

October 2013

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Recommended Citation

Emily Slusser, A. Ditta, and B. Sarnecka. "Connecting numbers to discrete quantification: A step in the child's construction of integer concepts" *Cognition* (2013): 31-41.

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Connecting Numbers to Discrete Quantification:
A Step in the Child's Construction of Integer Concepts

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Keywords: Word Learning; Number Concepts; Discrete Quantification

Word Count: 6,225

Abstract

The present study asks when young children understand that number words quantify over sets of discrete individuals. For this study, two- to four-year-old children were asked to extend the number word *five* or *six* either to a cup containing discrete objects (e.g., blocks) or to a cup containing a continuous substance (e.g., water). In Experiment 1, only children who knew the exact meanings of the words *one*, *two* and *three* extended higher number words (*five* or *six*) to sets of discrete objects. In Experiment 2, children who only knew the exact meaning of *one* extended higher number words to discrete objects under the right conditions (i.e., when the problem was first presented with the number words *one* and *two*). These results show that children have some understanding that number words pertain to discrete quantification from very early on, but that this knowledge becomes more robust as children learn the exact, cardinal meanings of individual number words.

Connecting Numbers to Discrete Quantification:
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James, at 2 ½ years old, turned off the faucet in his bathtub. His mom said, “Oh, you turned off the faucet because you noticed that it was full.” James replied, “Yes, we needed *enoughs* of water. We needed *one, two, three, four, five, six, seven, eight, nine, ten* of water.” This anecdote is interesting both for what James appears to know, and for what he does not know about number words. Although he uses number words to talk about quantity, he applies them to a continuous substance (water). Adults, on the other hand, know that number is inherently discontinuous. If we want to talk about water using number words, we impose discrete units. We might say, for example, that there are *ten gallons* or *ten inches* of water in the bath¹. The key point here is that adults, unlike James, understand that bare number words cannot quantify over a continuous substance.

James's partial knowledge reflects the kind of intermediate state predicted by a constructionist account of number-concept development. Under the *conceptual-role bootstrapping* account (e.g., Carey, 2009; see also Block, 1986; Quine, 1960), children first learn a set of symbols (in this case, the ordered list of number words), and then gradually imbue the words with meaning. In doing so, they are actually constructing the exact number concepts that the words denote. Although each piece of meaning must build on what was there before, changes accumulate in such a way that the final knowledge state is profoundly different than the initial knowledge state. The present paper investigates a piece of knowledge that is integral to the construction of natural-number concepts: Understanding that number is a property of sets of discrete individuals, rather than non-individuated substances.

¹ Children do not typically apply discrete measurement to continuous quantities in this manner until around 8 years of age (Fuson, 1988; Huntley-Fenner, 2001).

Children represent a distinction between objects and substances well before they acquire language (Chiang & Wynn, 2000; Huntley-Fenner, Carey, & Solimando, 2002; Rosenberg & Carey, 2009). In fact, infants as young as 5 months old hold different expectations for discrete (solid, rigid) objects and continuous (non-solid, non-rigid) substances, such as water or sand (Baillargeon, 2004; Hespos, Ferry, & Rips, 2009; Huntley-Fenner, Carey, & Solimando, 2002). For example, infants know that one object cannot pass through the space occupied by another, but they do not extend this expectation to continuous substances (Hespos, Ferry, & Rips, 2009). There is also evidence that children distinguish between objects and substances as they acquire language (Brown, 1957; Mervis & Johnson, 1991; see also Barner et al., 2007; Imai & Gentner, 1997; Soja, 1992; Soja, Carey, & Spelke, 1991). For example, two-year-olds readily apply plurality marking (*this shoe, these shoes*) to discrete individuals, but not to continuous substances (Brown, 1957).

Certain numerical information is also represented before the acquisition of language. Infants as young as six months old discriminate among small sets of individuals (up to three or four) as well as among larger, approximate numerosities—even when other factors (such as the total spatial extent of the arrays) are controlled (see Feigenson, Dehaene & Spelke, 2004 for review). Despite these early competencies, children take quite a long time to learn how number words represent exact, cardinal numbers (Briars & Siegler, 1984; Frye, Braisby, Lowe, Maroudas & Nicholls, 1989; Fuson, 1988; Le Corre, Van de Walle, Brannon & Carey, 2006; Sarnecka & Carey, 2008; Wagner & Walters, 1982). Children first learn to recite the counting list as a rote, ordered sequence. Then, through a process that takes many months (often more than a year) children work out the numerical meanings of the first few number words, one at a time and in order (Le Corre et al., 2006; Sarnecka & Lee, 2009; Wynn, 1990, 1992).

This progression shows up clearly on the Give-N task (Frye et al., 1989; Le Corre et al., 2006; Sarnecka & Lee, 2009; Wynn, 1990, 1992) where children are asked to produce a set of a given number (e.g., “Please give *three* bananas to the puppet.”). Some children give 1 object when asked for *one*, and 2 or more objects when asked for any other number word. We can call these children one-knowers, because they know that *one* means 1, and that other number words mean something greater than one. The one-knower level is followed by the two-knower level, where children give 1 for *one*, 2 for *two*, and 3 or more for all other number words. This is followed by a three-knower level and, in some cases, a four-knower level. Children at any of these levels are called subset-knowers because, although they can typically count to *ten* or higher, they know the exact, numerical meanings of only a subset of those counting words (Le Corre et al., 2006; Le Corre & Carey, 2007; Sarnecka & Carey, 2008). Eventually, after reaching the three- or four-knower level, children figure out the Cardinal Principle of counting – the rule that makes the cardinal meaning of any number word dependent on that word’s position in the counting list (Gelman & Gallistel, 1978). Cardinal Principle knowers (CP-knowers) effectively know the meanings of all the number words in their count list, because they know (at least in principle) how to generate the set size associated with any number they can count to.

