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Number gestures predict learning of number words

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Abstract

When asked to explain their solutions to a problem, children often gesture and, at times, these gestures convey information that is different from the information conveyed in speech. Children who produce these gesture-speech "mismatches" on a particular task have been found to profit from instruction on that task. We have recently found that some children produce gesture-speech mismatches when identifying numbers at the cusp of their knowledge, e.g., a child incorrectly labels a set of two objects with the word "three" and simultaneously holds up two fingers. These mismatches differ from previously studied mismatches (where the information conveyed in gesture has the potential to be integrated with the information conveyed in speech) in that the gestured response contradicts the spoken response. Here we ask whether these contradictory number mismatches predict which learners will profit from number-word instruction. We used the *Give-a-Number* task to measure number knowledge in 47 children (mean age=4.1 years, SD=0.58), and used the *What's on this Card* task to assess whether children produced gesture-speech mismatches above their knower level. Children who were early in their number learning trajectories ("one-knowers" and "two-knowers") were then randomly assigned, within knower level, to one of two training conditions: a Counting condition in which children practiced counting objects; or an Enriched Number Talk condition containing counting, labeling set sizes, spatial alignment of neighboring sets, and comparison of these sets. Controlling for counting ability, we found that children were more likely to learn the meaning of new number words in the Enriched Number Talk condition than in the Counting condition, but only if they had produced gesture-speech mismatches at pretest. The findings suggest that numerical gesture-speech mismatches are a reliable signal that a child is ready to profit from rich number instruction and provide evidence, for the first time, that cardinal number gestures have a role to play in number-learning.

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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? In previously studied mismatches, the information conveyed in gesture had the potential to be integrated with the information conveyed in speech (Goldin-Meadow, 2003b). But in the numerical mismatches we study here, the number conveyed in gesture contradicts the number conveyed in speech. We ask whether these contradictory number mismatches nevertheless predict which learners will profit from number-word instruction. 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 counting, spatial alignment (e.g., seeing two beads next to three beads), and cardinal labeling than from more basic number input involving counting sets presented one at a time, and does this effect depend on whether the child has produced gesture-speech mismatches, reflecting their "readiness to learn"?

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, 2000; 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 word. 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 & Presenti, 2011; Goldin-Meadow, Levine & Jacobs, 2014). Our study contributes to this growing research.

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, despite the ubiquity of number gestures among children and parents, little is known about their precise role in the development of verbal number fluency.

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 understood 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; Oswald, Gibson, Butts, Goldin-Meadow, & Levine, in prep.). 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, and possibly a stepping stone towards the acquisition of symbolic number language (Gunderson et al., 2015). In fact, historical accounts of the invention of symbolic number suggest that number gestures may have served precisely this purpose. Tally systems, many based on finger-counting, may have served as an intermediary step on the way to connecting arbitrary words to specific quantities (Ifrah, 2000). The word "five", for instance, is believed to stem from the root of the word for "fist," presumably because a fist uses five fingers (Winter, 1992). It is possible that, on an ontogenetic time scale, cardinal number gestures play a similar role in children's acquisition of symbolic number language.

In support of this hypothesis, there is evidence that children do, in fact, find it easier to match small quantities to number gestures than to number words (Gunderson et al., 2015). Specifically, children in the early stages of number development are more accurate on sets immediately above their knower-level when labeling them in gesture than when labeling them in speech. Moreover, children are more accurate in associating number words and number gestures than in associating number words and nonsymbolic quantities, such as arrays of dots (Gibson, Berkowitz, Goldin-Meadow & Levine, in prep). But even though it is widely theorized that number gestures play a role in number development (e.g. Alibali & DiRusso, 1999; Di Luca & Pesenti, 2011; Gelman & Gallistel, 1978; Fischer, Kaufman & Domhas, 2012; Fuson, 1988), whether young children's understanding of number gestures and their numerical referents has any bearing on their acquisition of number words remains an open question.

Importantly, we see that children are better at labeling small quantities with number gestures than with number words not only when we compare isolated gestures to isolated words, but also when we compare mismatching gestures to the words they accompany. Gesture-speech mismatches—utterances in which speakers convey different information in gesture than in the speech that accompanies those gestures (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., mathematical equivalence 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 box while saying "open" to request that the box be opened) when they are on the cusp of learning to use two-word utterances (e.g., "open box") (Iverson & Goldin-Meadow, 2005).

