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The Development of Language and Abstract Concepts: The Case of Natural Number

Kirsten F. Condry and Elizabeth S. Spelke

Harvard University

Correspondence: Elizabeth Spelke
Department of Psychology
Harvard University
1130 William James Hall
Cambridge, MA 02138
Email: spelke@wjh.harvard.edu

Abstract

What are the origins of abstract concepts such as *seven*, and what role does language play in their development? To address these questions, experiments probed the natural number words and concepts of three-year-old children who can recite number words to “ten” or beyond but produce an appropriate number of objects only when asked for “one” or “two.” Children judged correctly that a set labeled “eight” retains this label if it is unchanged, that it is not also “four,” and that “eight” is more than “two.” In contrast, children failed to judge that a set of eight objects is better labeled by “eight” than by “four,” that “eight” is more than “four,” that “eight” continues to apply to a set whose members are rearranged, or that “eight” ceases to apply if the set is increased by one, doubled, or halved. The latter errors contrast with children’s correct application of words for the smallest numbers. These findings suggest that children interpret number words by relating them to two distinct preverbal systems that capture only limited numerical information. In order to master number words and counting, children must construct the system of abstract, natural number concepts from these foundations.

Keywords: Language and thought, Number concepts, Cognitive development, Mathematics education

The Development of Language and Abstract Concepts: The Case of Natural Number

Human science, technology, economics, and other cultural achievements depend on systems of abstract concepts, especially the rich system of number concepts that supports counting, arithmetic, and the measurement of space and time. Before children begin formal schooling, most have developed a robust system of natural number concepts, expressed by the words of their verbal counting routine (Case & Griffin, 1990; Gelman & Gallistel, 1978; Siegler, 1991). Such children understand that each number word picks out a set of individuals, with one more individual than the set designated by the preceding count word. They can use verbal counting to perform the numerical operations of addition and subtraction (e.g., Carpenter, Moser, & Romberg, 1982; Siegler, 1991), and they understand that addition and subtraction change the cardinality of a set and hence the application of a number word (Lipton & Spelke, 2006). Their representations of number connect intimately to representations of space via a mental “number line” (Temple & Posner, 1998). Finally, many children understand that the natural numbers have no upper bound (Gelman, 1993), and that even number words to which they cannot count reliably pick out sets with specific cardinal values (Lipton & Spelke, 2006). Findings such as these have led some developmental psychologists to suggest that humans are innately predisposed to form natural number concepts (Dehaene, 1997; Gelman & Gallistel, 1978; Wynn, 1990; 1992).

Research exploring this suggestion has investigated the numerical abilities of human infants and non-human primates. The findings of this research provide evidence for two core systems capturing numerical information. One system serves to represent a set of individuals exactly and in parallel, with an upper bound of 3 to 4 objects or events (hereafter called the "small, exact number system": Feigenson & Carey, 2005; Hauser, Carey, & Hauser, 2000). The other system serves to represent sets of individuals with no clear upper bound and with a ratio limit on discriminability (hereafter, the “large approximate number system”: Brannon, Abbott, & Lutz, 2004; Hauser, Tsao, Garcia, &

Spelke, 2003; Lipton & Spelke, 2004). These findings suggest that knowledge of number develops from its own, inherent foundations. Because natural numbers show neither the set size limit of the small exact number system nor the ratio limit of the large approximate number system, however, something beyond these systems is required in order for children to gain entry into the world of natural number.

Natural language is often claimed to meet this requirement, both through its system of recursive rules (Chomsky, 1980) and through the verbal counting routine that children master during the preschool years (Carey, 2001; Mix, Huttenlocher, & Levine, 2002; Spelke, 2000; see Mix, Sandhofer, & Baroody, 2005, for review). By two to three years of age, and sometimes younger, children begin to count. When they are presented with a plate of cookies and asked, “How many cookies are on this plate?” they may exhibit their counting skill by pointing successively to each cookie while reciting an ordered list of number words (Gelman & Gallistel, 1978; Wynn, 1990). At this stage, however, children have limited understanding of number word meanings (Case & Griffin, 1990; Fuson, 1988; Mix et al., 2002; Wynn, 1990).

The limits of children’s understanding appear most clearly in experiments by Wynn (1990; 1992). After children counted a set of objects, they were asked to give the experimenter a specific number of objects. Most 2.5-year-old children produced a single object when asked for “one,” even in a context with no overt plural marker, and produced more than one object when asked for other numbers. In contrast, most children produced a handful of objects when asked for “two,” “three,” or other numbers designated by words that the children themselves had produced during counting; the numbers children produced bore no relation to the number words used in the request (Wynn, 1990). Even in a simpler task, in which children simply had to choose which of two pictures depicted (e.g.) “three fish,” children chose at random when presented with pictures of two and three objects; they succeeded in picking the array of three objects only when the contrasting array depicted a single object. All these findings provide evidence that children understood that “one” refers to a single individual and that other number words contrast with “one” in reference. Nevertheless, children evidently did not understand the reference of the other words in their own count list.

Further research by Wynn (1992) provides evidence that children come to master the reference of number words in a series of steps over a period of about 18 months. Many months after mastering the reference of “one,” children learn that “two” picks out a set of two objects. Then they learn the reference of “three.” Later still, children work out the logic and purpose of the counting routine and begin to use counting to produce the correct number of objects when tested with any of the number words in their counting routine. This protracted course of development is striking because children of this age are prodigious word learners, acquiring enduring representations of the meanings of many novel words in a single session (e.g., Carey & Bartlett, 1978; Markson & Bloom, 1997; Baldwin, 1991). Moreover, children readily and happily recite the number words as part of their counting routine, they quickly master part of their application (i.e., that number words above “one” do not apply to sets of just one object), and they use number words such as “two” in certain appropriate, though restricted, contexts (e.g., “two shoes”: Mix, 2002). Children’s failure to master the reference of number words therefore cannot plausibly be attributed to lack of exposure, attention, or interest.

The present research aims to shed light on the origins and development of children’s number concepts by distinguishing between two general accounts of children’s developing understanding of number words and the verbal counting routine. According to one family of accounts (Carey, 2001; Spelke, 2000), children initially have no understanding of the logic of the natural number system, and they construct this understanding by building on concepts that derive from the two nonsymbolic number systems described above: the concept *numerically distinct individual,* which arises from the small exact number system, and the concept *set,* which arises from the large approximate number system and supports the quantificational system of natural language.

On this view, “one” does not initially designate a set with one member but rather a single entity (it is roughly synonymous with “a” or “an”), and all the other number words initially designate collections of entities with an indeterminate cardinal value (roughly synonymous with the plural marker “s”). Over the course of learning verbal counting, on this view, children combine these concepts to construct the system of natural number. They learn, in sequence, (a) that “two” designates a set composed of an individual *A* and a numerically distinct individual *B,* (b) that “three” designates a set composed of numerically distinct individuals *A*, *B,* and *C,* (c) that a set of “three” can be formed from a set of “two” by the operation of *adding one*, and finally (d) that every count word designates a set of individuals with a unique cardinal value that exceeds, by *one,* the set designated by the previous word.

According to the second account (Gallistel & Gelman, 1990; Gelman & Gallistel, 2004; Pica, Lemer, Izard, & Dehaene, 2004; Wynn, 1990), children have an innate understanding of the logic of the natural number system, embodied in their system for representing large approximate numerosities. On this view, the large approximate system shows all the logical features of natural numbers: It is iterative, its internal states are in 1:1 correspondence with the items to be enumerated, and it represents each numerosity as a unique cardinal value. Children are not able to determine accurately the exact numerosity of any sets larger than three or four, however, because noise in the large-number system precludes discriminating higher numbers precisely. Nevertheless, children understand that each large set of objects has some unknown but determinate cardinal value, and that the cardinal value of a large set will change (albeit imperceptibly) if a single individual is added to or removed from the set.

On the second view, the verbal counting routine allows children to overcome the ratio limit to their discrimination of cardinal values, but it is difficult to learn because the counting procedure obscures the reference of count words (Mix et al., 2005; Wynn, 1992). When a child counts an array of six objects by pointing to each object in turn while reciting the words of the count list, each word is applied to single object, in the presence of the set of six objects, yet the words from "two" to "five" name neither the individual objects nor the cardinality of the full set. Instead, they specify the order of pointing and the cardinality of the subset of objects to which the child has pointed thus far. Although the logic of natural number is apparent to children from the beginning, on this view, the reference of each number word is obscured by noise in the large, approximate number system and by the complexity of the counting routine.

The second account posits that the cognitive state of a child who does not understand verbal counting is like that of an adult who is asked to apply her number concepts to large arrays of objects that she cannot count. Imagine, for example, that an adult is presented with two jars of marbles. If she is asked to point to “the jar with 371 marbles” when the numbers of marbles in the two jars differ minimally, she can only pick at random. The adult nevertheless would succeed at a variety of other verbal number tasks. In particular, if she were asked to estimate how many marbles were in each jar, she would be more apt to respond with “four hundred” than with “four” or “forty”: even without counting, she can map number words to approximate numerical values. If she were told that there were "371" marbles in one jar, she would know that there were not "372" marbles in that jar, for each distinct number word picks out a distinct cardinal value. If the marbles in the jar were stirred but nothing was added or removed, she would know that the same number word applied to the jar’s contents. Finally, if some marbles were removed from or added to the jar, she would know that the jar no longer held “371” marbles, for the application of a number word is changed by addition and subtraction.