The Present Study

Although the Cardinal Principle induction represents a breakthrough in the child’s understanding of numbers, this breakthrough must build on earlier knowledge. The present study focuses on one piece of such knowledge—the understanding that number words quantify over sets of discrete individuals. In this study, we assess children’s number-word knowledge using the Give-N task. Separately (in the Blocks and Water task), we ask whether children to extend the number words *five* and *six* (words whose exact numerical meanings are unknown to subset-

knowers) to either a set of discrete objects or a mass of continuous substance. We thus evaluate when, relative to their understanding of individual number words (i.e., relative to their number-knower level), children come to understand that number words refer to discrete quantification.

Experiment 1

Method

Participants

Participants included 82 children (51 girls, 31 boys) ranging from 2 to 4 years old (mean 3 years, 4 months). Four additional children (mean age 3 years, 10 months) began the study but failed to complete one or both tasks; these children's data were excluded from all analyses.

Children were recruited from private child-care centers in and around Irvine, CA. All children were monolingual and native speakers of English, as determined by parental report. No questions were asked about socio-economic status, race, or ethnicity, but participants were presumably representative of the community from which they were recruited. In this community, 95% of residents have at least a high-school education; most residents identify themselves either as white/Caucasian (61%) or as Asian/Pacific Islander (29%). Children received a prize (e.g., a small stuffed animal) at the time of recruitment but no prizes were given at the time of testing.

Procedure

Blocks and Water task. This was the first task presented to each child; its purpose was to probe children's understanding of relatively high number words (*five* and *six*). Materials for this task included eight stimulus sets, each of which included a collection of discrete objects (e.g., blocks) and a continuous substance (e.g., water). Objects and substances were presented to children in translucent cups, each approximately 480 cc in volume. Discrete objects were

dropped into the cup by hand; continuous substances were scooped into the cup with small (30 cc) or large (80 cc) measuring scoops.

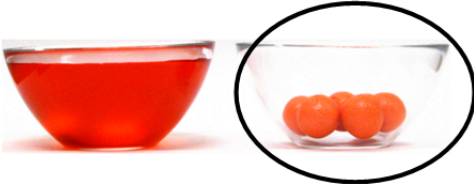
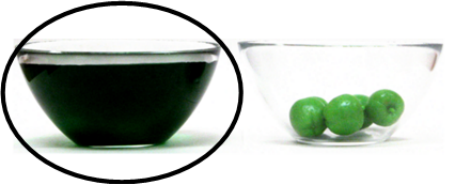
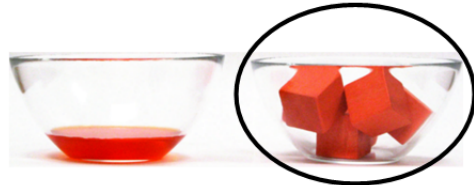
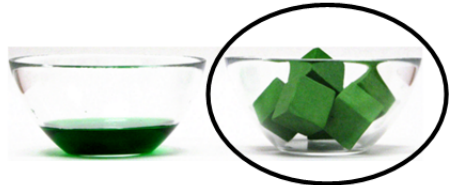
Children were tested at their child-care centers by a native English-speaking experimenter. To begin the task, the experimenter placed two empty cups in the middle of the table and asked the child to choose one of the object/substance pairs (allowing children to choose the stimuli served to randomize the order of the trials, as well as keep the children engaged in the task). The experimenter then said, “To play this game, I am going to put something in this cup...” (while the experimenter placed, e.g., five marbles into one cup) “...and something in this cup.” (while the experimenter placed, e.g., five scoops of water into the other cup). The experimenter then asked the test question, of the form, “Now I’m going to ask you a question about *five*. Are you ready? Okay, which cup has *five*?” The child responded by pointing to one of the cups. The experimenter recorded the child’s response and said, “Thank you.”

Children were randomly assigned to one of two conditions: Children in Condition A were asked about the words *five* and *more*, children in Condition B were asked about the words *six* and *a lot*. The numbers *five* and *six* were chosen because, although they are within the counting range of children this age and are recognized as numbers, subset-knowers have not yet learned their exact numerical meanings. Therefore, what children know about the meanings of *five* and *six* presumably reflects what they know about number words in general. Quantifier trials were included as a control, to confirm that the children understood the task. The quantifiers *more* and *a lot* were selected because they are familiar to children of this age (Dale & Fenson, 1996) and because, unlike number words, they can quantify over both discrete objects and continuous substances.

Children were discouraged from counting the objects. If a child began to count the objects, the experimenter covered both cups and said, “You know, this isn’t a counting game. You can just guess.”² Each child received eight trials (four number word trials and four quantifier trials) in a random order (randomized by the child’s selection of the stimuli for each trial, see above). The same stimuli were used for both conditions, but the pairings between discrete and continuous items were varied.

On 50% of trials, the cup with the continuous substance was full (i.e., the discrete objects were relatively small and the larger scoop was used for the substance); on the other 50%, the cup with discrete objects was full (i.e., the objects were relatively large and the smaller scoop was used for the substance). The design is illustrated in Figure 1. Trials were counterbalanced such that the cup with the discrete objects and the full cup were each presented on the child’s left-hand side exactly 50% of the time.

Figure 1. Experiment 1 design.

	Number Word Trials Which cup has <i>five</i> [<i>six</i>]? <i>4 trials</i>	Quantifier Trials Which cup has <i>more</i> [<i>a lot</i>]? <i>4 trials</i>
50% of trials cup with continuous substance is full		
50% of trials cup with discrete objects is full		

Note: Correct answer is circled.

² Only two children initiated counting, both of whom were classified as CP-knowers on the Give-N task.

Give-N task. This was the second task presented to each child; its purpose was to determine the child's number-knower level. Materials included one stuffed animal (named Peter), a red plastic plate, and 15 small plastic bananas. The experimenter began the task by placing the animal on the table and saying, "In this game, you will give Peter some bananas." The experimenter then placed the plate on the table and said, "When you are finished making his snack, slide the plate over to Peter." (The experimenter demonstrated the action and pretended to have the stuffed animal eat the bananas.) The experimenter then placed a tub of 15 bananas on the table and asked the child, "Can you give Peter *one* banana?" After the child responded to the request and slid the plate over to Peter, the experimenter asked the follow-up question, "Is that *one*?" If the child said "yes," the experimenter said, "Thank you!" and placed the bananas back in the tub. If the child said "no," the experimenter asked the child, "Can you fix it so we can give Peter *one* banana?"

