Children master the cardinal significance of counting after they learn to count

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Abstract

Children learn the meaning of number words by going through a systematic set of stages of knowledge that culminates in their mastery of counting. Theoretical work has long suggested that children's acquisition of counting is not procedural, but semantic: all counters understand that counting computes cardinality. Yet, recent research has cast doubt on whether early counters truly understand the meaning of these words. Here we show that early counters also have an immature understanding of how one-to-one correspondence between an ordered list and a set of objects can be used to compute exact cardinality. Nonetheless, this understanding is improved when cues to quantity, such as size, are highlighted. Our results add to a growing body of work suggesting that counting is not a final stage in children's path to number, but a powerful tool that they can use to build and strengthen their intuitions about cardinalities.

Keywords: Cognitive development; number cognition; one-to-one correspondence.

Introduction

Children go through a systematic set of stages of knowledge when they learn number words and counting (Carey, 2009; Wynn, 1990; Fuson, 1988). First, children memorize the count list without knowing what these words mean (akin to learning a song like "eeny, meeny, miny, moe, …"), usually around the age of two. Children then slowly, but steadily, uncover the meaning of the words "one," "two," "three," and sometimes even "four," taking approximately six months to learn the meaning of each word. Children at these stages are called one-, two-, three-, and four-knowers, respectively, or subset-knowers collectively. After learning the meaning of the first three or four words, something clicks in children's minds. Rather than continuing to learn the meaning of number words one at a time, children suddenly, in what seems like a stroke of insight, grasp the logic of counting. Children at this stage, called *full counters*[1], can determine the size of any set (as long as they have memorized the count list up to that number). This last transition is a major milestone: the mastery of counting (Carey, 2009; Wynn, 1990; 1992; Piantadosi, Tenenbaum, & Goodman, 2012; Sarnecka & Lee, 2009; Lee & Sarnecka, 2010).

Theoretical work suggests that, in order to count correctly, children must understand five principles (Gelman & Gallistel, 1987). First, children must understand that any collection of objects can be counted (abstraction principle). To do so, objects must be placed in one-to-one correspondence with number words (one-to-one correspondence principle). The order in which the objects are counted is irrelevant (order irrelevance principle) but the order in which the number words are recited is not (stable order principle). When these steps are executed correctly, the word associated with the last object refers to the total number of objects in the set (the cardinal principle).

Research has long focused on the acquisition of the cardinal principle, as it is thought to be the key principle that marks the difference between children who can count, and children who cannot (Carey, 2009; Piantadosi, Tenenbaum, & Goodman, 2012). Yet, recent research has cast doubt on whether early counters have indeed grasped the conceptual logic of the cardinal principle. In a now classical study, Davidson, Eng, & Barner (2012) showed that children who had recently learned to count failed seemingly simple questions like determining whether "five" is more than "four." This work suggests that children's mastery of counting is a procedural milestone—learning to perform a complex set of rules in a systematic way—rather than a sematic milestone—learning that all number words refer to exact quantities and that counting computes a set's cardinality.

Nonetheless, if early counters are only missing the cardinal principle, they should understand how the rest of the principles combined can be used to determine a set's cardinality. Consider, for instance, watching an agent count two sets of objects. If the agent counts up to "six" in one set and up to "seven" in the second set, we can recognize that the second set has more objects because the set of words "one, two, …, seven" is larger than the set of words "one, two, …, six." Conceptually, this kind of inference only requires understanding that the objects were placed in one-to-one correspondence with the ordered list of number words. In practice, however, this type of inference is unavailable because it requires representing the list of words as a set of objects. However, if the objects were placed in one-to-one

[1] Full counters are classically called Cardinal Principle knowers (or CP-knowers for short; Carey, 2009; Lee & Sarnecka, 2010; Sarnecka & Lee, 2009; Piantadosi, Jara-Ettinger, & Gibson, 2014). Here we use a more neutral term that describes procedural competence without commitment to conceptual change because recent work suggests full counters may not know the cardinal principle yet (Davidson, Eng, & Barner, 2012; Jara-Ettinger, Piantadosi, Spelke, Levy, & Gibson, 2017).

correspondence with a visible set of objects, young counters may be able to perform these inferences.

