, N = 34) = 208.79, $p < .001$. Excluding children's responses that matched neither the configuration nor the number of fingers, a binomial test revealed that responses matching the configuration were much more common than responses matching the number of fingers ($p<.001$). A second chi-square test found no difference in the distribution of configuration, number, and non-matches between the two Inconsistent Configuration trial types (X^2 (2, N = 34) = 4.41, $p = .110$.

We also compared the frequency with which children made configuration responses on the Inconsistent trials to the Consistent trials in order to test whether there was any consequence of an inconsistent number of fingers on children's judgments of gestures' configurations. On Consistent trials (set sizes 4 and 5), children selected the correct configuration on 196 out of 204 trials (96%). On Inconsistent Trials, children selected the correct configuration on 165 out of 204 trials (81%). A chi-square test revealed that the distribution of correct and incorrect configuration responses differed significantly between the two trial types, indicating that children were less likely to make the correct configuration response when presented with conflicting number cues. However, this seems to be attributable to only a subset of children as 20 out of 34 (59%) gave responses that were consistent with the configuration on all Inconsistent Trials.

4.4. Discussion

The results of these analyses clearly show that on the vast majority of Inconsistent trials, children base their responses on the configuration of the gesture rather than the actual number of fingers raised. This suggests that the non-numerical features of number gestures play a major role in young children's quick judgments of their numerosity. This builds on previous research showing that adults and older children are quicker to label canonical number gestures than non-canonical number gestures (Di Luca & Pesenti 2008; Noël, 2005). However, the present study was a particularly strong test of children's reliance on configural cues when interpreting number gestures. First, the children in our study (2.5-4.5 year olds) were much younger than these previous studies on the importance of number gestures' configuration. Furthermore, our experiment went beyond comparing children's interpretations of different configurations of the same number by truly pitting configuration and number against one another. Thus, we were able to show that children are not just better when number gestures are presented in a familiar configuration but they actually base their judgments on the configuration even when the numerosity of the gesture conflicts with the configural cues.

These findings are strong evidence that number gestures share some key properties with other number symbols, such as number words. Most importantly, children determine the meaning of a number gesture by its form rather than the number of items (i.e. fingers) displayed. This finding could be interpreted as suggestive that children view number gestures as relatively meaningless symbols (like children's interpretation of number words prior to learning the cardinal principle) and do not appreciate the cardinal value represented by number gestures. However, previous research has already shown that children are quite accurate when labeling small number words and have at least an approximate understanding of the cardinal value of the 5-gesture (Gunderson et al., 2015).

An important question is whether these results also imply that children view number gestures below four as symbolic. The finding that children pay attention to the conventional features of the gestures for four and five at least suggests that children likely also pay attention the conventional features of lower number gestures. Still, future research should attempt to answer this question by measuring children's accuracy and reaction time when presented with canonical and non-canonical number gestures (e.g. the index and middle finger vs. the middle finger and pinky finger raised to indicate "two").

Another important direction for future research is to extend the current study to subset-knowers, to see if they too appreciate the symbolic properties of number gestures. Given the similarity between subset and cardinal principle knowers' performance on set-size 5 in Study 2, the most parsimonious explanation is that the same attention to configuration explains the high performance of both groups of children. However, this confirming this conclusion requires future research.

To better understand these questions, the next chapter will discuss these results in combination with the findings of Studies 1 and 2 and outline several other directions for future research.

5. CHAPTER FIVE: General Discussion

Although children pay attention to numerical quantity early in infancy (Feigenson et al., 2004), they have difficulty mapping number words to the exact quantities they represent (Sarnecka & Carey, 2008; Sarnecka & Lee, 2009; Wynn, 1990; 1992). Previous research has suggested that number gestures – particularly counting gestures – may play a role in symbolic number development (Fuson, 1988; Gallistel & Gelman, 1978; Goldin-Meadow et al., 2014). However, there has been surprisingly little research into children's use and understanding of cardinal number gestures during the period when they matter most for the development of symbolic number comprehension. These types of number gestures are especially interesting because of their capacity to serve as an additional representational number format, somewhere between nonsymbolic, item-based representations and fully symbolic number systems such as number words and Arabic numerals. Accordingly, the present thesis investigated several questions concerning the plausibility of the hypothesis that number gestures serve as a bridge between nonsymbolic, item-based representations of number and symbolic representations of number.