The child was always asked for one banana on the first trial, and for three bananas on the second trial. If the child succeeded on both of those trials, the third request was for five bananas. Otherwise, the third request was for two bananas. Further requests depended on the child's answers: If a child succeeded at giving some number of bananas, N , the next request was for $N+1$, up to a maximum request of six bananas. If the child failed at giving N , the next request was for $N-1$, down to a minimum request of one banana. The task ended when the child had at least 67% successes at a given number N , and at least 67% failures at $N+1$. Failures at a given number (e.g., *three*) were counted both when the child gave the wrong number of bananas for that word (e.g., gave four objects when asked for *three*), or when the child gave that number in response to some other word (i.e., gave three bananas when asked for *one, two, four, five, or six*). (For other studies using a similarly structured Give-N task, see Barner, Chow, & Yang, 2009;

Barner, Libenson, Cheung, & Takasaki, 2009; Le Corre, et al., 2006; Le Corre & Carey, 2007; Sarnecka, et al., 2007; Sarnecka & Carey, 2008; Sarnecka & Lee, 2009; Slusser & Sarnecka, 2011, and Wynn, 1992.)

Results

Give-N task

Based on their Give-N performance, children were sorted into the following number-knower levels: one-knowers (n=13), two-knowers (n=15), three-knowers (n=19), four-knowers (n=3, these children were combined with the three-knower group for subsequent analyses), and Cardinal Principal (CP)-knowers (n=19). See Table 1 for the age range of each of the knower-level. Thirteen children failed on all set sizes. It is unclear whether these children failed because they did not understand the exact meanings of any number words, they did not understand the task itself, or there were otherwise distracted. These children's data were thus excluded from the analyses reported below (though see Appendix A for a summary of their performance).

As one would expect, older children tended to know more number words than younger children, $F(3,65)=11.60$, $p<.01$. Thus, in order to isolate the effect of number-knower level on performance on the Blocks and Water task, all analyses included age as a covariate.

Table 1. Number and age range of participants in each number-knower level.

Knower-Level	Experiment 1			Experiment 2		
	Number	Mean Age	Range	Number	Mean Age	Range
One-Knowers	13	3;2	2;5 – 4;0	18	3;2	2;6 – 3;11
Two-Knowers	15	3;3	2;7 – 3;10	15	3;0	2;4 – 3;8
Three-Knowers	19	3;6	2;9 – 4;5	20	3;7	2;10 – 4;2
Four-Knowers	3	3;6	3;4 – 3;9	1	3;10	<i>n/a</i>
CP-Knowers	19	3;11	3;6 – 4;4	20	3;8	3;2 – 4;1
Total	69	3;6	2;5 – 4;5	74	3;5	2;4 – 4;2

Blocks and Water task

For this task, children were asked to indicate (e.g.) “Which cup has *five*?” Children’s responses were coded as correct or incorrect (see Figure 1). Instances where a child responded with “both” or “neither” were infrequent (12 out of 552 responses), and were excluded (treated as missing data points) from the following analyses.

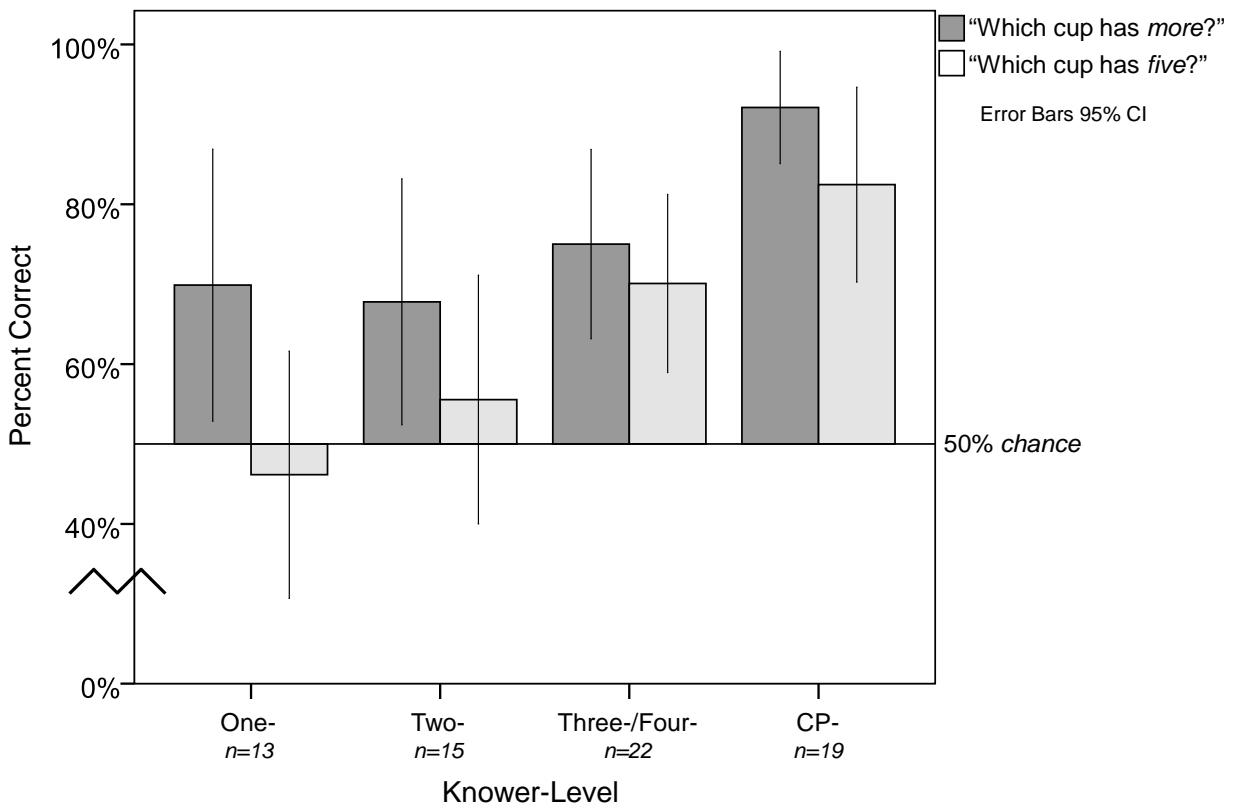
A mixed model analysis of covariance (ANCOVA), with child’s age as a covariate, showed no effect of sex (male or female) or condition (Condition A, which asked children about *five* and *more*, or Condition B, which asked children about *six* and *a lot*) on overall performance, $p > .05$, ns. Thus, subsequent analyses merged data across sex and condition.