Gesture-speech mismatch 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.

However, in previous research on gesture-speech mismatches, the information conveyed in the gestural component of a mismatch has always been potentially integratable with the information conveyed in the accompanying speech. As an example from early language, a point at daddy, combined with the word "hat," together indicate that the hat is daddy's, a notion that neither modality conveys on its own. As an example from a conservation task, a gesture indicating the narrow width of a container, combined with words focusing on its tall height, together indicate that the container's height compensates for its width. Even the mismatches produced on mathematical equivalence problems which often contain two incorrect problem-solving strategies, display this property. Although the two strategies may lead to different solutions, the information conveyed in both strategies needs to be integrated in order for the learner to master the problem. For example, on the problem 5 + 4 + 3 = ___ +3, a child may display an *add-all-numbers* problem-solving strategy in gesture by pointing at the 5, 4, left 3, and right 3; when combined with the words, "I added the 5, the 4, and the 3" (an *add-to-equal-sign* strategy), the two modalities taken together indicate that the child has noticed the 3 on the right side of the equation, and has also noticed that the equation has two sides. Although the solutions that these strategies lead to are not the same (and, in this sense, appear to be contradictory), the information that they convey not only can, but must, be integrated in order for the child to solve the mathematical equivalence problem successfully.

The gesture-speech numerical mismatches that young children produce contain a number label in gesture that clearly contradicts the number label in speech (holding up three fingers while saying "two"). Moreover, the information conveyed in the two modalities are not obviously integratable. It is therefore possible that this type of mismatch will *not* predict learning if integrability of the elements expressed in gesture and speech is critical. However, it is also possible that cardinal number mismatches reflect children's attempts to integrate their understanding of a given number with the numbers immediately above and below it, which may be a critical step in learning the meanings of number words (Barner & Brachrach, 2010). In this case, the contradiction between children's number gestures and spoken number labels may (as in the mathematical equivalence case) be more apparent than real.

Young children's ability to convey precise numerical information more accurately using gesture than speech has been shown only for numbers up to 3 (Gunderson et al., 2015), which means that number gestures may be more likely to predict small number learning than large number learning or acquisition of the cardinal principle. As a result, 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). (We chose to exclude children who do not yet understand "one" because they may be months away from beginning this difficult mapping process). If so, our study would provide the first evidence that any aspect of children's use of cardinal number gestures is relevant to their developing verbal number knowledge.

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, it is surprising that experimental intervention studies designed to accelerate children's learning of number words or the cardinal principle typically have a limited impact. This unexpected finding may reflect the difficulty of providing enough input to make a difference, the fact that the experimentally-manipulated input may not be optimal, or the fact that many children are simply not ready to learn the next number word. Previous intervention studies often lead to improved performance on tasks that closely resemble instruction, rather than to 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).

Nevertheless, 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 tested (6 and 10), which require children to have an understanding of the cardinal principle (Carey, 2009). Since the cardinal principle, by definition, represents a basic understanding of how counting relates to cardinality (Gallistel & Gelman, 1978), it is not surprising that input designed to connect counting to cardinality would benefit children in the process of learning the cardinal principle. What is not yet clear is whether this sort of rich number instruction has an advantage over more counting-focused instruction when teaching children the meanings of individual small number words (i.e., "one," "two," and "three"), the focus of our study. This is an important question since counting without cardinal labeling represents a significant portion of children's early number input (e.g. Gunderson & Levine, 2011) and learning the meanings of the small number words is critical for getting children's verbal number knowledge off the ground.

Another characteristic of rich number instruction that has been relatively unexplored, and may be particularly useful to learning the meanings 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 early number learning, the present study compared two different types of number instruction: one that resembles a common form of input (i.e., counting alone; Mix et al., 2012), and one that incorporates counting, cardinal labeling, and spatially-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 learning 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, which we hypothesized would vary in their effectiveness. 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). This condition was intended to provide a baseline level of improvement given the delay between pretest and posttest and some basic number instruction with an experimenter. 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 addresses some of the unique learning needs of mismatchers.

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 excluded 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 (Spaepen, Gunderson, Gibson, Goldin-Meadow, & Levine, 2018).