Specifically, we looked for evidence that number gesture's role in children's acquisition of number words mirrors their role in the cultural invention of symbolic number systems. Historical accounts of symbolic number development suggest that symbolic numbers arise through a series of stages (Ifrah, 2000). First, nonsymbolic number systems are developed for communicating about large, exact quantities i.e. using fingers to enumerate sets via one-to-one correspondence (Stage 1). Second, particular number gestures are given names (e.g. "whole hand"; Stage 2). Finally, these names become associated with the quantities themselves, and the intermediary iconic representation of number is dropped (Stage 3). The present set of studies provides some evidence that children also progress through each of these stages. The results described in Study 1 and Gunderson et al. (2015) indicate that children accurately map number gestures to quantities before mapping number words to the same quantities (Stage 1). Studies 2 and 3 show that children learn the number word names associated with certain number gestures (Stage 2). Finally, Study 1 provides some evidence that these first steps are relevant to achieving Stage 3 by showing that mismatches in children's associations between number gestures, number words, and quantities predict subsequent learning of number words. In this chapter, I will summarize the findings of Study 1-3, try to answer remaining questions by considering the results of these studies together, outline plans for future research into these questions, and ultimately discuss the theoretical and broader impacts of this work.

5.1. Summary of Results

Study 1, explored the consequences of children's mismatches between number gestures and number words when each was used to label nonsymbolic quantities. We found that above children's knower-levels, they tended to accurately align number gestures with the number of items displayed in a set but often failed to align number gestures with corresponding number words. Moreover, mismatches between number gestures and number words predicted who was likely to learn from rich number input. This is some of the first evidence that children's use of cardinal number gestures is relevant to their acquisition of number words. However, why this relation exists and whether number gestures can play a causal role in accelerating number development could not be determined from the results of Study 1.

Therefore, in Studies 2 and 3 we investigated children's conception of number gestures in relation to other number formats. In previous research, my colleagues and I have shown that children display an early proficiency in labeling sets using number gestures compared to number words (Gunderson et al., 2015). We suggested that this advantage is likely due to the item-based representational format of number gestures. However, this calls into question whether children also appreciate number gestures functionality as summary symbols for specific quantities. If number gestures do serve as a bridge between nonsymbolic and symbolic representations of number than we would expect to see an advantage of mapping number words to gestures compared to mapping number words to other item-based representations of number.

In Study 2, we found that children form precise mappings between number gestures and number words, particularly within the 1-5 range (one handed gestures). Within this range, there was a much shallower decline in accuracy between gestures for 1 to 5 items than is observed in estimations of dots. Surprisingly, this was true for subset knowers as well as cardinal principle knowers. Subset knowers' enumeration of gestures was particularly accurate relative to their enumeration of dots for set size 5, despite the fact that subset knowers typically fail on standard measures of comprehension of the word "five". These results suggested that children may have mapped number words to the configuration of number gestures rather than solely to the quantity displayed by the gestures. We tested this proposal in Study 3.

Study 3 showed that the advantage in mapping number words to number gestures likely stems from children mapping number words to particular canonical configurations of number gestures. Specifically, when fingers were digitally removed or added to conventional four and five gestures, children labeled these gestures in accordance with their configuration rather than the actual number of fingers. This clearly shows that children have mapped number words to particular gesture configurations, and suggests number gestures are not merely item-based representations. Study 3 demonstrated that this is at least the case for the gestures for 4 and 5.

Study 3 did not include subset knowers nor did examine children's use of the configuration for sets sizes 1 to 3. Therefore, to gain the clearest picture of children's understanding of number gestures from the current findings, we next consider these three studies together.

5.2. Considering Studies Together

Studies 2 and 3 explored the relation between number gestures and number symbols (i.e. number words) and asked whether number gestures are themselves number symbols in the minds of young children. Across four experiments, Studies 2 and 3 showed that children's associations between number gestures and number words differ significantly from their associations between number words and nonsymbolic quantities, even before children learn the cardinal principle. Moreover, at least by the time children learn the cardinal principle, they label number gestures using the configuration rather than the actual number of fingers raised. Given that the strongest evidence that children conceive of number gestures as symbols came for particular numbers, i.e. 5 and to a slightly lesser extent 4, it is important to examine whether children conceive of all number gestures as number symbols or only a select few.