An evaluation of performance across trial types (multivariate ANCOVA with age as a covariate) showed a strong relationship between children’s number-knower level (from the Give-N task) and their performance on number-word trials (from the Blocks and Water task), $F(3,68) = 2.47$, $p = .07$ (without age as a covariate, $F(3,68) = 6.08$, $p < .01$). This result reflects the fact that children in the three-, four-, and CP-knower levels were more likely than children in the one- and two-knower levels to extend the number word (*five* or *six*) to the cup with discrete objects

(Tukey's post-hoc comparisons, $ps < .05$). In fact, only children in the three-, four-, and CP-knower levels succeeded on this trial type, with performance significantly above chance, $t(21)=3.74$, $p < .01$ for three- and four-knowers, $t(18)=5.59$, $p < .01$ for CP-knowers. One- and two-knowers, on the other hand, were just as likely to extend number words to a continuous substance as a set of discrete objects, $t(12)=-.54$, $p = .60$, ns for one-knowers, $t(14)=.77$, $p = .46$, ns for two-knowers. See Figure 2.

There was no effect of number-knower level on children's performance on the quantifier trials, $F(3,68)=1.58$, $p = .20$, ns. When asked to indicate which cup had *more* or *a lot*, children at all knower levels chose the full cup over the half-empty cup, $t(12)=2.54$, $p = .03$ for one-knowers, $t(14)=2.48$, $p = .03$ for two-knowers, $t(21)=4.39$, $p < .01$ for three- and four-knowers, and $t(18)=12.61$, $p < .01$ for CP-knowers. See Figure 2.

Figure 2. Children's performance on each trial type, Experiment 1.



Children's success on the *more* and *a lot* trials likely means that they knew the meanings of those quantifiers. It is also possible, however, that children succeeded due to a general bias toward choosing the full cup over the half-empty cup (Carey, 1978; Clark, 1997; Klatzky, Clark, & Macken, 1973). Such a bias could also lead children to choose the full cup on the number trials (which results in chance performance because the full cup was the correct choice only 50% of the time) thereby obscuring the number-word knowledge they might have. To explore this possibility, we ran a univariate ANCOVA with knower level as an independent variable and children's choice of the *full* cup on the number trials as a dependent variable (age was included as a covariate). While there was no main effect of knower level, children as a group were more likely to choose the full cup over the half-empty cup, even on number trials, $t(68)=3.73$, $p<.01$. This tendency was particularly evident in one-knowers, $t(12)=2.55$, $p=.03$. Thus, one of the motivations for Experiment 2 (below) was to tease apart the variable of interest (discrete vs. continuous referents) from the effect of an indiscriminate 'full-cup' bias.

These quantifier trials also provided a way to test whether the children showed any overall bias toward choosing either the discrete objects or the continuous substances. No such bias was observed for children at any knower-level. When asked, "Which cup has *more* [*a lot*]?" children at all levels chose objects and substances with equal frequency, $ps>.05$, ns.

Summary

The purpose of this experiment was to determine when, relative to their understanding of individual number words (i.e., their number-knower level), children understand that higher number words (*five* and *six*) refer to sets of discrete individuals. In Experiment 1, this knowledge was demonstrated only by children who knew the exact meanings of at least three number words

(i.e., three-knowers and above). One- and two-knowers were as likely to extend *five* or *six* to continuous substances as to sets of discrete objects.

Why did the three- and four-knowers perform better on this task than the one- and two-knowers? One possibility is that only the three- and four-knowers had extrapolated what they know about *one*, *two*, *three* (and *four*) to the higher number words *five* and *six*. (Presumably, children recognize that number words up to and including their knower-level refer to discrete quantification. For example, two-knowers must know that *two* refers to sets of discrete objects, even if they don't know that this is also true of *five* and *six*.)

Another possibility is that one- and two-knowers performed at chance on the number trials because they applied the word *five* or *six* equally to the actions of dropping the items or scooping the substances into the cups, as to the final arrays. Previous research has shown that infants quantify over discrete events as well as discrete objects (Wood & Spelke, 2005; Wynn, 1996) and, when prompted, young children will count discrete events (Wagner & Carey, 2003). Thus, one- and two-knowers might view the actions associated with the presentation of stimuli in the Blocks and Water task as equally good examples of *five* or *six* (e.g., five grab-and-drop events for the discrete objects; five scoop-and-drop events for the continuous substance). Perhaps one- and two-knowers differed from the three- and four-knowers in that only the latter group saw the discrete objects as a *better* example of *five* or *six*.

Experiment 2 evaluated these possibilities by modifying the Blocks and Water task in the following ways: 1) Trials asking about *more* and *a lot* were replaced with trials asking about the words *red*, *yellow*, *green*, and *blue*. This provided a way to evaluate whether children understood the task, while eliminating the possibility that children's choice of the full cup on number trials was a carry-over from trials asking about *more* and *a lot*. 2) Object and substance pairs were pre-

measured (rather than dropped or scooped into the cups while children watched), to eliminate the opportunity to apply *five* or *six* to the number of events. 3) Number trials included not only the high numbers, *five* and *six*, but also the low numbers, *one* and *two*, which made it possible to check whether children apply the ‘discrete objects’ constraint to number words they know.

Experiment 2

Method

Participants

Children were recruited from the same community as in Experiment 1; all were monolingual and native speakers of English. Families received a prize when they signed up to participate in the study; no prizes were given at the time of testing.

One participant (4 years, 2 months old) failed to complete both tasks and was thus excluded from the following analyses. Remaining participants included 88 children (44 girls, 44 boys) ranging 2 to 4 years old (mean 3 years, 4 months).