Of the 59 one- and two-knowers who were 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), leaving 47 children in the final sample.

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; Spaepen et al., 2018). 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, and each was marked correct or incorrect depending on whether it matched the number of items on the card. 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 and each was considered correct if the number word used or number of fingers held up matched the number of items on the card.

Procedure: Training

Children were randomly assigned to the Counting Condition or Enriched Number Talk Condition (see Figure 1 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".

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 who 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).

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.

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/her 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 2 displays children's speech and gesture accuracy in mismatches produced on the WOC-Gesture and WOC-Speech tasks, combined.

Interestingly, the disparity between the number word and its accompanying gesture in a mismatch stayed within a narrow range. The gestured and spoken number label differed by one on 51 of the 77 mismatches (66%) that children produced during trials immediately above their knower-levels and differed by two on an additional 12 of these 77 trials (16%). The most common type of mismatch that children produced (25 of the 77 mismatches) was a verbal label that was one greater than the target and a gestured label that matched the target (e.g., saying "four" and gesturing three for a set size of three).

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 (assessed at pretest) 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 a child's status as a mismatcher predicted whether the child would profit from instruction. Figure 3 presents the data.

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 the 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 improve from pretest to posttest; $b=.148$, $p=.039$). 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 ($b=-.158$, $p=.303$).

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=0.523).

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=0.588).

Since gesture-speech mismatches when labeling sets may differ from previously studied examples of mismatches (in that the gesture and speech contradict rather than potentially complement one another), we also explored an alternative hypothesis that ability to label sets above one's knower-level *per se* (rather than mismatching) predicted likelihood to learn. In support of this hypothesis, we found that mismatchers were more accurate than non-mismatchers on the WOC-gesture task for the two set sizes immediately above their knower-level (t(45)=−2.14, p=.038). However, nearly every child (46 out of 47 participants) in our sample provided the correct answer in gesture on at least one trial of the two set sizes immediately above their knower-level, suggesting that successfully labeling sets above one's knower level in gesture is not unique to children on the precipice of learning. Likewise, children's accuracy (proportion of trials correct) on the two WOC-Gesture set-sizes immediately above their knower level (*Mean*=0.52, *SD=0.24*) was not related to children's likelihood of learning, either alone (b=−.49, p=.811) or in an interaction with Condition (*b=.35, p=*.285). In contrast, children's mismatching status did interact with Condition and predicted learning in the Enriched Number Talk Condition (controlling for Highest Count and Pretest Knower Level).

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 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 by 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. One interesting aspect of this particular instance of gesture-speech mismatch is that cardinal number gestures are part of a conventionalized system for expressing numerical quantity (Di Luca & Pesenti, 2008). Moreover, the present study differs from previously studied cases of mismatching by focusing on a case in which children's gestures actually contradicted their speech in contrast to previously studied cases in which gestures provide information that can be integrated with the information contained in the accompanying speech (Church & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988; Goldin-Meadow, 2003).

The extent to which the same mechanisms underlie the predictive power of mismatching in various domains is an important and ongoing question. We did find some evidence that children who mismatched were more accurate when labeling the sets above their knower-level in gesture than children who did not mismatch. However, we did not find evidence that knowledge of number gestures above one's knower level predicted learning better than mismatching *per se*. This finding suggests that perhaps the information children convey in gesture and in speech is less contradictory than it may seem. Barner and Bachrach (2010) suggested that children learn the meanings of number words not individually but in relation to other number words. For instance, to learn the meaning of “two” children must learn that “two” has a lower bound of “one” and an upper bound of “three”. In other words, a one-knower would need to learn something about “three,” which is two numbers above their knower-level, in order to advance. Consistent with this possibility, children’s gestured and spoken labels differed by two or less on 82% of the mismatches they produced on sets immediately above their knower-level. Moreover, the most frequent type of mismatch involved children gesturing the correct number while saying the number one greater than the target. Thus, gesture-speech mismatches could be children’s early attempts at bringing their knowledge of nearby set-sizes to bear on the set-size they are currently being asked to label.

The present study provides initial evidence that children’s use of number gestures may in fact be relevant to their developing understanding of number language. However, given the limited sample-size and brief timeline of the current study, future research is needed to corroborate these findings and resolve remaining questions.