For instance, in Study 2, we found almost no significant differences between the gesture and dots tasks for set-sizes 1-3. Children were close to ceiling in both tasks within this range, making it more difficult to observe differences between the tasks. Moreover, since children are able to subitize 1 to 3 items (e.g. Jansen et al., 2014; Potter & Levy, 1968), it is likely that the aspect of the number gestures' that children rely on to determine their configuration within this range is the number of fingers displayed. Therefore, we might not expect there to be any difference between children's accuracy labeling gestures for 1-3 and sets of 1-3 dots. This contrasts to the gestures for four and five which are beyond the subitizable range and for which children may also rely on other configural cues such as whether the thumb is extended. In light of this, the lack of significant differences between the tasks for individual set sizes within the 1 to 3 range should not be taken as evidence that children's conceptions of these gestures differ fundamentally from their conceptions of the gestures for 4 and 5. A more parsimonious conclusion is that children, at least after learning the cardinal principle, learn to recognize the configuration of all number gestures within the 1 to 5 range.

A similar argument can be made in regards to subset-knowers' accuracy advantage on the fast gestures task compared to the fast dots tasks. Study 3, which provided the strongest evidence that children view number gestures as summary symbols and not merely item-based representations, only tested cardinal principle knowers. However, given subset knowers' high performance on set size 5 of the Fast-Gestures task, a number not only outside of the subitizable range but also above their knower-levels, it would be surprising if a different mechanism explained their gesture-advantage than explained the gesture-advantage of cardinal principle-knowers. It is more likely that subset knowers also view number gestures as single configurations and not just item-based representations.

Therefore, we can tentatively conclude that beginning prior to learning the cardinal principle, children recognize canonical number gestures for 1 to 5 in a way that goes beyond mere item-based representations like collections of dots. The evidence that this view of number gestures extends above 5 is less clear. Subset knowers' did not show an advantage when labeling gestures vs. dots higher than 5. Amongst cardinal principle knowers, accuracy was lower for sets above 5 than the sets below 5. Although we did not formally collect reaction time, experimenters observed that children often took longer to respond to these larger number displays. Therefore, rather than memorize what the 10-gesture looks like, children might rely on their knowledge of the five-gesture and addition or a similar procedure.

Studies 2 and 3, suggest that children view number gestures as whole configurations rather than collections of fingers as they do for collections of other objects. However, this alone does not mean that number gestures are symbols. Importantly, these studies only tested children's ability to name number gestures using number words and thus it is not entirely clear that children understand the exact quantities that these gestures reference. Of course, there is some evidence that children accurately map number gestures to exact quantities. In Chapter 1 and 2, I described evidence that children are quite accurate when labeling small sets using number gestures. However, without testing children's understanding of these relations within a single study, it is difficult to definitively conclude that number gestures are truly number symbols. It is possible that children map number gestures to quantities via one-to-one correspondence (like other item based mappings) and learn the names of number gestures relying on the configuration, but do not integrate these various uses of number gestures until later in development. On the other hand, it is possible that children fully conceive of number gestures as summary symbol, even at this young age. As discussed in the next section, future research is necessary to explore how and when these various uses of number gestures become integrated.

Still, the evidence that number gestures are more than merely item-based representations warrants a reexamination of children's advantage when labeling sets using gestures compared to words in Study 1 and Gunderson et al. (2015). Previously, we interpreted children's greater success in gesture compared to speech as an indication that children likely do not think of number gestures as summary symbols. However, the fact that subset knowers treat number gestures like other number symbols, in that they map words to the holistic configurations of number gesture, suggests that perhaps even at this stage children conceive of number gestures as summary symbols. If so, children's acquisition of number gesture might represent their first entry into symbolic number, a major achievement in children's early numerical development.