Procedure

Blocks and Water task. Materials included 24 pairs of objects and substances in translucent storage containers. Each container was divided in half (with approximately 480 cc capacity on either side) with the discrete objects on one side and the continuous substance on the other. The objects and substances (e.g., five blocks on one side of the container; five small scoops of water on the other) were placed in the container prior to the experiment. The volume occupied by the objects and substances was controlled such that one side of the container was always full, while the other side was less than half full. Stimuli were presented such that the discrete objects were on the left side for 50% of trials and on the right for the other 50%.

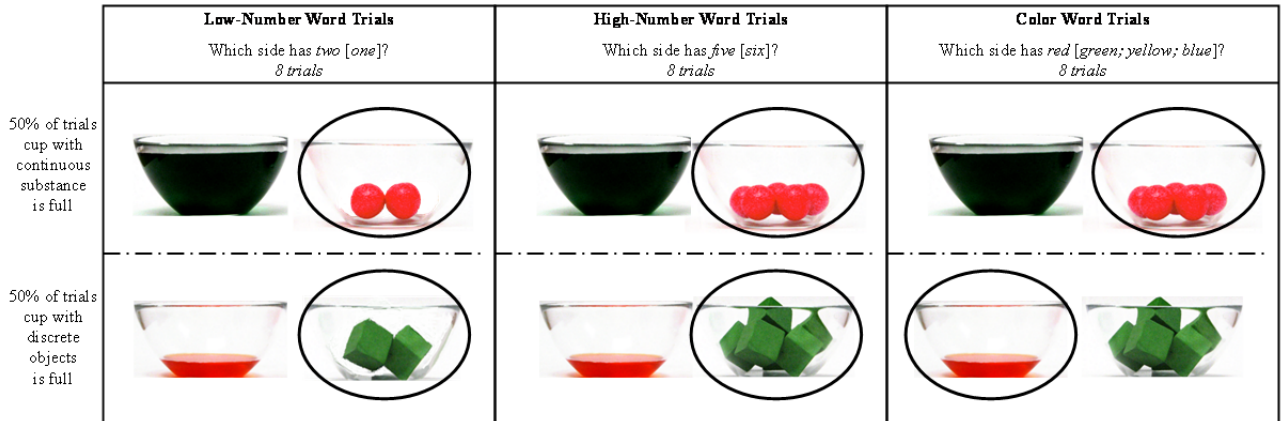
Orthogonally, the side with more volume was on the left side for 50% of trials and on the right side for the other 50%.

On each trial, the experimenter simply set the open container on the table in front of the child and said (e.g.) “I’m going to ask you a question about *five*. Are you ready? Okay, which side has *five*?” The child responded by pointing to one side of the container. As with Experiment 1, children were discouraged from counting the objects. If the child ever began to count, the experimenter covered up the container and said, “You know, this isn’t a counting game. You can just guess.”³

Each child completed 24 trials, divided into two blocks of 12 trials each. The high-number block asked about *five* and *six* (four trials each). The low-number block asked about *one* and *two* (four trials each). The remaining eight trials were interspersed within each number block and asked about the color words *red*, *yellow*, *green* and *blue* (2 trials each). The correct answer for these trials was the continuous substance on exactly 50% of trials. The design is illustrated in Figure 3. The order of blocks was counterbalanced across children.

³ Four children initiated counting behavior. Two of these children (both two-knowers) pointed to each of the objects, but did not count aloud. The other two children (both CP-knowers) counted aloud on the first trial and were discouraged from counting on subsequent trials.

Figure 3. Experiment 2 design.



Note: Correct answer is circled.

Give-N task. Materials and procedure were as described for Experiment 1.

Results

Give-N task.

Based on their performance on the Give-N task, children were sorted into the following number-knower levels: one-knowers ($n=18$), two-knowers ($n=15$), three-knowers ($n=20$), four-knowers ($n=1$, this child's data was merged with data from three-knowers for all of the following analyses), and CP-knowers ($n=20$). See Table 1 for the age range of each of the knower-level. Fourteen children failed at all set sizes and were excluded from subsequent analyses (though see Appendix B for a summary of their performance). There was a main effect of age on knower-level, $F(3,70)=16.71$, $p<.01$, so age was included as a covariate in the following analyses.

Blocks and Water task

As in Experiment 1, children were asked to indicate which side of the container had (e.g.) *five*. Responses were coded as correct or incorrect (see Figure 3). Again, answers of “both” or “neither” were infrequent (14 out of 1,776 responses) and were excluded from the following analyses.

A mixed model analysis of covariance (ANCOVA) with age as a covariate showed no effect of sex (male or female) or trial order (high numbers first or low numbers first) on overall performance, $p > .05$, ns.