Further, the present study cannot tell us whether number gestures play a causal role in children’s acquisition of number language or what exact role they might be playing. 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 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.

Another unresolved question resulting from the brief timeline of this study is whether children who did not mismatch would also have improved in the Enriched Number Talk condition if we had continued providing training sessions, 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). Likewise, the multiple differences between the training conditions make it difficult to conclude whether a specific feature of the Enriched Number Talk training drove the interaction between condition and mismatcher status or if mismatchers would be more likely to learn than non-mismatchers from a broad range of input if given sufficient time. A more nuanced understanding of the individual differences among 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 easily detected and measured, and that have implications for subsequent growth and instruction. Future research will need to explore the nuances of the relation between number gestures and number words, as well as the relation between rote-counting ability and the acquisition of number words. Continuing to investigate how these specific number skills are related to children's understanding of number language will improve not only our understanding of the factors that affect number development, but also our ability to design effective educational interventions to help young children learn foundational number concepts.

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References

Alibali MW, & DiRusso AA (1999). The function of gesture in learning to count: more than keeping track. Cognitive Development, 14(1), 37–56. doi: 10.1016/s0885-2014(99)80017-3

Alibali MW, & Goldin-Meadow S (1993). Gesture-speech mismatch and mechanisms of learning: what the hands reveal about a child's state of mind. Cognitive Psychology, 25(4), 468–523. doi: 10.1006/cogp.1993.1012 [PubMed: 8243044]

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

Barner D (2012). Bootstrapping numeral meanings and the origin of exactness. Language Learning and Development, 8(2), 177–185.

Barner D, & Bachrach A (2010). Inference and exact numerical representation in early language development. Cognitive Psychology, 60(1), 40–62. doi: 10.1016/j.cogpsych.2009.06.002 [PubMed: 19833327]

Barner D, Libenson A, Cheung P, & Takasaki M (2009). Cross-linguistic relations between quantifiers and numerals in language acquisition: Evidence from Japanese. Journal of experimental child psychology, 103(4), 421–440. [PubMed: 19162276]

Bender A, & Beller S (2012). Nature and culture of finger counting: Diversity and representational effects of an embodied cognitive tool. Cognition, 124(2), 156–182. doi: 10.1016/j.cognition.2012.05.005 [PubMed: 22695379]

Bloom P (2002). How Children Learn the Meanings of Words. MIT Press.

Bloom P, & Wynn K (1997). Linguistic cues in the acquisition of number words. Journal of Child Language, 24, 511–533. [PubMed: 9519584]

Butterworth B (1999). A head for figures. Science, 284(5416), 928–929. [PubMed: 10357680]

Butterworth B (2005). The development of arithmetical abilities. Journal of Child Psychology and Psychiatry, 46(1), 3–18. [PubMed: 15660640]

Carey S (2009). The Origin of Concepts. Oxford: Oxford University Press.

Christie S, & Gentner D (2010). Where hypotheses come from: Learning new relations by structural alignment. Journal of Cognition and Development,11(3), 356–373.

Church RB, & Goldin-Meadow S (1986). The mismatch between gesture and speech as an index of transitional knowledge. Cognition, 23(1), 43–71. doi: 10.1016/0010-0277(86)90053-3 [PubMed: 3742990]

Coppola M, Spaepen E, & Goldin-Meadow S (2013). Communicating about quantity without a language model: Number devices in homesign grammar. Cognitive Psychology, 67, 1–25. 10.1016/j.cogpsych.2013.05.003. [PubMed: 23872365]

Davidson K, Eng K, & Barner D (2012). Does learning to count involve a semantic induction? Cognition, 123(1), 162–173. doi: 10.1016/j.cognition.2011.12.013 [PubMed: 22245033]

Di Luca S, & Pesenti M (2008). Masked priming effect with canonical finger numeral configurations. Experimental Brain Research, 185(1), 27–39. doi: 10.1007/s00221-007-1132-8 [PubMed: 17909768]

Di Luca S, & Pesenti M (2011). Finger numeral representations: More than just another symbolic code. Frontiers in Psychology, 2(272), 1–3. doi: 10.3389/fpsyg.2011.00272 [PubMed: 21713130]

Dowker A (2008). Individual differences in numerical abilities in preschoolers. Developmental Science, 11, 650–654.
[PubMed: 18801119]

Duncan GJ, Dowsett CJ, Claessens A, Magnuson K, Huston AC, Klebanov P, Pagani LS, Feinstein L, Engel M, Brooks-Gunn J, Sexton H, Duckworth K, Japel C. School readiness and later achievement. Developmental Psychology 2007;43:1428–1446. doi: 10.1037/0012-1649.43.6.1428 [PubMed: 18020822]

Fuson K (1988). Children’s counting and concepts of number. New York: Springer-Verlag.