Research by Lipton and Spelke (2006) provides evidence that five-year-old children, who have mastered number word reference at least to “twenty” and who use counting to determine exact cardinal values, appreciate all these aspects of number word meanings. Children who had not mastered the base system of count words, could not count to 80, and could not judge whether “eighty” or “sixty” designated a larger value, were shown a jar and were told that it contained “eighty” objects. These children then judged that the jar still contained “eighty” objects when it was shaken or when one object was removed and a different object replaced it, and that it did not contain “sixty” objects. Finally, they judged that the jar did not contain “eighty” objects when a single object was removed, or after a sequence in which one object was removed, a second object replaced it, and then the original object was returned. These findings provide evidence that five-year-old children have mastered the logic of number word reference, and that their mastery extends beyond their counting skill. Nevertheless, the findings do not reveal whether younger children, who have not yet mastered the logic of the verbal counting routine, have a similar understanding.

Answering this question could contribute to the debate over the origins of natural number concepts. Considerable research reveals that children use lexical contrast to work out the meanings of new words within a semantic domain for which they possess the relevant concepts. For example, children who know the meaning of “red” can learn, in a single session, the reference of a new color term like “chromium,” if they are presented with red and green objects and asked for “the chromium one, not the red one” (Carey & Bartlett, 1978). This learning ability shows that children possess a set of color concepts, understand that distinct colors are contrastive (i.e., a single uniformly colored object cannot be both red and green), and draw on this understanding in working out the reference of new color terms.

If the logic of natural number is innate and only the verbal counting routine must be learned, then children also should pass the above tasks, once they have mastered the reference of the first few words in their count list. For example, children who understand the reference of “two,” and who take “two” and “six” to contrast in meaning, should infer that “six” picks out a specific cardinal value, even though they have no means to determine which visible sets have exactly six members. In contrast, if natural number concepts are constructed during or after learning to count verbally, then children who have not yet mastered the logic of verbal counting should fail to appreciate that the later words in their count list pick out specific cardinal values. Although children may appreciate that "two" and "six" contrast in reference, they should fail to understand that the basis of this contrast is *numerical*.

To date, research provides mixed evidence concerning young children's partial knowledge of number word meanings. In one experiment (Sarnecka & Gelman, 2004), three-year-old children were told that an array contained "six" elements, a single element was removed, and then they were asked whether the array contained "five" or "six" elements. Children tended to respond correctly, consistent with the thesis that they understand that each number word picks out a specific, unique cardinal value. In a second experiment, however, children were shown two arrays that either differed in number (six vs. five elements) or were the same in number (both six elements). After they judged, correctly, that a pair of arrays was numerically equal or different, they were told that one array contained "six" elements. When children then were asked whether the second array contained "five" or "six" elements, their judgments were unaffected by the equality or inequality of the two arrays. In light of these conflicting findings, it is not clear whether children master the logic of number word reference before, or after, they master the system of verbal counting.

The present experiments addressed this question. Like Sarnecka and Gelman (2004), we focused on children who could recite the first eight or more words in the count list, but who failed to understand the counting routine or the reference of words for all but the smallest numbers. Six experiments probed children's understanding of the number words that they produced in their count list: both those whose reference they had mastered (e.g., "one" and "two") and those that they failed to map to the correct cardinal values (e.g., "five" and "ten"). In the first experiment, we asked whether children understand that each number word contrasts in reference with other number words but not with the quantifier "some" or with adjectives. Our findings provide evidence that children make this contrast at every point in their mastery of counting, replicating and extending Wynn (1992) and setting the stage for our studies of children's understanding of number word meanings. In Experiment 2, we asked whether children map each number word to an approximate numerical value. In Experiment 3, we asked whether children understand that number words occurring later in the count list refer to larger numerosities. In the remaining experiments, we asked if children appreciate that a number word no longer applies to a set after the set is transformed by addition or subtraction, whereas it continues to apply to a set after its objects are rearranged.

Experiment 1

Experiment 1 investigated whether 3-year-old children infer that different words in their count list apply to different arrays of objects, but that a given number word can apply to the same array of objects as do other quantifiers and adjectives. In light of Wynn's (1990, 1992) findings that children who understand only the meanings of "one" and "two" take the other words in their count list to contrast with "one" and "two" in reference, we investigated whether children also take the later words in their count list to contrast in reference. Do children infer that an array labeled "five fish," is not also an array of "six fish," although it may be an array of "some fish" or "happy fish"?

Method

This experiment and all its successors consisted of a counting pretest, designed to assess children's ability to recite the number words, in order, to "twenty," a pretest of number word reference, designed to determine which number words designate correct cardinal values for each child, and then the critical test of children's understanding of number word meaning. Performance on the critical test was analyzed only for children who could recite the count list without error at least to "eight," who passed the test of number word reference for "one," and who failed the test of number word reference for all number words above "four." In the main text, performance of all such children is analyzed as a single group. In the supporting online materials, performance of children who differed in counting skill or number word knowledge is compared.

Participants. Thirty-two 3- to 3.5-year-old children (15 males) ranging in age from 37.0 to 42.3 months (mean age 38.7 months) took part in either the numerical contrast group (n = 16) or the non-numerical contrast group (n = 16). Children were recruited from birth records and by letter and phone from the greater Boston area. An additional 12 children participated in the experiment but were excluded from the analyses for failure to complete enough test questions (*n*=5), failure to produce a count sequence (*n*=1), or for ceiling performance on the give-a-number pretest (*n*=6).

Displays. Pretest materials consisted of 20 1" (2.5cm) multi-colored plastic fish and a small, rectangular cardboard box. Displays for the numerical contrast group consisted of 4" x 8" (10 x 20cm) cards with familiar 3D objects (e.g., horses, stars) glued onto them. Cards were presented in pairs containing identical objects in sets of varying numerosity. On the two trials contrasting "one" with a different number word, the two cards depicted objects whose labels lacked an overt plural marker (e.g., sheep). Displays for the non-numerical contrast group consisted of color images of familiar animals printed on 8" x 11" (20 x 28cm) paper. Pictures were presented in pairs depicting animals of different colors (e.g., one picture of 10 red sheep and one picture of 5 blue sheep).

Design. Children who could count at least to "eight" in the counting pretest, but who failed to respond correctly to numbers requested beyond "four" in the give-a-number pretest, were included in the experimental session. For the numerical contrast group, children were presented with a total of 18 trials divided into two conditions defined by the type of words tested: (a) a known number word condition (6 trials, in which one of the sets contained a number of objects that the child named reliably on the give-a-number pretest), and (b) an unknown number word condition (12 trials, number pairs 3 vs. 6 and

4 vs. 8 for 2-knowers and 4 vs. 8 and 5 vs. 10 for 3-knowers, with numbers differing by a 2:1 ratio). The test session was divided into three types of questions: Same-number word questions, different-number word questions, and *some* questions (6 trials each, 4 with unknown number words). On half the trials in each condition, the number word produced by the experimenter designated the larger set. For the non-numerical contrast group, children were presented with 8 to 10 trials each in two conditions defined by the type of comparison the child saw: (a) number-number and (b) number-adjective. The number words used in the test session were "five," "seven," "nine," and "ten," which were produced by all children during the counting pretest and fell outside each child's known number word range; no known number words were tested in this part of the experiment. The adjectives were "happy," "hungry," "smart," and "brand-new": words that were found in informal pretesting to be familiar to children but whose reference to either of the two arrays of objects was ambiguous with respect to the visible properties of those arrays (which showed animals of indeterminate mood or state).

<u>Procedure.</u> The child entered the study room with his/her parent and was seated across a small table from the experimenter. A coder was seated to the side at a small table and recorded the child's responses. Video cameras, one focused on the child's face and the other on the experimenter's face, recorded the test session for future recoding and analysis of possible experimenter bias.