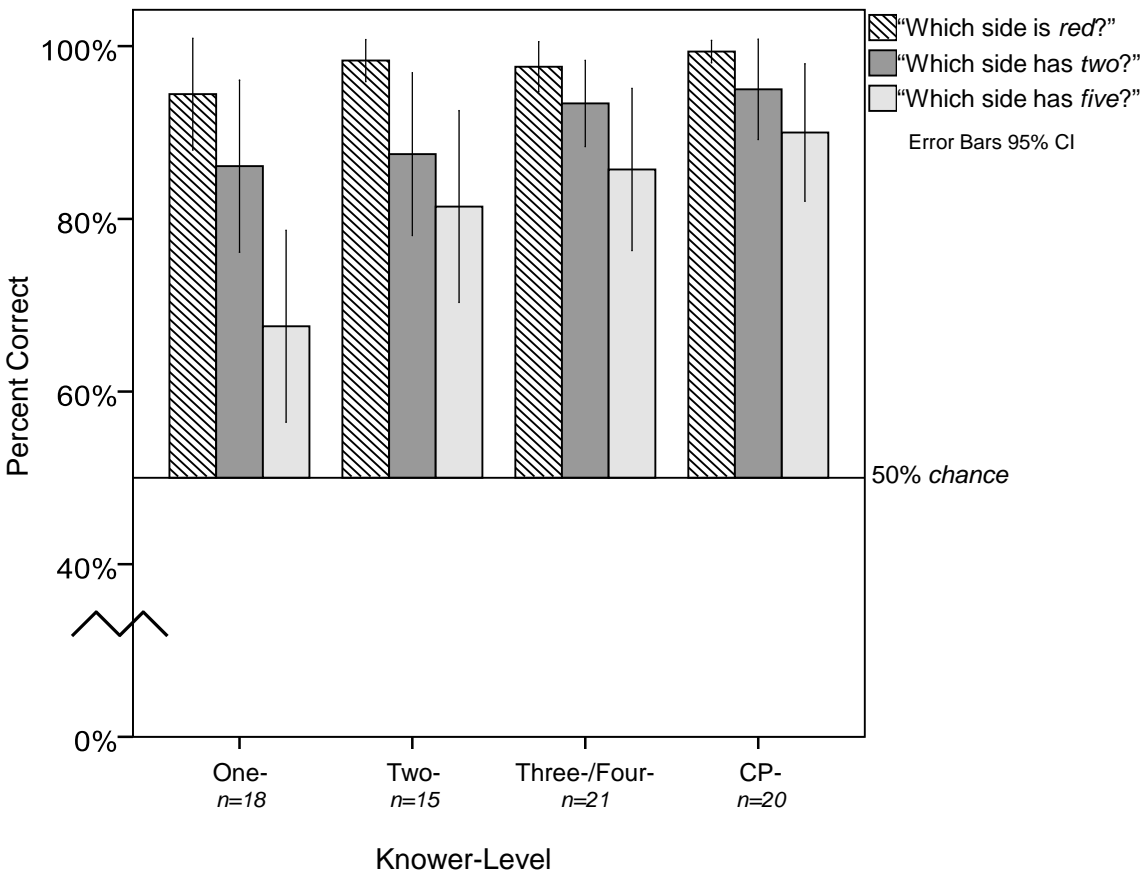
Performance across trial types showed no effect of knower level on color trials, $F(4,73)=1.13$, $p=.35$, ns. In fact, children at all knower levels were able to match the color word to the correct set of objects or substance at rates of 94-99% correct (see Figure 4). Children also performed well on the low-number trials, with rates of 85-95% correct, significantly above chance for each knower level, $p < .01$. While performance tended to increase with knower level (see Figure 4) the differences among knower levels did not reach statistical significance, $F(4,73)=2.13$, $p=.09$, ns.

There was, however, a strong relationship between children's knower level and their performance on high-number trials (i.e., the trials asking about *five* and *six*), $F(4,73)=3.48$, $p=.01$. As in Experiment 1, children at the three-, four-, and CP-knower levels were more likely than children in the one- and two-knower levels to apply the word *five* or *six* to a cup with discrete objects (Tukey's post-hoc comparisons, $p < .05$). However, unlike in Experiment 1, all knower levels performed significantly above chance on this trial type, $t(17)=3.33$, $p < .01$ for one-knowers, $t(14)=6.06$, $p < .01$ for two-knowers, $t(20)=7.936$, $p < .01$ for three- and four-knowers, and $t(19)=10.51$, $p < .01$ for CP-knowers. In other words, unlike Experiment 1, one- and two-knowers, on average, performed above chance on the high-number trials (see Figure 4).

A comparison of performance on low- and high-number word trials within subjects (repeated measures ANCOVA with knower-level as a between-subjects factor, trial type as a within-subjects factor, and age as a covariate) shows a main effect of knower level, $F(3,69)=19.06$, $p < .01$, reflecting the fact that one- and two-knowers were more likely to choose

the cup with discrete objects on low-number trials than high-number trials, while children in the three-, four-, and CP-knower levels chose the cup with discrete objects for both trial types (Tukey's post-hoc comparisons, $ps < .05$).

Figure 4. Children's performance on each trial type, Experiment 2.



To explore the possibility (noted in Experiment 1) that children might have a general bias toward choosing the full cup, we ran a multivariate ANCOVA with knower level as the independent variable and children's choice of the *full* cup (on low-number, high-number, and color trials) as dependent variables (age was included as a covariate). While there was no main effect of knower level, post-hoc analyses showed that children, as a group, were likely to choose the full cup over the half-empty cup when prompted with high-number words, $t(73)=2.37$, $p=.02$.

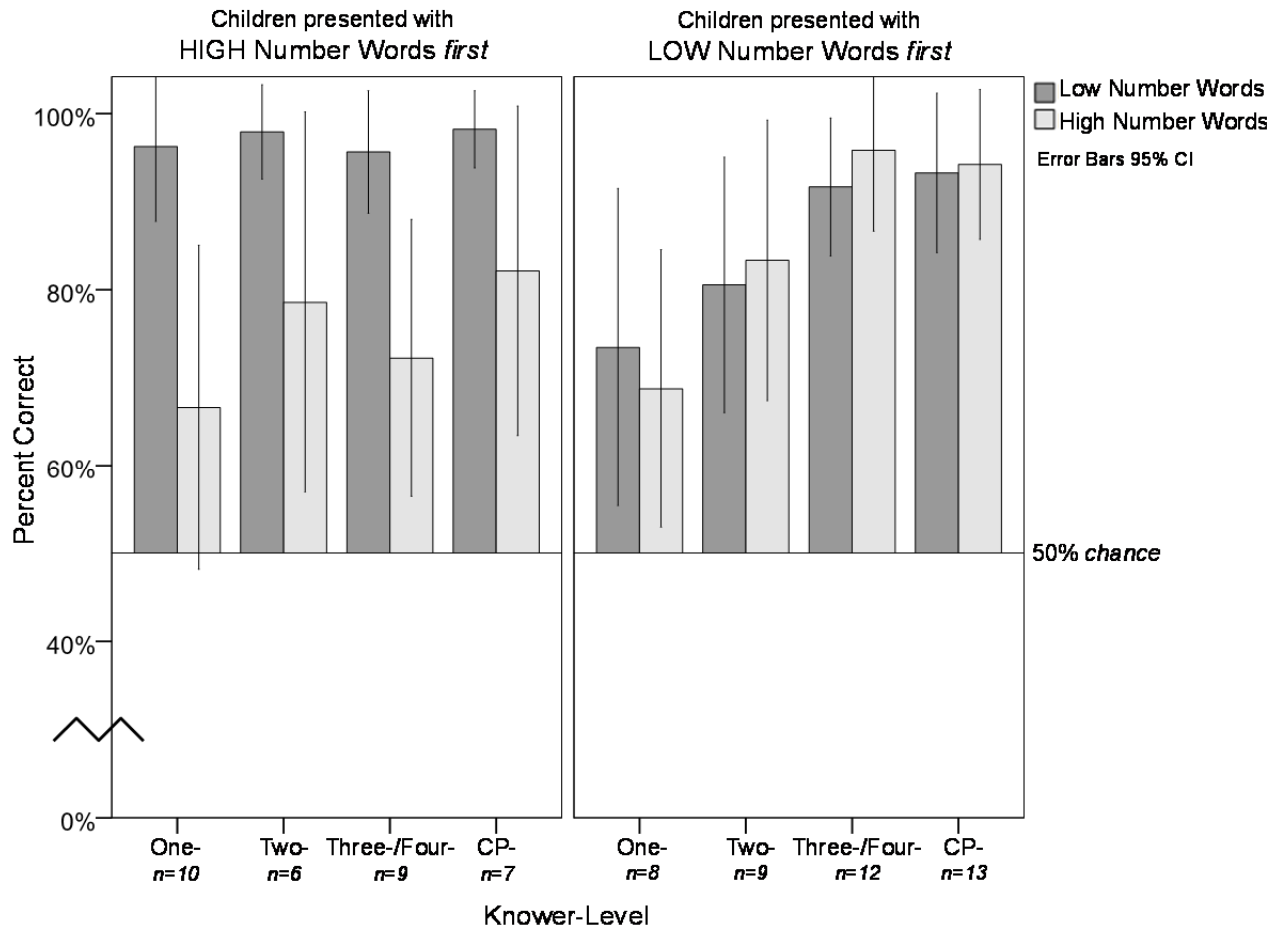
This tendency did not show up on low-number trials, $t(73)=.11$, $p=.92$, ns, or on color trials, $t(73)=.69$, $p=.50$, ns.