Fuson K, Richards J, & Briars D (1982). The acquisition and elaboration of the number word sequence In Brainerd C (Ed.), Progress in cognitive development research Vol. 1: Children’s logical and mathematical cognition (pp. 33–92). New York: Springer
V erlag.

Gelman R, & Gallistel CR (1978). The child’s understanding of number. Cambridge, MA: Harvard University Press.

Gentner D (1982). Why Nouns Are Learned before Verbs: Linguistic Relativity Versus Natural Partitioning. Technical Report No. 257.

Gentner D (1983). Structure mapping: A theoretical framework for analogy. Cognitive Science, 7, 155–170.

Gentner D, & Boroditsky L (2001). Individuation, relativity, and early word learning In Bowerman M & Levinson S (Eds.), Language acquisition and conceptual development (pp. 215–256). Cambridge, UK: Cambridge University Press.

Gentner D, & Gunn V (2001). Structural alignment facilitates the noticing of differences. Memory & Cognition, 29(4), 565–577. [PubMed: 11504005]

Gentner D & Namy LL (2004). The role of comparison in children’s early word learning In. Hall DG & Waxman SR(Eds), Weaving a lexicon (pp. 533–568). Cambridge: MIT Press.

Gleitman LR, Cassidy K, Nappa R, Papafragou A, & Trueswell JC (2005). Hard words. Language Learning and Development, 1, 23–64.

Goldin-Meadow S (2003a). The Resilient of Language: What gesture creation in deaf children can tell us about how all children learn language. N.Y.: Psychology Press.

Goldin-Meadow S (2003b). Hearing gesture: How our hands help us think. Cambridge, MA: Harvard University Press.

Goldin-Meadow S, Levine S, & Jacobs S (2014). Gesture’s role in learning arithmetic Emerging perspectives on gesture and embodiment in mathematics. Charlotte, NC: Information Age Publishing.

Gracia-Bafalluy M, & Noël MP (2008). Does finger training increase young children’s numerical performance?. Cortex, 44(4), 368–375. [PubMed: 18387567]

Graham TA (1999). The role of gesture in children’s learning to count. Journal of Experimental Child Psychology, 74(4), 333–355. doi: 10.1006/jecp.1999.2520 [PubMed: 10552922]

Gunderson EA, & Levine SC (2011). Some types of parent number talk count more than others: relations between parents' input and children's cardinal-number knowledge. Developmental Science, 14(5), 1021–1032. doi: 10.1111/j.1467-7687.2011.01050.x [PubMed: 21884318]

Gunderson EA, Spaepen E, & Levine SC (2015). Approximate number word knowledge before the cardinal principle. Journal of Experimental Child Psychology, 130, 35–55. 10.1016/j.jecp.2014.09.008. [PubMed: 25462030]

Gunderson EA, Spaepen E, Gibson D, Goldin-Meadow S, & Levine SC (2015). Gesture as a window onto children's number knowledge. Cognition, 144, 14–28. doi: 10.1016/j.cognition.2015.07.008 [PubMed: 26210644]

Huang YT, Spelke E, & Snedeker J (2010). When is four far more than three? Psychological Science, 21(4), 600–606. doi: 10.1177/0956797610363552 [PubMed: 20424108]

Iverson JM, & Goldin-Meadow S (2005). Gesture paves the way for language development. Psychological Science, 367–371. doi: 10.1111/j.0956-7976.2005.01542.x [PubMed: 15869695]

Klibanoff R, Levine SC, Huttenlocher J, Vasilyeva M & Hedges L (2006). Preschool Children's Mathematical Knowledge: The effect of teacher "math talk". Developmental Psychology, 42, 59–69. [PubMed: 16420118]