For the counting pretest, the experimenter placed 20 toy fish on the table in front of the child and asked the child to count the fish out loud. If a child refused to count, the experimenter prompted the child by beginning the count sequence, saying, "one, two…" while pointing to fish. Children were not probed to continue counting after they reached 20. For the give-a-number pretest, the experimenter placed 15 toy fish on the table in front of the child and identified a small blue box as "the pond where some fish like to swim." Then the experimenter asked the child to put a particular number of fish in the pond. The pretest always began with the experimenter asking for "one fish," followed by

2, 3, 4, 5 and 6 fish in an irregular order (never consistently ascending or descending). Once the child failed to give a number accurately, the experimenter asked for the number below the failed number and then asked for the failed number again. If a child succeeded once and failed once at a particular number, the number was probed a third time as a tiebreaker. Thus, a child who successfully gave 1, 2, and 3 objects but failed twice to give 4 objects was coded as a "3-knower" based on this pretest. If a child failed to produce a number correctly by producing a previous number, this was considered a failure at both the requested number and the produced number (e.g., a trial on which a child produced 3 objects when asked for 4, was scored as a failure for both 3 and 4). Number words inside each child's known number word range are referred to hereafter as *known number words*; the other words that the child produced while counting are referred to as *unknown number words.*[i]

For the test session, the experimenter placed a pair of cards in front of the child, at least 8" (20cm) apart, and identified the objects while pointing to both cards (e.g., "Look at these sheep"). On all the numerical contrast trials, the experimenter then pointed to the target card and identified it by number twice while calling attention to the other card ("This card has *ten* sheep, there are *ten* sheep here, and this card has sheep as well"). The experimenter removed her hands from the cards and asked the child one of three questions. On same-word questions, the experimenter asked the child to point to a picture designated by the same number word she had just used (e.g., "Can you point to a card with *ten* sheep?"). On different-number questions, the experimenter asked the child to point to a picture designated by a different number word (e.g., "*five* sheep"). On *some* questions, the experimenter asked the child to point to a card with "*some* sheep." On the non-numerical contrast trials, the initial picture was identified by either a number word or an adjective (e.g., "This picture has *hungry* sheep") and the child was then asked to point to a card with the other type of modifier ("Can you point to a picture with *five* sheep?"). In each condition for both the numerical and non-numerical contrast groups, the different types of questions occurred in a quasi-random, intermixed order such that a single type of question did not occur twice in succession; the specific order of questions was varied across children. On all trials of this and the subsequent experiments, the experimenter was careful to look only into the child's eyes when asking the question to avoid cueing the child to an answer. Generalized positive feedback was given on every trial regardless of the accuracy of the child's choice (e.g., "Thank you" or "Nice job"). If a child refused to point, the experimenter repeated the question and asked the child to either touch or hand the experimenter the picture. If the child continued to refuse, the question was dropped from the analyses and the experimenter moved on to the next question.

Analyses. Trials were included in the analysis only if they tested numbers that children spontaneously produced on the counting pretest. Trials were categorized as known or unknown number word trials in accord with the child's performance on the give-a-number pretest. For example, a test question contrasting 3 vs. 6 was coded as an unknown number trial for a child categorized as a two-knower on the give-a-number test, and as a known number trial for a child categorized as a three-knower.

Children's responses were coded as the proportion of trials on which the child chose the target card (which had just been identified by the experimenter). For the numerical contrast group, the mean proportion of target responses was analyzed by a 3 (Question: same-number vs. different-number vs. *some*) x 2 (condition: known vs. unknown number word) x 2 (sex) mixed-factor analysis of variance (ANOVA), with the last factor between subjects. A second analysis for the numerical contrast group compared responses in the unknown number word condition only by means of a 3 (Question: same-number vs. different-number vs. some) x 2 (sex) mixed factor ANOVA with the last factor between subjects. For the non-numerical contrast group, the ANOVA factors were 2 (Question: same-word vs. different-word) and 2 (Condition: number word vs. adjective). Two-tailed t tests compared performance in each condition to chance (50%). Further t tests compared performance on unknown number words across the two groups based on type of contrast: wholly numerical (number vs. number), quantificational (number vs. *some*) and non-numerical (number vs. adjective).

Results

Pretests. On the counting pretest, all children produced every number word from one to ten. On the give-a-number pretest, of the 32 children included in the final analyses, 2 were 1-knowers, 16 were 2-knowers, 9 were 3-knowers, and 5 were 4-knowers. No child in this or later experiments succeeded on a particular number word on the give-a-number pretest without also passing the test for the previous number words.

Main experiment. Children's performance is depicted in Figures 1a and 1b. In the known number word condition, children always chose the originally labeled card when tested with the same word, and they almost always chose the other card when tested with a different number word. The same patterns were observed, though somewhat less strongly, in the unknown number word condition. Performance differed from chance for both types of questions and for both known and unknown number words (all ts $(15)>3.65$, all ps$<.01$, $h^2=0.974$). In contrast, children chose the two arrays at random when asked for a card with *some* items or for a card with *happy* items. The analysis of the unknown number word trials of the numerical contrast condition revealed a main effect of question ($F(2, 13)=61.25$, $p<.001$, $h^2=.904$), reflecting the fact that children rejected the target differently depending on whether they were asked for the same number, a different number, or *some*. A further analysis revealed that children avoided a card with a single object when asked for *some* items: Children chose the target card on only 20% of trials when the target card depicted one object. Thus, children tended not to apply the word *some* to arrays containing one object but otherwise applied this term indiscriminately to arrays that were or were not first designated by a known or unknown number word. The analysis of the non-numerical contrast condition revealed only a main effect of condition (F $(1,14)=16.38$, $p<.001$, $h^2=0.539$), reflecting children's greater rejection of the target on number-number trials (74%) than on number-adjective trials (57%).

Finally, a further analysis compared the performance of children showing different levels of counting skill and number word mastery on the two pretests (see supporting online materials). Children's performance was unaffected by the length and accuracy of their count list. In contrast, performance on the number-number trials was higher for children categorized as "three-knowers" and "four-knowers" than for those who had mastered the reference only of "one" and "two." Across several experiments, nevertheless, even the children who had mastered only one or two number words tended to use all the words in their count list both stably and contrastively (see supporting online materials).

Discussion

The findings of Experiment 1 replicate and extend those of Wynn (1992). They provide evidence that 3-year-old children, who have not mastered the exact reference of most number words in their counting lists, take those number words to contrast in meaning both with known and with other unknown number words. Children who were told that a set contained "five" objects chose a different set when asked to point to "ten" objects. This performance does not reflect a general bias to point to an unlabeled set, because children did not tend to choose the unlabeled set when asked for a different quantifier ("some sheep") or an adjective ("happy sheep"). In particular, children appeared to interpret "some" as referring to any sets larger than one, whether or not those sets were previously designated by a word in their counting list. Similarly, children were equally likely to apply non-numerical adjectives to both labeled and unlabeled sets. These findings provide evidence that children's number words, like their color terms (Carey & Bartlett, 1978), form a domain in which different number words contrast specifically with one another. The findings do not reveal, however, whether the basis for the contrast is *numerical* (i.e., different count words apply to sets with different cardinal values), *non-numerical but quantitative* (e.g., different count words apply to sets containing differing amounts of material), or *non-quantitative* (e.g., different count words apply to sets in different locations, or to sets of different objects).

These findings set the stage for the present tests of the origins of natural number concepts. If humans possess the system of natural number concepts prior to learning counting, then children like those in Experiment 1, who have learned the reference of the first few number words and who take all the words in their count list to contrast in meaning, should appreciate that each word in the count list has numerical content. Although children lack an effective procedure for determining the exact cardinal values of arrays of objects, they might be able to map number words to approximate numerosities (Experiment 2), judge that words later in the list designate larger numerosities (Experiment 3), and change their application of a number word when elements are added to or removed from the set that it designated (Experiments 4-6). The remaining experiments test for these abilities.

Experiment 2

Children who recited the number words at least to "ten," but who failed to show mastery of the reference of any number words beyond "four," were shown two arrays of objects. The arrays differed in cardinal value by a 2:1 ratio, and both cardinal values could be labeled by words that the children produced in the correct order when counting: for example, arrays of five four vs. ten eight objects. Children then were asked to point to the array with "five" or with "ten" objects. Because sets differing by a 2:1 ratio are discriminable even by infants (e.g., Brannon, 2002; Xu & Spelke, 2000), children who have mapped the words in their counting routine to approximate numerical magnitudes should succeed at this task.

Method

The method was the same as for Experiment 1, except as follows.

Participants: Participants were 16 3- to 3.5-year-old children (8 males) ranging in age from 36.5 to 40.2 months (mean age 37.6 months). An additional 8 children participated in the experiment but were excluded from the analyses for failure to complete enough test questions (*n*=2), ceiling performance on the give-a-number pretest (*n*=1), low counting (*n*=2) or failure to produce a count sequence (*n*=3) in the counting pretest.

Displays: Displays for the main experiment consisted of color pictures of familiar animals printed on 8" x 11" (20 x 28cm) paper. Pictures were presented in pairs containing identical objects in sets that varied by at least a 2:1 ratio. Both pictures depicted sets whose cardinal values were named by words that the child herself produced in the counting pretest.

Design: After the counting and give-a-number pretests, children were presented with 10 to 20 trials in the test session. For each trial, the experimenter presented a pair of pictures and asked the child to point to a picture designated by one of the two appropriate number words. On known number word trials, at least one array presented a cardinal value named by a word that the child had fully mastered ("one," "two," and for some children, "three" or "four"). On unknown number word trials, both arrays presented cardinal values named by words that the child produced on the counting pretest but failed to comprehend on the give-a-number pretest (for most children, 4 vs. 8 and 5 vs. 10; for children who were 2-knowers, the unknown number word pairs also included 3 vs. 6). In each category, the experimenter asked for the larger array on half the trials.