Moreover, if children do use number gestures as interim number summary symbols prior to learning number words, it suggests an interesting explanation of the results of Study 1. Specifically, it would suggest that many children who mismatch might already have learned to map a symbol (i.e. a number gesture) to a specific quantity above their knower level. In this case, in order to learn the next number word children only need to learn the correct number word-number gesture mapping. As demonstrated in Study 2, this may be easier than making the direct mapping between number words and nonsymbolic quantities, resulting in faster learning in the mismatcher group than the non-mismatcher group.

5.3. Limitations and Directions for Future Research

Future research should explore the extent to which children can integrate their symbolic and item-based representations of number gestures. In separate experiments, we found that children accurately map number gestures to quantities (Gibson et al., under review; Gunderson et al, 2015) and accurately map number gestures to number words. Importantly, the task used to demonstrate children's ability to match number gestures to quantities, the What's-on-this-Card (WOC) task, did not require children to conceive of number gestures as symbolic representations of number. Trials were untimed and children, therefore, could match number gestures to sets on the basis of one-to-one correspondence. Similarly, Studies 2 and 3 suggest that children do recognize number gestures without relying solely on their numerical properties. However, this task did not require that children pay attention to the numerical properties of these gestures (beyond what is necessary for identifying the configuration) so children could be thinking of these number gestures as purely meaningless symbols similar to their initial understanding of number words or Arabic numerals (e.g. Wynn, 1990;1992).

Therefore, future research should investigate the extent to which children's understanding of number gestures' numerical meaning is integrated with their recognition of number gestures' symbolic configuration. For instance, it would be interesting to test whether children who are presented with number gestures only briefly (as in the Fast-Gestures task) are more accurate when matching those gestures to nonsymbolic quantities (as in the WOC task) than they are when matching number words to nonsymbolic quantities. A similar modification of Study 3 would also be an interesting avenue for future research. Specifically, would children match inconsistent number gestures to a quantity matching the gesture's configuration or the actual number of fingers? Answering these questions would provide insight into the extent to which children truly do conceive of number gestures as summary symbols and when this occurs during development.

Relatedly, future research should continue to explore children's developing knowledge of number gestures prior to learning the cardinal principle. The present study provided strong evidence that by the time children learn the cardinal principle, they recognize number gestures as single configurations and provided some initial evidence that this begins prior to learning the cardinal principle. However, the size of our sample of subset-knowers prevented us from exploring differences between children at different subset-knower levels in regards to their recognition of canonical number gesture configurations. When children begin to map number gestures to number words constrains when and how number gestures may have an impact on children's acquisition of number words.

This leads into a third important direction for future research. Additional work is needed to test the correlational and causal relation of number gestures and children's acquisition of number words. As described above, the current studies suggest that number gestures could have a positive impact on children's development of symbolic number at several stages of number development, i.e. during the subset-knower levels when children are learning individual number words, during the acquisition of the cardinal principle, and during the period when children are developing an understanding of the successor function. However, currently, the only evidence that cardinal number gestures are relevant to symbolic number development is Study 1. Study 1 was limited to exploring this relation in the context of learning the meanings of the first few number words. Study 1 was also limited by a somewhat small sample-size, especially considering only children within the rich number input condition showed an advantage if they had mismatched at pretest. Future research should seek to replicate this finding and also test whether children's actual knowledge of number gestures (not merely mismatching which could represent more or less accurate use of number gestures compared to speech) is related to growth in number word knowledge. Additionally, future studies should look for evidence that number gestures serve a causal role in the acquisition of number words through number-gesture based interventions. The results from the present set of studies present a strong case that number gestures *could* be useful for developing a full understanding of symbolic number but future research is necessary before concluding that number gestures actually do (or can) serve this purpose. Moreover, as suggested above, number gestures could also impact children's symbolic number development beyond learning the meanings of the first few number words. Future research should also explore the relation between children's use of cardinal number gestures and their understanding of the cardinal principle and successor function and how these effects during the earliest stages of symbolic number development relate to later observations of the role of number gestures on children's arithmetic skills (e.g. Butterworth, 1999; Jordan, Hanich & Kaplan, 2003)

A final direction for future research is to look at parents' and children's number gestures in naturalistic settings and how their uses of number gestures may be related to children's knowledge of number words. Although some research has looked at this question with respect to children's counting gestures and pointing to sets (e.g. Suriyakham), more research is needed specifically on parents' and children's use of cardinal number gestures. Understanding the natural variation of cardinal number gesture use and how it is related to symbolic number can provide important guidance in determining how to design successful interventions. We have begun preliminary investigations into parents' and children's use of number gestures and found that parents' frequently use number gestures when children are young but as children grow older and their own use of number gestures increases, parents use of number gestures decreases.