Le Corre M, & Carey S (2007). One, two, three, four, nothing more: An investigation of the conceptual sources of the verbal counting principles. Cognition, 105, 395–438. doi: 10.1016/j.cognition.2006.10.005 [PubMed: 17208214]

Lee MD, & Sarnecka BW (2010). A model of knower-level behavior in number concept development. Cognitive Science, 34(1), 51–67. [PubMed: 20228968]

Mix KS, Sandhofer CM, Moore JA, & Russell C (2012). Acquisition of the cardinal word principle: The role of input. Early Childhood Research Quarterly, 27(2), 274–283. doi: 10.1016/j.ecresq.2011.10.003

Nicoladis E, Pika S, & Marentette P (2010). Are number gestures easier than number words for preschoolers? Cognitive Development, 25(3), 247–261. doi: 10.1016/j.cogdev.2010.04.001

Perry M, Church RB, & Goldin-Meadow S (1988). Transitional knowledge in the acquisition of concepts. Cognitive Development, 3(4), 359–400. doi: 10.1016/0885-2014(88)90021-4

Piantadosi ST, Jara-Ettinger J, & Gibson E (2014). Children's learning of number words in an indigenous farming-foraging group. Developmental science, 17(4), 553–563. [PubMed: 24766463]

Pine KJ, Lufkin N, & Messer D (2004). More gestures than answers: Children learning about balance. Developmental Psychology, 40(6), 1059–1067. [PubMed: 15535756]

Ping R, Larson SW, Decatur M-A, Zinchenko E, & Goldin-Meadow S (under review). Unpacking the gestures of chemistry learners: What the hands tell us about correct and incorrect conceptions of stereochemistry.

Potter MC, & Levy EI (1968). Spatial enumeration without counting. Child Development, 39(1), 265–272. doi: 10.2307/1127377 [PubMed: 5645801]

Ramscar M, Dye M, Popick HM, & O'Donnell- McCarthy F (2011). The enigma of number: Why children find the meanings of even small number words hard to learn and how we can help them do better. PLoS ONE, 6(7), e22501. [PubMed: 21818329]

Sarnecka BW, & Carey S (2008). How counting represents number: What children must learn and when they learn it. Cognition, 108, 662–674. doi: 10.1016/j.cognition.2008.05.007 [PubMed: 18572155]

Sarnecka BW, Kamenskaya VG, Yamana Y, Ogura T, & Yudovina YB (2007). From grammatical number to exact numbers: Early meanings of 'one','two', and 'three'in English, Russian, and Japanese. Cognitive psychology, 55(2), 136–168. [PubMed: 17070794]

Sarnecka BW, & Lee MD (2009). Levels of number knowledge during early childhood. Journal of Experimental Child Psychology, 325–337. doi: 10.1016/j.jecp.2009.02.007 [PubMed: 19345956]

Saxe GB (1977). A developmental analysis of notational counting. Child Development, 48(4), 1512–1520. doi: 10.2307/1128514

Saxe GB, & Kaplan R (1981). Gesture in early counting: A developmental analysis. Perceptual and Motor Skills, 53(3), 851–854. doi: 10.2466/pms.1981.53.3.851

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

Spaepen E, Coppola M, Spelke ES, Carey SE, & Goldin-Meadow S (2011). Number without a language model. Proceedings of the National Academy of Sciences, 3163–3168. doi: 10.1073/pnas.1015975108

Spaepen E, Gunderson EA, Gibson D, Goldin-Meadow S, & Levine SC (2018). Meaning before order: Cardinal principle knowledge predicts improvement in understanding the successor principle and exact ordering. Cognition, 180, 59–81. doi:10.1016/j.cognition.2018.06.012 [PubMed: 30007878]

Suriyakham LW (2007). Input effects on the development of the cardinality principle: Does gesture count? Doctoral dissertation, University of Chicago.