Procedure: For the test session, the experimenter placed a pair of pictures in front of the child, as in Experiment 1, and identified the objects while pointing to both pictures ("Look, I have pictures of sheep here"). After removing her hands from the pictures, the experimenter asked the child to point to the picture with a particular number of objects (e.g., "Can you point to the picture with *eight* sheep?"). The session was ended when 20 questions were completed, or once the child refused to answer any more questions.

Analyses: Only test trials presenting numbers whose count words were produced by the child during the counting pretest were included in the final analyses of the test session. Children's responses were scored as correct/incorrect and each question was coded with regard to each child's known number word range. Mean correct responses were compared across the two types of trials with a 2 (trial type: known vs. unknown number words) x 2 (sex) repeated measures ANOVA with the last factor between subjects. Two-tailed t tests compared performance in each condition to chance (50%).

Results

Pretests. All children in the final sample counted at least to ten. Three of the 16 participants were categorized as 1-knowers, 8 as 2-knowers, 4 as 3-knowers, and 1 as a 4-knower.

Test session. For the main experiment children performed well on known number trials (mean proportion correct=0.86, SD=0.18, $t(15)=8.08$, $p<.001$) but at chance levels on unknown number trials (mean proportion correct=0.49, SD=0.35, $t(15)<1$, NS). The analysis revealed only a significant main effect of Trial type, $F(1,14)=13.02$, $p<.001$ ($h^2=0.473$), reflecting children's lower levels of correct responding when both sets presented numbers of elements for which the number word was unknown. This difference was confirmed by a non-parametric analysis (Wilcoxon matched-pairs signed-rank test $z = 2.9$, $p<.01$).

Discussion

Experiment 2 provides evidence that children who have not mastered the exact meanings of their counting words also do not map those words onto representations of approximate numerosity. This failure cannot be attributed to a failure to discriminate between the two numerosities, because the numerosities presented on each trial differed by a ratio that even infants can discriminate (Xu & Spelke, 2000). The failure also cannot be attributed to a failure to recognize or order the number words, because all the number word pairs probed in this study were spontaneously produced by the children in the correct order when they were asked to count. The failure cannot be attributed to lack of understanding of the task or lack of motivation to perform it, because children succeeded robustly on the same task when tested with a known number. Finally, children's failure cannot be attributed to a lack of attention to, or processing of, the unknown number word, because children performed well when queried with an unknown number word, provided that the contrasting set presented a cardinal value designated by a known number word. Children accurately pointed to a picture of ten sheep when asked for "ten" and shown a comparison picture presenting one or two sheep, but they succeeded no better than chance when the comparison picture depicted a set of five sheep. Although one can never be certain that an ability is wholly absent at a particular age, the present findings provide evidence against the thesis that children endow all the words in their count list with (approximate) numerical meaning.

In the next study we continue to address this issue by investigating whether the words in children's counting routine have weaker numerical meaning. Children may understand that the counting words are ordered, such that words that appear later in the count list refer to larger numerosities, even if the ordinal list is poorly calibrated to true numerical values. This possibility is not implausible, because both adults and older children show monotonically increasing but poorly calibrated functions when they give verbal estimates of large numerosities (Izard, 2006; Lipton & Spelke, 2005). Accordingly, Experiment 3 tested children's understanding of the ordering of the numerosities conveyed by the words in their count list.

Experiment 3

In Experiment 3, children were told to imagine that they and the experimenter had different numbers of objects (with the numbers conveyed only verbally), and they were asked who had more objects. If children understand that unknown number words designate higher numbers than known number words, then a child who can count to ten but only has mastered the reference of "one" and "two" should judge that a person with "seven" objects has more objects than a person with "two" objects. If children also understand that unknown number words occurring late in the count list designate higher numbers than those occurring earlier in the count list, then children also should judge that a person with "ten" objects has more objects than a person with "five" objects.

Method

The method was the same as Experiment 1 except as follows.

Participants. Sixteen 3- to 3.5-year-old children (8 males) ranging in age from 36.9 to 42.0 months (mean age 39.0 months) took part in the study. An additional 7 children were excluded from the experiment for failure to complete enough test questions (n=4) or ceiling performance in the give-a-number pretest (n=3).

Displays. Displays for the main experiment consisted of four pictures containing an image of a familiar object (a single apple, butterfly, rock, or flower) presented on 8 x 11" (20 x 28cm) paper.

Design. Each child was presented with 12 trials in two conditions: known number words (4 trials) and unknown number words (8 trials). The former trials tested the number pair 2 vs. 7, while the latter trials were chosen from the pairs 4 vs. 8, 5 vs. 10, and 6 vs. 12 based on the child's pretest performance. The order of the number words presented (larger first vs. smaller first) and the pairing of number words with characters (child has more vs. experimenter has more) were counterbalanced across trials. One known number word and two unknown number word trials were presented with each of four types of objects. The number word pairs used in the test session were produced by all children, in the correct order, during the counting pretest. Children who did not complete at least 4 trials in each condition were excluded from the analyses.

Procedure. After the counting and give-a-number pretests, children were shown the first of four pictures (e.g., an apple) that served as the theme for three trials each. The experimenter told the child a short, three-sentence story that began with an introduction of the theme (e.g., "Let's pretend that we went apple picking"). In the next sentence, two number words were presented in contrast to each other (e.g., "I picked 8 apples and you picked 4 apples"). Then the experimenter asked the child, "Which is more: 8 or 4?". If the child failed to answer or responded that he did not know, the experimenter asked if he would like to hear the story again and repeated the trial. If the child again answered that he did not know, that answer was coded as incorrect. Each child's test session began with a warm-up question with the pair of number words 1 v. 3 (e.g., "Let's pretend that we went apple picking. I picked 3 apples and you picked 1 apple. Which is more: 3 or 1?") that was not analyzed. (All participants answered the warm-up question correctly.)

Analyses. Children’s responses were coded as the proportion of correct responses when asked which number was more. Mean correct responses were analyzed by means of a 2 (condition: known vs. unknown number word) x 2 (sex) mixed factor ANOVA, with the last factor between subjects. Two-tailed t-tests compared responses in each condition to chance (50%).

Results

Pretests. On the counting pretest, all children counted correctly at least to 10 and produced all the number words used in the test session. On the give-a-number pretest, of the 16 participants included in the final analyses, 7 were 2-knowers, 7 were 3-knowers, and 2 were 4-knowers.

Main experiment. Results were analyzed as the the proportion of trials on which children answered correctly that the larger number word of each pair was *more*. On known number word trials, children successfully identified the larger number word as *more* on the majority of trials (M=0.79, SD=0.23, $t(15)$=5.02, p<.001). On unknown number word trials, in contrast, children chose the larger number word as *more* on only half of trials (M=0.49, SD=0.22, $t(15)$=.22, NS); the distribution of performance across children was unimodal and centered on 50%. The results of the mixed-factor ANOVA revealed only a main effect of condition (F (1,14)=10.29, p<.01, h^2=0.424), reflecting children’s greater correct responding with known as compared to unknown number words. This finding was confirmed by a non-parametric analysis comparing performance with known vs. unknown number words (Wilcoxon $z = 2.64$, $p<.001$).

Discussion

The findings of Experiment 3 provide evidence that children understand that the unknown number words in their count lists refer to greater quantities than their known number words. This finding accords with those of Wynn (1990) and reveals that children understood the task, interpreted the question “which is more: two or seven?” as intended, were motivated to answer it, and showed no reluctance to produce a large and unknown number word (“seven”) as an answer. In contrast, the findings provide no evidence that children were sensitive to the numerical ordering among the unknown number words in their count list. Presented with the same question but with two unknown number words (e.g., “which is more, five or ten?”), children produced each of the words at random. Although children produced these words in a stable and appropriate order when counting, and although the words picked out numerosities that differed by a 2:1 ratio, children showed no tendency to judge as more numerous the set labeled by the word that appeared later in the count list.

Children’s failure with the unknown number words could stem from a failure to segment and order the words in their count lists. Studies of children’s counting (e.g., Fuson, 1988; Ginsburg & Baroody, 2003) suggest that in the early stages of counting, children recite the count list as an “unbreakable list.” During this phase, children do not understand the order and position of each separate number word in their count list, despite the fact that they produce the list in a stable order. Alternatively, children may have succeeded in parsing the count list but still fail to appreciate that the order of words in the list corresponds to the order of numerical magnitudes that the words designate. Research in progress is now attempting to distinguish these possible reasons for children’s failure to judge that “ten” is more than “five” (LeCorre & Carey, personal communication, October 10, 2006).

Together, the findings of Experiments 1 – 3 indicate that 3-year-old children lack much of older children's understanding of the number words in their count sequence. Most children of this age can recite the number words to "ten" but do not appreciate that "five" is a better label than "ten" for a set of five objects. These children also fail to judge that a set labeled "ten" objects is more numerous than a set labeled "five.". Further analyses of the data from Experiments 2 and 3 revealed no evidence for these abilities, even among the subset of children with the highest counting skill or with command of the reference of the most number words (see supporting online materials). These findings suggest that the children in the present studies have not begun to map the later words in their count list to approximate numerical magnitudes.