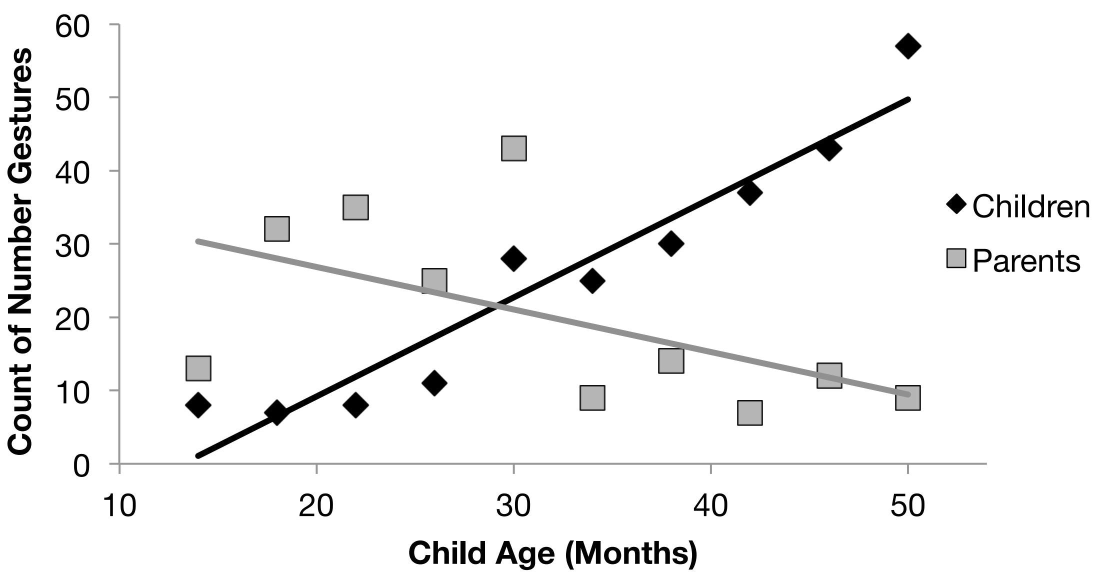


Figure 17. Count of cardinal number gestures used by parents and children during 10 ninety-minute home-visit sessions between 14 and 50 months (n=45 parent-child dyads).

In line with the possibility that number gestures serve as a bridge between nonsymbolic and symbolic representations of number, this could be evidence that parents employ number gestures as a crutch while children are first learning to communicate about number. Of course, further research is necessary to fully understand the role that number gestures play in parents' and young children's discourse about numbers.

5.4. Conclusion: Contributions and Practical Implications

The present studies make several important contributions to the existing literature on children's understanding of cardinal number gestures and symbolic number development. Previously, the youngest age at which there was evidence that children view number gestures as symbols was 6 to 8 years (Noël, 2005). The present studies extend that finding to children roughly between the ages of 3 to 5, some of whom had not yet learned the cardinal principle. Likewise, we used a particularly strong test of children's reliance on configuration to determine the meaning of a number gesture since the configural cues were actually inconsistent with the numerical cues. This suggests that while number gestures may initially get their meaning from their iconicity, eventually children's representation of number gestures becomes more arbitrary. This finding is particularly interesting in light of research suggesting even adults do not view number gestures as symbols if they do not learn a symbolic counting system (Spaepen et al., 2011; Spaepen et al., 2013). When and how children living in numerate societies come to think of number gestures as symbols is another interesting question for future research. It is quite possible that the process of learning number words is important for recognizing the symbolic nature of number words.