No general bias toward choosing either objects or substances was observed for any knower level. When asked (e.g.) “Which side is *green*?” children at all levels chose objects and substances with equal frequency, $ps>.05$, ns.

Although there was no *overall* effect of trial order (low-number trials first or high-number trials first), a multivariate ANCOVA looking at the effects of trial order and knower-level showed significant main effects of trial order on both low-number ($F(1,73)=16.46$, $p<.01$) and high-number trials ($F(1,73)=4.92$, $p=.03$). This reflected the fact that children who were presented with high numbers first did better on low-number trials, and children who were presented with low numbers first did better on high-number trials (see Figure 5). In other words, children tended to perform better on whichever block of trials they received *last*. However, children who were tested on high numbers first, and then low numbers, showed a much greater improvement than children who tested on low numbers first, and then high numbers $F(2,64)=14.44$, $p<.01$.

In fact, one-knowers who started with high numbers performed near chance on those high-number trials, $t(9)=2.04$, $p=.07$, ns (similar to Experiment 1, where there were no low-number trials at all). In contrast, one-knowers who started with low numbers performed above chance on the later block of high-number trials, $t(7)=2.81$, $p=.03$ (see Figure 5). Thus, in Experiment 2, even the least knowledgeable children did show some understanding that *five* and *six* apply to discrete objects; but they only showed this understanding if they had first been asked the same questions about *one* and *two*.

Figure 5. Children's performance on low- and high-number word trials.



Summary of Results

In Experiment 2, as in Experiment 1, children who knew the meanings of at least three number words (i.e., three-knowers and higher) were more likely to extend the words *five* and *six* to sets of discrete objects than to continuous substances. This effect was not carried by the CP-knowers, but was independently true for the three- and four-knowers, even though these children did not yet know the exact cardinal meanings of *five* or *six*.

For children who knew the meanings of only one or two number words (i.e., one- and two-knowers) the story was more complicated. These children reliably extended number words they knew (i.e., *one* and *two*) to sets of discrete objects, but were less confident about the words

five and *six*. Two-knowers succeed on the task—that is, they applied *five* and *six* to the discrete objects more often than chance would predict. The success of one-knowers, however, depended on whether they were asked about high or low numbers first. Children who were asked about *one* and *two* first made better-than-chance judgments about *five* and *six* later on. In contrast, children who were asked about *five* and *six* first performed at chance on these numbers.

As in Experiment 1, children did show a tendency to choose the full cup (regardless of whether it contained a set of discrete objects or a continuous substance), but this tendency only showed up on the high-number trials (not on the color or low-number trials). This finding might be explained in either of two ways: The first explanation is that children have a general bias toward choosing the full cup, but this bias is overridden when the child is confident of a word's meaning (as is the case with color words and low-number words). Thus, the full-cup bias may have surfaced on trials asking about *five* and *six* because children were unsure of which cup to choose. An alternative explanation is that children at the lower knower levels see *five* and *six* as words for large quantities and so choose the full cup on those trials. The first explanation would be more consistent with the existing literature (e.g., Carey, 1978; Clark, 1997; Klatzky, Clark, & Macken, 1973; Sarnecka & Gelman, 2004), but the question could certainly be taken up in future studies.

Another interesting and somewhat unanticipated result from Experiment 2 was how the presentation order of high- and low-number trials affected children's performance – children were more likely to succeed on the high-number trials if they had completed the low-number trials first. This finding seems to provide some support for the notion that children extrapolate properties of higher number words from their understanding of the first few low-number words. This may explain why one-knowers performed above chance on high-number trials *only* when

they were given the chance to do the task with low numbers first. However, the reverse is also true: Children performed better on the low-number trials if they had completed the high-number trials first (with performance on low-number word trials around 95% correct, regardless of knower level). In this case, it would seem odd to describe the knowledge as being ‘extrapolated’ from the previous block of trials, because these children clearly knew more about the low numbers than high numbers. Instead, it may be that the high-number trials simply served as a warm-up for the low-number trials.