In contrast, the experiments provide evidence that children understand two aspects of number word meaning. First, children judge that a set labeled by an unknown word in their count list is "more" than a set labeled by a known number word. Second, children who have heard a set of objects labeled by one unknown number word systematically choose that set when asked for that number word, and choose a different set when asked for a different unknown number word. Children's rejection of a set labeled "five" when asked for "ten" does not depend on a purely pragmatic bias, because children accept that a set of ten and a set of five can both be called "some," and that a set of "five fish" can also be called a set of "hungry fish." Thus children appear to understand that the words in their count list contrast with one another in their application to sets of objects.

These positive findings are consistent with both of the principal accounts of the development of number word meanings. First, children may understand that each number word depicts a specific, ordered numerosity, but they may have mastered the ordering relationship only for the first few words. Thus, children may judge that "seven" designates a larger number than "two" because they know that "one" and "two" designate the smallest cardinal values, and they may judge that "ten" and "five" apply to different sets because each refers to a distinct cardinal value. Children may fail to judge whether "five" or "ten" is more numerous, and they may fail to apply "five" to a set of five rather than ten objects, because they have not yet discovered that the sequential ordering of words in the count list maps to the numerical order of the natural numbers (Wynn, 1992). Discovering this relationship may be difficult, in part, because children's count list itself is not yet parsed into a set of independent and ordered elements (Fuson, 1988).

Alternatively, children may understand that the unknown words in their count list contrast in reference with one another and with known number words, without understanding that the basis of the contrast is numerical (Carey, 2001). Children may be unclear, for example, whether pictures of "four cats" and "eight cats" differ in number or in some continuous quantitative variable, such as total volume or density. Children even may fail to appreciate that the basis of the distinction between "four" and "eight" is quantitative. Children who have not mastered the basic principles of counting may understand the differences among "four," "six," and "eight" the way children who have not mastered the basic principles of reading understand the differences among "A," "B," and "C." Such children may appreciate that "seven" and "ten," and "A" and "B" refer to different sorts of entities without knowing what those entities are or how they differ.

The plausibility of each of these two accounts depends in large part on the nature of children's prelinguistic number representations. If children possess a single set of natural number concepts and lack only the ability to apply these concepts exactly to perceived arrays of objects, then the first account is more plausible. Given that children view different number words as contrasting in meaning, and given that they interpret words for small numbers as designating specific numerical values, children should appreciate that words for large numbers also designate specific numerical values. In contrast, if children possess two distinct and limited systems for capturing numerical information--a system for representing exact small numbers and a separate system for representing approximate large numbers--then the second account is more plausible. If the meanings of known number words derive from the small, exact number system, then children may master their meanings without understanding how these words contrast with unknown number words. Because the exact small number system has a set size limit of 3 or 4, it does not provide the numerical concepts that define the basis of this contrast.

Although the primary goal of our research is to distinguish these two accounts, we must first consider a third possible explanation for children's performance in Experiments 1-3. Children may have a single set of underlying, natural number concepts, consistent with the first view, and they may represent all the words in their count list as contrasting in meaning with one another. Children may fail to understand that the relevant contrast is numerical, however, because they do not yet endow their *known* number words with numerical meaning. One-, two-, and three-knowers may succeed at the give-a-number task, and at the tasks involving known numbers in Experiments 2 and 3, by mapping each number word to a non-numerical visual representation such as a spatial pattern or a specific configuration of objects (see Simon, 1997; Mix, 1999). If children fail to confer numerical meaning on their known number words, then they would not be expected to confer such meaning on their unknown number words, even if they possessed the full set of natural number concepts.

To distinguish the third account from the first two accounts, Experiment 4 investigated whether children who have mastered the reference of the first words in their count list apply those words to representations with numerical content. In this experiment, children were presented with a small set of objects, the set was named by a known number word, and then the objects were placed in an opaque box, out of the child's view. On different trials, the set of objects in the box was subjected to one of three transformations: addition of objects, subtraction of objects, or rearrangement (moving the box). Without revealing the objects, the child was then asked whether the same number word, or a different number word, applied to the set. If children's first number words convey numerical information, children should apply a different word to the set after the addition or subtraction transformation, and they should apply the same word to the set after the rearrangement transformation. In contrast, if the first number words are mapped to visual patterns lacking numerical content, then children might fail to take account of the different transformations in applying the number words.

Experiment 4

Method

The method was the same as the previous experiments, except as follows.

Participants. Twenty-four 3-year-old children (9 males) ranging in age from 37.2 to 42.0 months (mean age 39.3 months) took part in the study. An additional 9 children were excluded from the analyses for refusal to provide a count sequence (*n*=5), ceiling performance on the give-a-number pretest (*n*=1), or failure to complete enough test trials (*n*=3).

Displays. Displays for the main experiment consisted of small, familiar, toy objects (e.g., sheep) and a large, red, opaque box with a hinged top lid.

Design. In the test session, each child was presented with a total of 6 trials presenting three types of transformations: Addition, subtraction, and displacement (2 trials each). The numbers presented in the test session were chosen from between 1 to 4, with the restriction that that only numbers produced by each child in the counting pretest and comprehended by the child in the give-a-number pretest were included in the analyses. Because this test concerned only known number words, the largest array presented to each child (either as the sum or as the initial collection prior to transformation) never exceeded the child's highest known number word.

Procedure: After the counting and give-a-number pretests, the experimenter placed a single set of objects in front of the child and identified the set twice by number ("Look, there are *two* sheep here"). Then the experimenter gathered the objects and placed them inside an opaque box while narrating ("Look, I'm putting these sheep in the box"). Then the experimenter asked a memory question ("Do you remember how many sheep I said went into the box?"). Trials on which the child failed the memory check were excluded from the analyses (a total of 4 trials were eliminated: 1 trial each for 4 participants). In the displacement condition, the experimenter made no change to the set other than to place it in the box, but to match the procedural delay of the other transformations, she used a placeholder statement ("So we have nice sheep in this box"). In the addition condition, the experimenter added objects to double the number in the box while narrating ("Look, I'm putting these sheep in the box"). In the subtraction condition, the experimenter removed half of the objects from the box while narrating ("Look, I'm taking these sheep out of the box"). Then on all trials the experimenter asked the child two counterbalanced yes/no questions involving the same number word and a second number word that was half or twice as large (e.g., "Are there *two* sheep in the box? Is there *one* sheep in the box?"). For the Addition and Subtraction transformations, the different number word that was proposed was always correct.

Analyses. Children's responses were coded as the proportion of trials on which the child responded *yes*. Responses were analyzed by means of a 3 (transformation: addition, subtraction, or displacement) x 2 (question: same or different) x 2 (sex) mixed-factor ANOVA with the last factor between subjects.

Results

Pretests. On the counting pretest, all children counted correctly at least to 10. On the give-a-number pretest, 13 of the 24 children were 2-knowers, 9 were 3-knowers, and 2 were 4-knowers.

Main experiment. Children performed with high accuracy in all three conditions (Figure 2). For the displacement transformation, children judged reliably that the unchanged set should retain the same number word (98% correct) and should not be designated by the different number word (87% correct, both ts(27)>6.1, p<.001). For the addition transformation, children judged reliably that the altered set should be designated by the different word and not by the same word (92% and 83% correct, respectively, both

ts > 5.1, $p < .001$). For the subtraction transformation, children again accepted the different word and rejected the same word for the transformed array (94% and 97% correct, respectively, both ts > 12.6, $p < .001$). The ANOVA revealed a main effect of question (F $(1,22) = 25.72$, $p < .001$, $h^2 = 0.539$), qualified by an interaction between transformation and question (F $(2,22) = 229.61$, $p < .001$, $h^2 = 0.851$). Children answered *yes* more often on different than on same number word questions, but they answered *yes* more often on same number word questions after the no-change transformation than after the addition or subtraction transformations.

Discussion

Experiment 4 provided evidence that children endow known number words with numerical meaning. Even when the words designated sets of objects that were out of view, children changed their application of the words when the sets were transformed by addition or subtraction, and they maintained their application of the words when the sets underwent a non-numerical transformation (displacement from a tray to a box). These findings accord with those of recent case studies of number development in very young children: For example, one child labeled an initial collection “one,” then after another item was added, she commented, “another one,” and labeled the collection “two” (Baroody, Lai, & Mix, 2006).

In this and subsequent experiments, the different number word offered by the experimenter gave the correct cardinal value after the addition or subtraction transformation. It is not clear, however, whether children understood this exact value. Children may appreciate that a small set of objects cannot be designated by its original number word after addition or subtraction, without knowing which new number word designates the set. Although children responded as confidently to the different-word questions as to the same-word questions (“I don’t know” responses did not occur in either condition), they may have accepted the new number word because it was offered by the experimenter as an alternative to the old number word, as did the children in Experiment 1.