Additionally, previous research has suggested counting gestures play a significant supportive role in children's understanding and implementation of the counting principles (Alibali & DiRusso, 1999; Di Luca & Pesenti, 2008; Fuson, 1988; Gelman & Gallistel, 1978; Graham, 1999; Potter & Levy, 1968; Saxe, 1977; Saxe & Kaplan, 1981). Study 1 provided the first evidence that children's use cardinal number gestures is also relevant to their developing understanding of number words. This also extends the existing literature on the predictive power of gesture-speech mismatches (e.g. Church & Goldin-Meadow, 1986; Iverson & Goldin-Meadow, 2005; Perry, Church, & Goldin-Meadow, 1988) to children's early number development. This large and growing body of research suggests that children's gestures reveal important information about what they know. In the present case, it suggests that there are important divisions within knower-levels that are relevant to the effectiveness of input. This is consistent with another line of my research showing the differential effects of various types of number input on children's number development at different knower-levels (Gibson, Gunderson & Levine, in prep). Thus, knowing more about individual children's current level of number knowledge – including children's use of number gestures – appears significant in designing effective number interventions.

Together, the present studies demonstrate young children's extensive knowledge of number gestures even at young ages and before fully grasping the meanings of number words. Along with previous research, these studies satisfy several conditions that suggest number gestures may serve as a useful bridge between nonsymbolic and symbolic representations of number. Children display an advantage when mapping number gestures to nonsymbolic quantities (Study 1; Gunderson et al., 2015) and when mapping number gestures to number words (Study 2) relative to their ability to map number words directly to nonsymbolic quantities.

Moreover, there is some evidence that children's use of number gestures is at least relevant to their development of symbolic number comprehension. These findings represent initial evidence that children can use number gestures as a bridge between nonsymbolic and symbolic representations of number. However, as discussed above, more research is necessary to fully understand the role that number gestures play in children's acquisition of symbolic number language.

This possibility resembles several other theories that suggest certain representations of number bridge representations that are more challenging to map on their own. For instance, Hurst et al. (2016) have suggested that children learn the relation between Arabic numerals and nonsymbolic quantities by mapping each of these to number words. Similarly, previous researchers have suggested tally systems do help bridge the gap between nonsymbolic quantities and number words. However, rather than number gestures these theories tend to focus on the verbal count list, since children initially appear to use it as a tally system (i.e. they match number words to individual items via the counting routine but do not understand the cardinal value of these words; Barner, 2017; Weise, 2003). However, whereas the count list (as a tally system) represents quantities serially in time (i.e. one recites additional numbers for additional items), cardinal number gestures represent number spatially with a static iconic display. Therefore, number gestures are certainly not redundant and may serve an important supportive role in bridging nonsymbolic and symbolic number representations. Importantly, these proposals are not mutually exclusive.

Number gestures do not even need to play a necessary role in order for them to play an important one. The present set of studies suggests that knowledge of number gestures is quite ubiquitous, even at the early ages we tested. This raises the possibility that number gestures play a major role in the acquisition of number words for most children. However, even if number gestures are just one of many useful tools in advancing children's number knowledge, this would be an important finding.

A basic comprehension of number is essential to for success in school, the workplace, and everyday life. The general population in the United States is not acquiring the level of mathematics knowledge needed for the 21st century workplace (IES, 2010; OECD, 2007). In fact, recent NAEP data (National Center for Education Statistics, 2015) showed a decrease in math achievement scores compared to two years ago, and students in the U.S. do not compare favorably to their counterparts in other developed countries (PISA, 2012). Within the U.S. there are vast differences in early number knowledge based on factors like SES (Ginsburg & Russell, 1981; Lee & Burkam, 2002; Saxe, Guberman & Gearhart, 1987; Jordan, Huttenlocher, & Levine, 1992). Moreover, differences in number knowledge are predictive of future academic success (Duncan et al., 2007) and life outcomes (Murnane, Willett & Levy, 1995; Rivera-Batiz, 1992; Reyna, Nelson, Han & Dieckmann, 2009).

Finding ways to accelerate young children's entry into symbolic number is critical for reducing these disparities. The availability of number gestures, which are literally at parents' and children's fingertips, makes them a particularly attractive candidate for large-scale interventions. Moreover, the present studies demonstrate that children's knowledge of number gestures is extensive during the ages when they are acquiring an understanding of symbolic number and the counting system. Future work will continue to clarify number gestures' role in symbolic number development and hopefully provide new insight into fostering children's understanding of number.

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