Wynn K (1990). Children's understanding of counting. Cognition, 36, 155–193. doi: 10.1016/0010-0277(90)90003-3 [PubMed: 2225756]

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

Research Highlights

- Children frequently use cardinal number gestures (e.g., hold up three fingers to indicate “three”) when communicating about numbers.
- Children who produced gesture-speech mismatches when labeling numbers (e.g., held up three fingers but said “two”) were particularly likely to learn a new number word when provided with rich number instruction.
- Learning depended not only on child’s readiness to learn (as indexed by the production of gesture-speech mismatches), but also on the quality of the number instruction.
- Mismatching indicates that a child is ready to learn new number words from high-quality input, indicating, for the first time, that cardinal number gestures may play a role in numerical development.

Figure 1.
Example stimuli used in Enriched Number Talk (left panel) and Counting Training conditions (right panel).

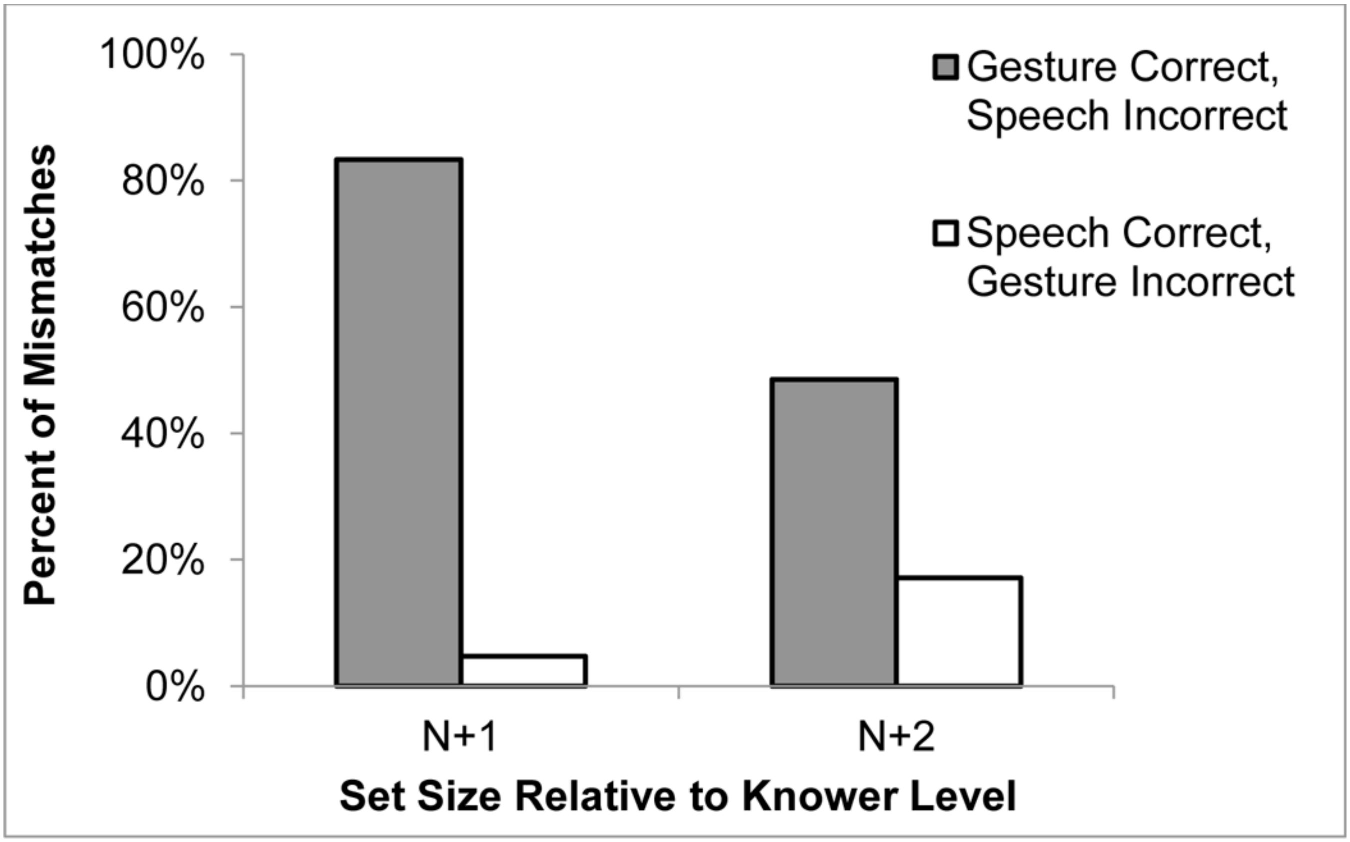

Fig. 2.
Accuracy in speech and gesture during mismatches.