The last two experiments investigated whether children endow the unknown number words in their counting routine with the same numerical meanings. In these experiments, children were presented with an array of objects that was designated by a number word. Then the array was transformed by moving the objects around, adding new objects to the array, or removing objects from the array. Studies of human infants and of adult non-human primates provide evidence that nonlinguistic number systems represent these transformations differently: addition and subtraction result in a *change in cardinal value*, whereas rearrangement of the objects in a set does not (e.g., Feigenson & Carey, 2005; Hauser et al., 2000). Five-year-old children who have mastered verbal counting generalize this understanding to unknown number words (Lipton & Spelke, 2006), and the 3-year-old children in Experiment 4 demonstrated this understanding for their known number words. If such children also understand that the unknown number words in their count list pick out sets with different cardinal values, therefore, children should fail to apply the original number word to a set after elements have been added to or taken from it, and they should continue to apply that number word to the set after elements have been moved around with no addition or subtraction.

Experiment 5

The method for this experiment was adapted from Lipton & Spelke (2006) for use with smaller numbers and younger children. Three-year-old children were presented with two trays of objects, one of which was named with a number word (e.g., “this tray has five sheep”). Then the labeled tray was transformed in one of two ways: sheep were moved around, or one more sheep was added to the pile. Finally children were asked to point to the tray with “five sheep” or the tray with “six sheep.” Because children used these number words contrastively (Experiment 1), they were expected to use opposite pointing responses for the two number words. If they understood that the application of these number words changed after addition but not rearrangement, then they should have shown systematic and opposite pointing responses after the two transformations.

Method

The method was the same as the previous experiments, except as follows.

Participants. Sixteen 3- to 3.5-year-old children (9 males) ranging in age from 36.0 to 41.8 months (mean age 38.3 months) took part in the study. An additional 8 children were excluded from the experiment for failure to complete enough test trials (*n*=5) or failure to give a count sequence (*n*=3).

Displays. Displays for the main experiment consisted of small, familiar, 3D toy objects (e.g., sheep, horses) presented on trays. Trays were presented in pairs containing identical objects in sets of varying numerosity.

Design. For the main experiment, each child received 2-4 trials in each of four conditions defined by the type of transformation applied to the named array (addition vs. rearrangement) and the type of number word in the question posed to children (same vs. different from the number word used initially to label one array). The number words used in the test session were "five," "six," "seven," and "eight"; all of these numbers were outside each participant's known number word range and were produced by all children in the counting pretest. All conditions and questions were presented in an intermixed order. Children who did not complete at least 2 trials in each condition were excluded from the analyses.

Procedure: After the counting and give-a-number pretests, the experimenter placed a pair of trays in front of the child and identified the objects while pointing to both trays ("Look, I have lots of sheep here"). In the addition condition, the trays initially contained the same number of objects; in the rearrangement condition, the trays contained sets that differed in numerosity by one object (although the difference between sets was not highlighted for the children). In both conditions, the experimenter pointed to the target tray and identified it twice by number while also calling attention to the non-target tray ("This tray has *five* sheep, there are *five* sheep here; and there are sheep here as well"), before performing the transformation. In the addition condition, the experimenter produced another object from below the table and added it to the target tray while narrating ("Look, I'm putting *another* sheep on this tray"). In the rearrangement condition, the experimenter rearranged the objects on the target tray ("Look, I'm putting these sheep *in a row*"). In both conditions, the experimenter then removed her hands from the trays and asked the child to point to a tray designated by either a different number word or the same number word (e.g., "Can you point to the tray with *six/five* sheep?").

Analyses. Children's responses were coded as the proportion of trials on which the child chose the originally named tray. Responses were analyzed by means of a mixed-factor 2 (transformation: addition vs. rearrangement) x 2 (question: same vs. different number word) x 2 (sex) mixed-factor ANOVA, with the last factor between subjects.

Results

Pretests. On the counting pretest, all children counted correctly at least to 8. On the give-a-number pretest, 8 children performed as 1-knowers, 6 as 2-knowers, and 2 as 3-knowers.

Main experiment. Children were equally likely to choose the originally named set and the comparison set on all questions and for both transformations (all Fs $(1,14)<1.32$, NS; Figure 3). After the addition transformation, children chose the originally named tray (incorrectly) on 57% of same word trials, and (correctly) on 61% of different word trials. These choices did not differ from chance (both ts$(15)<1.95$, NS) or from one another ($t(15)<1$). After the rearrangement transformation, children chose the originally named tray (correctly) on 60% of same question trials and (incorrectly) on 60% of different question trials. These identical choice rates did not differ from chance (both ts$(15)<1.51$, NS).

Discussion

Children who heard an unknown number word applied to a set of objects were equally likely to apply that number word, and a different number word, to the set after rearrangement of the objects. These findings provide no evidence that children understand that a number word that falls outside their known number word range should still apply to a given set if the items in the set are rearranged. Moreover, children who heard a number word applied to a set were equally likely to apply that word, and a different number word, to the set after one object was added to it, changing the set's cardinal value. Thus, the experiment provides no evidence that 3-year-old children, like older preschool children (Lipton & Spelke, 2006), understand that an unknown number word ceases to apply to a set of objects if an item is added to the set. These findings provide initial evidence against the view that children take the unknown number words in their count list to designate specific cardinal values.

Children's poor performance in Experiment 5 contrasts with their excellent performance in Experiment 4. In Experiment 4, children judged correctly that a known number word continued to apply to a set after addition of one item, and that it no longer applied to the set after rearrangement of the items, even though the sets were out of view. In Experiment 5, children made the same inference about known number words applied to visible sets. In contrast, the children in Experiment 5 failed to make the same inferences about the application of unknown number words. Children's poor performance cannot plausibly be attributed to a lack of knowledge of the new number word offered by the experimenter, because children performed at least as poorly when tested with the original number word (47% correct) as when tested with the new number word (50% correct). Children therefore do not appear to extend the numerical meanings of known number words to the unknown words in their count list.

It is possible, nevertheless, that children failed the present task because it was confusing, insufficiently motivating, or unduly taxing of memory or perception of numerosity. For example, the children in Experiment 5 were presented with two arrays of objects and were asked to choose the array best named by a given number word. Although this procedure is more similar to Experiment 1 (in which children were successful) than is the one-array method of Experiment 4, it is possible that the use of two piles confused children or overtaxed their memory. Moreover, the children in Experiment 5 were presented with the transformation of adding one rather than doubling or halving an array. Although the operation of adding one led to successful performance in one past study (Sarnecka & Gelman, 2004), it is possible that the doubling and halving transformations used in Experiment 4 are more salient and motivating to children.

To address these possibilities, we conducted two further experiments in which children viewed a single set of objects that was transformed either by addition, subtraction, or rearrangement (see supporting online materials). To make the numerical changes more perceptually apparent, the addition and subtraction transformations doubled or halved the number of objects in the array. In Experiment A, children simply were asked to produce the original target number word after the transformation, and they succeeded, showing memory for the relevant number word. In Experiment B, children were asked whether the original number word, or a word for a number that was half or twice as large, applied to the transformed array. As in Experiment 4, children rejected the original number word, and accepted the new number word, when they were tested with known numbers. When the tests involved unknown numbers such as "five" and "ten," in contrast, children were equally likely to accept the original and the new number word after doubling or halving of the numbers of objects in the array. Together with the findings of Experiment 5, these findings suggest that the children failed to understand that the unknown number words in their count lists denote specific cardinal values and therefore change their application when the arrays they designate change in number.

Nevertheless, this conclusion must be offered with caution. The most important conditions in Experiment 5 and its extensions are those in which sets labeled by unknown number words are transformed by addition, subtraction, or rearrangement. It is possible that children were confused by the presence of multiple transformations on large sets of objects. Perhaps children suffered from proactive interference across these experiments: on any given trial, they may have forgotten whether a set was transformed by addition, subtraction, or rearrangement. On the known number trials of Experiment 5, children may overcome this confusion by using either exact, nonsymbolic number representations or known verbal labels to enhance memory for the events. On unknown number trials, in contrast, children may remember the number word labels but forget the critical addition, subtraction, or rearrangement events. The final experiment reduced this potential source of error by means of a between-subjects design, in which each child was presented with only a single type of transformation throughout the study.

Experiment 6

Children were presented with two sets of objects, one set was labeled by a number word, and then the set was transformed. Separate groups of children were presented with four different transformations: addition (doubling), subtraction (halving), rearrangement, and no change. Children were tested with known number words on some trials and with unknown number words on other trials. Based on the findings of Experiments 1 and 5, children were expected to succeed on all questions with known number words and in the no-change condition with unknown number words. The critical question concerns children's performance when unknown number words are applied to sets that then are transformed by addition, subtraction, or rearrangement.

Method

The method is the same as in the previous experiments, except as follows.

Participants: Forty 3- to 3.5-year-old children (18 males) ranging in age from 36.0 to 42.0 months (mean age 39.4 months) took part in the study. An additional 16 children were tested but excluded from the analyses for failure to complete enough test questions (*n*=5), failure to give a count sequence (*n*=2), low counting on the counting pretest (*n*=2), ceiling performance on the give-a-number pretest (*n*=4), or parent interference (*n*=3).