General Discussion

The purpose of this study was to explore children’s early understanding of number words. We were specifically interested in the question of when children come to understand that number words quantify over sets of discrete individuals. At the outset, we could imagine at least three possibilities. One is that children understand this semantic constraint before they have acquired the exact meanings of any number words, and that this knowledge guides their acquisition of individual number-word meanings. A second possibility is that children may learn this constraint about each number word individually. A third possibility is that children learn this constraint as part of the individual meanings of a subset of number words, and then infer that the constraint is also true for other number words.

Clearly, evidence from these experiments does not favor the second account, as the children tested here extended *five* and *six* to sets of discrete objects before they knew the exact meanings of these words. This leaves the first and third possibilities (i.e., that children apply this constraint to number words from the outset, or that they learn it as a constraint on the meanings for the first few, low-number, words and then extrapolate it to the meanings of higher number words).

Our evidence seems to favor the latter account, for two reasons. First, although children at the one- and two- knower levels performed above chance on trials asking about *five* and *six*, their performance was significantly worse than that of three-knowers and above. In other words, the more low-number words a child knew, the better they performed on the high-number trials. This finding is consistent with other recent studies showing that children gradually learn that number words pick out numerosity (as opposed to some other dimension of experience) as they learn the exact meanings of individual number words (Condry & Spelke, 2008; Slusser & Sarnecka, 2011). For example, Condry & Spelke (2008) found that subset-knowers do not understand that the number word used to describe a set changes if and only if an object is added to or taken from the set. Similarly, Slusser & Sarnecka (2011) found that prior to understanding the Cardinal Principle, children do not understand that number words refer only to the numerosity of a set, and not to the properties of individuals in the set (i.e., their color) or to the set's continuous spatial extent (i.e., total area). The present study investigated an even broader aspect of number-word knowledge (i.e., what kinds of entities can be quantified using number words) and found that children in the early stages of learning have only a very fragile understanding that number words quantify over discrete objects.

The bulk of evidence seems to favor an account wherein children do not understand many aspects of number at the outset (c.f., Sarnecka & Gelman, 2004; Wynn, 1992). Instead, their understanding seems to be constructed as they gradually learn the meanings of the first few number words. The present study suggests that at least some aspects of the meanings of *five* and *six* are extrapolated from what children know about the meanings of *one*, *two* and *three*. While this inference alone will not provide the insight needed to acquire the exact meanings of higher

number words, it may serve to facilitate the process by constraining the possible meanings available for each unknown number word.

In sum, the present findings illustrate an intermediate step in the child's construction of number concepts. Of course, knowing that number words are about discrete quantification is not the first or the last step in constructing their meanings. Even before this step, there are things children have to know about the number words. For example, James (the child quoted at the beginning of this paper, who had *not* yet restricted their meaning to discontinuous quantification) had already memorized the number word list up to *ten*. Moreover, by reciting the words all together, James demonstrated an implicit understanding that these words somehow belong together— a necessary precondition for inferring anything about higher numbers from the lower ones. James also seemed to recognize that the number-word list had something to do with quantity; he produced the list to convey the idea that there was *enough* water in his bath. This is another precondition – one cannot connect number words to a particular type of quantification (discrete or continuous) without first connecting them to quantification in general.

Understanding that number words refer to discrete sets does not mark the end of the integer-concept construction process either. Three- and four-knowers may know that *five* and *six* apply to collections of discrete entities, but they do not yet understand how counting relates to exact numerosity (which is why they do not perform as Cardinal Principle Knowers on the Give-N task). Nevertheless, applying number words to discrete quantification is an important step. Its intermediate status (being neither the beginning, nor the end of the process) makes it evidence for the sort of extended conceptual-change process that so often characterizes human learning. By investigating the specific question of how children build number concepts one step at a time,

we gain insight into a general process by which humans transform their own conceptual resources from the ground up.

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Acknowledgements

This research was supported by the National Institute of Health (NIH R03HD054654 to B.S) and by a University of California, Irvine Social Science Fellowship (to E.S). The authors thank the children, families and staff of the preschools where this research was conducted. Thanks also to Meghan Goldman, Geoff Iverson, Michael Lee, Penelope Maddy, James Negen, Lisa Pearl, and Ted Wright for their helpful comments on earlier versions of the manuscript. Finally, thanks to lab managers Helen Braithwaite and Emily Carrigan, and to research assistants Elaine Cheong, Christina Do, Niyati Gupta, Elisa Hasrouni, Meghan Li, Sarah Pachman, Grace Park, Lori Park, Roxanna Salim, Diego San Martin, Jill Sorathia, Rochelle Telebrico, Farah Touiller, Archana Vaidyanathan, Simon Vakili and Vanessa Yanez. Preliminary analyses of a subset of these data were presented at the biennial meetings of the Society for Research in Child Development in 2007 and 2011.

Appendix A. Performance of *all* Experiment 1 participants who completed the Blocks and Water task.

Knower-Level	N	Mean Age	Age Range	Number Trials		Quantifier Trials	
				Mean % Correct	SD	Mean % Correct	SD
No Level	13	2;6	2;0 – 3;11	50%	32	62%	19
One-Knowers	13	3;2	2;5 – 4;0	46%	26	70%*	28
Two-Knowers	15	3;3	2;7 – 3;10	56%	28	68%*	28
Three- & Four-Knowers	22	3;6	2;9 – 4;5	70%*	25	75%*	27
CP-Knowers	19	3;11	3;6 – 4;4	83%*	25	92%*	15

Appendix B. Performance of *all* Experiment 2 participants who completed the Blocks and Water task.

Knower-Level	N	Mean Age	Age Range	Low-Number Trials		High-Number Trials		Color Word Trials	
				Mean % Correct	SD	Mean % Correct	SD	Mean % Correct	SD
No Level	13	2;9	2;6 – 3;6	71%*	27	62%	25	81%*	17
One-Knowers	18	3;2	2;6 – 3;11	86%*	20	68%*	22	94%*	13
Two-Knowers	15	3;0	2;4 – 3;8	88%*	17	81%*	20	98%*	4
Three- & Four-Knowers	21	3;7	2;10 – 4;2	93%*	11	86%*	21	98%*	6
CP-Knowers	20	3;8	3;2 – 4;1	95%*	12	90%*	17	99%*	3