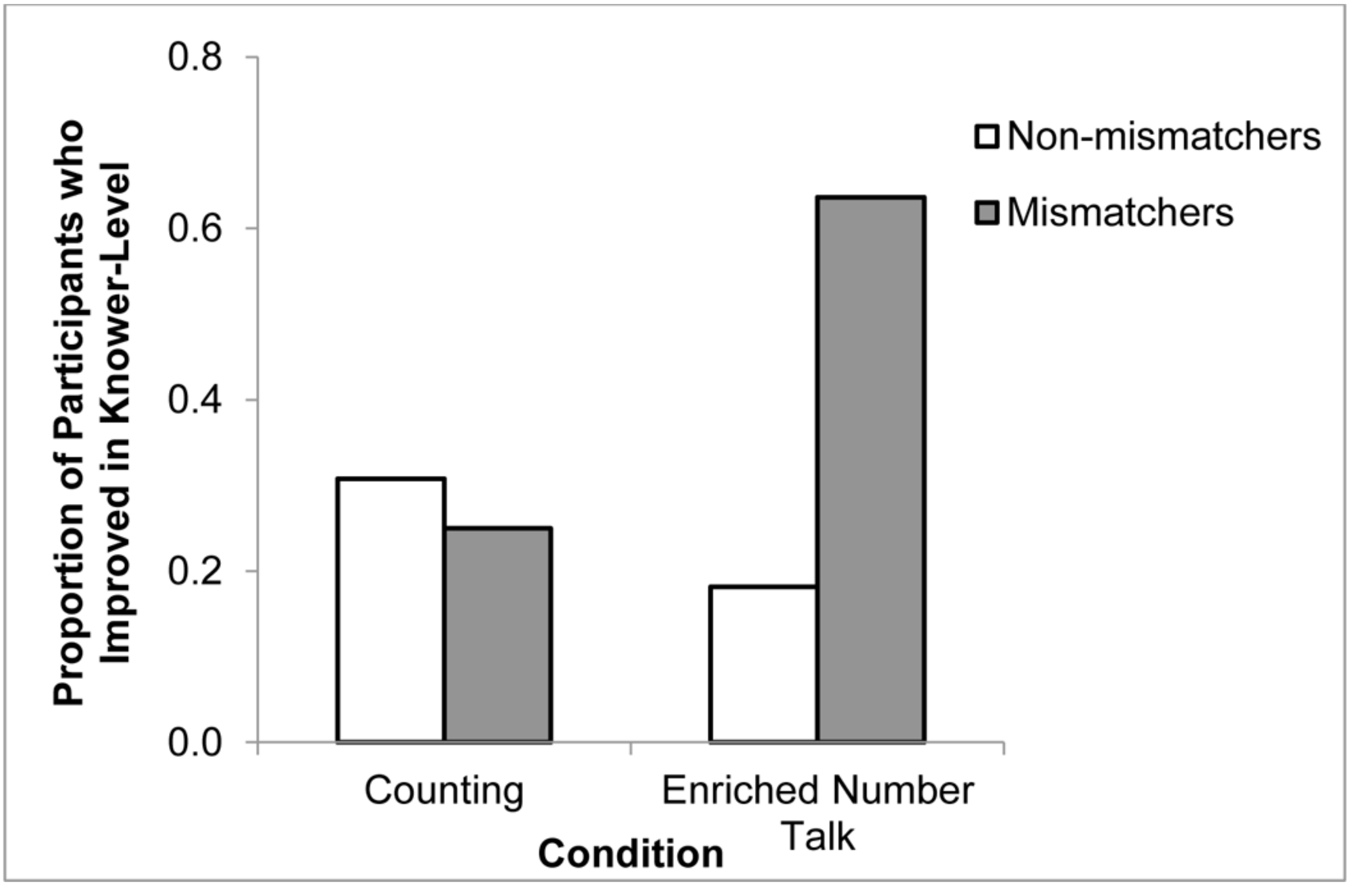

Figure 3.
Proportion of children who improved in knower level by Condition and Mismatching Status.

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

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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

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

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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