<u>Displays.</u> Stimuli for the main experiment consisted of small, familiar, 3D toy objects (e.g., sheep, horses) presented on trays as in Experiment 5.

<u>Design.</u> In the test session, four transformations were presented between participants, such that 10 children each received 12 trials with a single transformation: No change, rearrangement, addition, or subtraction. Each child received 4 trials with known number words and 8 trials with unknown number words within their count list. Each trial ended with one of two types of question presenting either the same or a different number word as the previously identified target (2 known and 4 unknown number word trials with each type of question). The number words used in the test session were selected from between 1 to 14, with the restriction that the pair of outcome sets were in a 2:1 ratio and one member of the pair corresponded to the number in the question. Children who did not complete at least one question of each type were excluded from the analyses.

<u>Procedure.</u> After the counting and give-a-number pretests, the experimenter placed a pair of trays in front of the child and identified the objects while pointing to both trays ("Look, I have lots of sheep here"). For the no-change and rearrangement transformations, the trays contained sets that differed in number by a 2:1 ratio; for the addition and subtraction transformations, the trays initially contained equal sets. For all children, the experimenter pointed to the target tray and identified it twice by number while calling attention to the non-target tray (e.g., "This tray has *five* sheep, there are *five* sheep here, this tray also has sheep") before performing the transformation. For the addition transformation, the experimenter then added more objects to the array to double the number while saying "Look, I'm putting these sheep on the tray." For the subtraction transformation, the experimenter removed half of the objects from the tray while saying "Look, I'm taking these sheep off the tray." The rearrangement transformation matched the other transformations in duration: the experimenter arranged the objects on the target

tray into a row while narrating ("Look, I'm putting all these sheep in a row”). Then, on all trials, the experimenter removed her hands from the trays and asked the child to point to the tray with either a different or the same number of objects (e.g., “Can you point to the tray with *ten*/*five* sheep?”). The different number word corresponded to the number of objects in the non-target set on no-change and rearrangement trials, and in the target set on addition and subtraction trials.

Analyses. Children’s responses were coded as proportion of trials on which the child chose the originally named array. Responses were first analyzed by a 2 (question: same vs. different) x 2 (condition: known vs. unknown numbers) x 4 (transformation: no-change, addition, subtraction, or rearrangement) mixed-factor overall ANOVA with the last factor between subjects. Further analyses then focused separately on transformation trials with known vs. unknown numbers, by 3 (transformation: addition, subtraction, or rearrangement) by 2 (sex) x 2 (question: same vs. different) mixed-factor ANOVAs with the first two factors between subjects. Performance on the No-change transformations was analyzed separately by a 2 (condition: known vs. unknown numbers) x 2 (question: same vs. different) x2 (sex) mixed-factor ANOVA with the last factor between subjects. Finally, two-tailed t-tests compared responses to the same and different number words for each transformation and each condition.

Results

Pretests. On the counting pretest, all children counted correctly at least to 10. On the give-a-number pretest, 5 of the 40 children were 1-knowers, 15 were 2-knowers, 17 were 3-knowers, and 3 were 4-knowers. One-way ANOVAs comparing number knower status and highest counted word (with no mistakes) across the four conditions revealed no differences between conditions (both Fs $(3,36)<1.22$, NS).

Main experiment. Results are shown in terms of the proportion of trials on which children correctly applied the number word for each type of transformation, for known and unknown numbers (Figure 4). The overall ANOVA revealed the expected three-way interaction of condition, question, and transformation (F (3,36)=4.046, p<.05). Children showed high success on the no-change condition with both known and with unknown numbers (85% and 78% correct, respectively, when tested with the same number word, and 87% and 73% correct when tested with the different number word). Children altered their choice dramatically, and appropriately, when asked to point to the same vs. different number (for known numbers, $t(9) = 4.97$, p<.001; for unknown numbers, t (9) = 4.70, p<.001). The analysis of performance in this condition revealed a main effect of question type (F (1,8)=30.74, p<.001, h^2=0.793), reflecting the fact that children chose the originally named array more often when asked for the original number than when asked for a different number.

Children also showed high success on the three transformations with known numbers: On same and different questions, respectively, their performance was 88% and 100% correct for the addition transformation, 97% and 97% correct for the subtraction transformation, and 100% and 80% correct for the rearrangement transformation. In all three cases, children responded differently, and appropriately, when asked for the same vs. different number (all ts(9) >9.80, p<.001). The analysis of performance in these three transformation conditions revealed a main effect of question (F (1,24)=75.15, p<.001, h^2=0.758), qualified by an interaction between question and transformation (F (2,24)=211.89, p<.001, h^2=0.946). Children chose the originally named array when asked for the same number word (and rejected the originally named array when asked for a different number) after the rearrangement transformation more than after the addition and subtraction transformations.

In contrast, children performed poorly on the addition, subtraction, and rearrangement transformations with unknown numbers in their count list. When asked for the array designated by the original number word, children correctly avoided the target array on 55% of addition trials and 30% of subtraction trials (42.5% correct performance). They showed the same rate of pointing to the originally named array on rearrangement trials as on subtraction trials (70% choice of that array). When asked for the array designated by the new number word, children pointed to the original array on 73% of addition trials (correct) and 90% of subtraction trials (correct), but also on 76% of rearrangement trials (incorrect). The analysis of performance with unknown number words in these three conditions revealed a main effect of question (F (1,24)=5.45, p<.05, h^2=0.185), reflecting children's slightly greater choice of the target for different questions than for same questions (79% vs. 62%, respectively) across all three transformations. Importantly, however, there was no interaction of question by transformation (F (2,24)=0.60, NS). Children did not apply unknown number words differently for transformations that changed numerosity (doubling and halving the set of objects), relative to a transformation that preserved numerosity (rearranging objects in a line).

Discussion

The findings of Experiment 6 replicate and extend those of the previous experiments. Children judged reliably that a set that does not change at all should still be labeled with the same unknown number word and should not be labeled with a different unknown number word. This pattern replicates the findings of Experiment 1 and provides evidence that children remembered the number words and were motivated to use them systematically. In contrast, children failed to show the same pattern of number word usage when the objects in a set were rearranged. Moreover, children failed to judge that an unknown number word no longer applied to a set after the set was transformed by addition or subtraction. These failures cannot be attributed to any confusion between the transformations, because each child in this study viewed only a single transformation on every trial, and children responded to the transformation successfully when tested with known numbers. Children’s failures also cannot be attributed to motivational problems or cognitive overload caused by the use of large numbers, because children succeeded on large-number trials in the no-change condition. Although some of the items in the study queried children about number words whose application had not previously been indicated (the different-word trials of the unknown number condition), children performed no worse on these questions (62% correct) than on questions using number words whose reference was indicated (the same-word trials of the unknown number condition: 52% correct). Finally, the failures cannot be attributed to the use of a heterogeneous population of children who varied in counting skill and number word knowledge, because performance was equivalent in children with higher vs. lower counting skill and number word knowledge (see supporting online materials). Children's failure to distinguish number-relevant and number-irrelevant transformations on the trials with unknown numbers therefore suggests that children fail to understand that the application of their counting words to arrays of objects changes when the arrays change in number. Although unknown number words contrast in meaning for young children, the children do not appear to appreciate that the relevant contrast is numerical.

General Discussion

Verbal counting is intimately connected to natural number: each counting word designates one cardinal value, and the counting procedure serves to enumerate sets whose cardinality is too large to be determined, with precision, by nonsymbolic processes. But what is the nature of the relationship between the system of natural number concepts, on one hand, and the system of number words and verbal counting, on the other? The present research provides evidence that natural number concepts emerge in children along with or after, rather than prior to, the acquisition of language. These concepts likely emerge, in part, as a consequence of children's efforts to make sense of number words and to learn to use the counting routine to represent number: achievements that the children in the present experiments had not yet attained.

Evidence for this conclusion comes from three findings. First, every child in the present studies had mastered the reference of "one" sufficiently to produce a single object when asked for "one," to label arrays containing a single object as "one," and even to label as "one" the hidden contents of a box into which two objects were placed and one object was removed (Experiment 4). Further studies provide evidence that children who have gained the ability to apply “one” appropriately to arrays of objects also are able to apply the word appropriately to sequences of sounds and actions (Huang, Snedeker, & Spelke, 2005).

Thus, the children in the present studies had mastered the abstract meaning of at least one word in their count list, and children likely had mastered aspects of the application of the other number words as well. Because Wynn’s give-a-number task is relatively stringent, it is likely that children who fail to demonstrate understanding of “two” by this task nevertheless use “two” appropriately in certain limited contexts (see Mix et al., 2005). Nevertheless, learning the meaning of “one,” or even of “one,” “two,” and “three,” does not suffice to bring mastery of the meanings of the other words in the child’s counting routine.

Second, children take all the words in their count list to contrast in reference both with their known number words (a finding previously shown by Wynn, 1990, 1992) and with one another (Experiment 1). Children appreciate that a single array of toy animals, that undergoes no change, cannot be said to consist of both “five sheep” and “ten sheep.” Moreover, the contrast is specific to number words: children appreciate that such an array can be said to consist of both “five sheep” and “some sheep,” or “hungry sheep.”

The children in Experiments 1, 6, and B (see supporting online materials) used the contrasting reference of number words in order to answer questions that otherwise would be unanswerable. When a two-knower is told that one array has “five sheep” and then is asked which array has “ten sheep,” a reasonable response would be to plead ignorance, for the child has not mapped “ten” even to an approximate numerical magnitude (Experiments 2 and 3). Nevertheless, children used the contrasting reference of the number words to solve this task: When asked for “ten sheep,” they pointed systematically to the array that had not been labeled as “five.”

If such children possessed a full set of natural number concepts, then the above abilities should be sufficient for children to induce that each word in the count list picks out a specific, unique number. Just as children learn new color words by contrast with terms already mastered, children should learn new number words by contrast with “one,” “two,” and “three.” Contrary to this prediction, the third finding of the present experiments is that children who have learned the application of the first words in their count list still fail to appreciate that the other words in their count list refer to cardinal values.

Children’s failure to endow the later words in their count list with numerical content was shown in four ways. First, children fail to appreciate that the words in their count list refer to approximate numerosities. Presented with arrays of five and ten objects, children who could count to ten failed to choose the set of five objects when asked for “five,” even though they succeeded with large-number words when the contrasting set contained a known number of objects. Second, children fail to appreciate that words occurring later in their count list pick out larger cardinal values. Children failed to judge that “ten objects” is more than “five objects,” even though they correctly placed “five” before “ten” in their recitation of the count list, and they correctly judged that “ten objects” was more than “two objects.” Third, children who heard a number word like “five” applied to a set of objects failed to appreciate that the word should continue to apply to the set if the objects were rearranged, with no objects added or removed. Fourth, children failed to appreciate that "five" should no longer apply to the array after the array was transformed by addition or subtraction.

Children’s failure to make these inferences truly would be puzzling if they possessed the system of natural number concepts. Given that children understand that “two” refers to the cardinal value *two* (and thus no longer applies to a set labeled “two” after the set is doubled) and that “five” contrasts with “two” in meaning, how could they fail to understand that “five” refers to a cardinal value as well (and thus no longer applies to a set labeled “five” after the set is doubled)? Children’s patterns of success and failure in the present studies provides evidence that the unitary system of natural number concepts plays no role in children’s efforts to understand number words and verbal counting. This system likely emerges as a consequence of learning to count.

The above findings accord with recent findings from two other laboratories. The tasks of Sarnecka and Gelman (2004) have revealed a dissociation between 3-year-old children’s judgments of numerical equality and children’s application of number words: children who judged that two sets had the same number and who were told that one set had “five” objects failed to judge that the other set had five objects, even though the sets were presented in rows that highlighted one-to-one correspondence. These findings accord with the findings of Experiments 5 and 6 and provide evidence that children fail to understand that unknown number words refer to specific cardinal values.

Our findings also accord with new research by LeCorre and Carey (in press), in which 3-year-old children are presented with brief views of pictured sets and asked to guess the cardinality of the sets without counting. Children successfully produced number words corresponding to the approximate number of items in the pictured set up to the level of their highest known number word, but not beyond. Based on this production task, LeCorre and Carey (in press) conclude that children have not yet mapped the unknown number words in their count list onto approximate numerosities. Their conclusion accords with the conclusions from our comprehension tasks in Experiments 2 and 3.

Although the children in the present studies appear to lack the system of natural number concepts, studies of number representations in prelinguistic human infants and nonlinguistic nonhuman primates suggest they have two other systems of numerical representation: a system for representing exact numbers of individuals with a set size limit of 3-4, and a system for representing large, approximate numerical magnitudes with a set size ratio limit of about 2:1 in infants (e.g., Xu, 2003) and about 5:4 in preschool children (e.g., Barth, LaMont, Lipton, & Spelke, 2005). These two systems have been found to have dissociable properties in animals and in infants (see Brannon et al., 2004; Feigenson, Dehaene, & Spelke, 2004). Although the small-number system allows children to represent numbers exactly, it is subject to a set size limit of 3 or 4 that precludes representations of larger numbers (Feigenson & Carey, 2005) and that predisposes infants to form summary representations of non-numerical attributes of an array such as its total area or contrast (Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002). The large-number system allows children to represent larger cardinal values, independently of and in preference to summary representations of continuous quantitative variables (Brannon et al., 2004; Xu et al., 2005). Nevertheless, the ratio limit to this system does not allow children to discriminate these cardinal values exactly. Neither system, therefore, suffices to represent exact numbers like *seven*. Moreover, the existence of two systems of numerical representation, rather than one, may obscure the unity of the natural number system and the relationship between the meanings of words for small vs. large numbers.

Further properties of the exact, small number system may explain why children have trouble mastering the reference of “one,” “two,” and “three.” The exact, small number system allows young children to focus attention on multiple individuals at once and to form summary representations of a group of individuals, such as the total amount of contrast they create or substance they contain (Clearfield & Mix, 1999; Feigenson et al., 2002). This system does not, however, readily allow young children to represent the cardinality of a set of individuals. Infants who view two dogs, followed by two cups and then two shoes do not readily extract, from these arrays, the common cardinal value *two* (Feigenson et al., 2002; see also Mix et al., 2002). Children only begin to respond to these abstract cardinal values when they learn the corresponding number word (Mix et al., 2002). With no explicit and accessible, language-independent representation of cardinality, young children have no clear basis for discovering the relevant contrast between arrays designated by the words "one," "two" and "three."

Cardinal representations are more readily extracted from the large number system. Infants presented with sets of objects larger than four respond to the cardinal values of the sets and not to continuous quantitative variables like contrast or summed area (Brannon et al., 2004; Xu et al., 2005). Indeed, infants do not appear to be sensitive to these continuous variables in large-number arrays (Brannon et al., 2004), as they are for small-number arrays (Clearfield & Mix, 1999). Because infants extract different quantitative information from arrays containing small vs. large numbers of elements, however, they have no single system of numerical representations that can serve to relate the meaning of "seven" to that of "two." Children who have learned that "seven" and "two" contrast in meaning may have no basis for appreciating the numerical nature of this contrast.

The above considerations may explain why children have difficulty learning the meanings of the words in their count list, but they fail to explain how children eventually succeed at this task. Because the present experiments focused on children who have not yet made this induction, answering this question lies beyond the scope of the present research. Nevertheless, the findings from our experiments support some suggestions.

First, the findings of Experiment 4 provide evidence that before children come to understand counting, they learn that adding a single object to a set labeled "one" yields a set labeled "two," and that adding a single object to a set labeled "two" yields a set labeled "three." This learning likely depends on inductions over representations from the small, exact number system, and it has a natural interpretation in the operation, within that system, of marking the entry of a new object or the occurrence of a new event (LeCorre & Carey, in press).

Second, the findings of Experiments 1, 5 and 6 provide evidence that children understand that an unknown number word continues to apply to a set if nothing happens to the set--its application is *stable*. Moreover, two distinct number words do not apply to the same set if nothing happens to it--the application of number words is *contrastive*. Stability and contrast also characterize the children's application of their known number words, and they may allow children to take the first steps toward working out the counting system.

The critical remaining steps may require a reanalysis of all the number word meanings so that properties that are represented for small sets are applied to large sets, and the reverse. Children may need to discover that the known words "one" to "three" pick out distinct cardinal values, and that the higher number words change their application systematically with the addition of one. By integrating the small-number and large-number systems, and constructing representations of all number words as referring to distinct *sets of individuals,* children may build system of numerical concepts to which their counting words can apply (Spelke, 2000).

All of human science and technology, and much of human culture, depend on the development of symbolic number and mathematics. That development, in turn, begins with the acquisition of verbal counting. Although young children's emerging counting and number concepts have been studied systematically for almost a century, psychologists and educators still do not know how children gain these uniquely human abilities, or what cognitive primitives they build on. Based on the present findings, we hypothesize that the counting routines of specific human cultures engender spontaneous, constructive processes within the child, and that these processes build a unitary system of natural number concepts from a set of conceptual primitives delivered by distinct, core cognitive systems. This suggestion, however, is far from proven. Further studies of children on the cusp of mastering verbal counting are needed to test it, especially through training interventions that probe the process by which children learn new number words at and beyond the limit of *three*. We hope that such studies will benefit from the characterization of children's partial knowledge that the present studies afford.

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Footnotes

[1] On the give-a-number pretest, children who could successfully produce any number requested (up to 15) were considered to be “at ceiling.” These children typically responded to a request for any number word by counting out fish with perfect one-to-one correspondence, a strategy they could also have used to answer the test session questions. Because the present studies are concerned with children who have partial knowledge of the words in their count lists, children who performed at ceiling on the give-a-number pretest were not included in the analyses.