Research into children's understanding of number principles suggests this may be the case. Three-year-olds understand that two small sets placed in one-to-one correspondence must be of equal size (Sophian, 1988; Gelman, 1982), and, at an earlier age, 18-month-olds preferentially look at counting events that follow one-to-one correspondence over events that do not (and this preference disappears when the agent uses novel words or beeps; Slaughter, Itakura, Kutsuki, & Siegal, 2011). At the same time, classical studies were performed with small sets that even infants can track, independent of their knowledge of number (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002), and children's performance in other numerical tasks suggests that young children do not grasp the full significance of how one-to-one correspondence relates to exact number (Shipley & Shepperson, 1990; Izard, Streri, & Spelke, 2014).

Here we test if young counters can determine a set's cardinality by watching an agent apply all the counting principles using a list where the words are not names for cardinalities. We introduced participants to an ordered list of animals that someone used to count two sets of objects. Children could not see the two sets of objects, but they could see the agent placing them in one-to-one correspondence with the animal list in a stable order. If children understand the logic of these principles, they should be able to determine which of the two sets has more objects (as this only requires seeing on which set the counter reached an animal further along in the list). If, however, children are unable to identify which set has more objects, this would suggest that a robust understanding of how these counting principles help reveal exact cardinality emerges after children learn to count.

Experiment 1

In Experiment 1 participants watched an agent count two sets of hidden objects by placing them in one-to-one correspondence with an ordered list of animals (Figure 1a). Participants were then asked to determine which of the two boxes had more objects. Participants completed three trials. Two of these trials were controls to ensure that children understood that the agent was placing the animals in one-to-one correspondence with the objects. The first control trial contrasted two with three objects (such that, if children understand that the agent was placing the unobservable objects in one-to-one correspondence with the animals, they should identify the box with three objects by simply tracking the small quantities; Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002). The second control trial contrasted three with six objects (such that if children understand the one-to-one correspondence between objects and animals, they should identify the box with six objects by relying on their approximate number system; Xu & Spelke, 2000; Xu, 2003; Lipton & Spelke, 2003; Wood & Spelke, 2005). Finally, the critical trial contrasted six versus seven objects, which can only be solved if children understand how a proper application of counting principles reveals exact cardinality. Hypotheses, procedure, exclusion criteria, and analyses were pre-registered.

Methods

Participants. 60 full counters, as determined by the Give-N Task (Wynn, 1992; Carey, 2009, Sarnecka & Lee, 2009; Lee & Sarnecka, 2010) were recruited for this study (mean age: 4.88 years; range = 3.35-5.98). Twenty-nine additional children were recruited for the study, but not included because the experimenter determined they did not know how to count based on pre-registered criteria (n=16; see Procedure); because a coder blind to hypothesis determined that the participant did not know how to count (n=10; see Results) or because they declined to complete the study (n=3 participants; see Results).

Stimuli. The stimuli consisted of two bowls and ten bouncy balls for the Give-N task. For the animal task, the stimuli consisted of an ordered animal list, composed of eight animals ordered by size (Figure 1a), eight erasers, and three videos, each showing an agent counting objects in two opaque boxes using the ordered animal list.

Procedure.

Give-N Task. Children were presented with one bowl with ten bouncy ball and one empty bowl. The task always began with a request to move four bouncy balls from one bowl to the other. After each query, all bouncy balls were returned to the first bowl. If the child succeeded in this first trial, the next request was to move five bouncy balls. If the child failed, the next request was to move one bouncy ball. The task then followed a stair-cased procedure: children were asked to move $N+1$ bouncy balls if they moved N bouncy balls correctly, and were asked to move $N-1$ bouncy balls otherwise, with two exceptions: the same request was repeated when children failed at $N=1$ and when they succeed at $N=8$ (ensuring that moving all bouncy balls was never the correct answer).

Whenever children's error was off by (at most) two bouncy balls, the experimenter asked "Is that N bouncy balls? Can you count them for me please?" If the child recognized an error, the experimenter asked "Can you fix it so there are N bouncy balls in the bowl?" The experimenter recorded the original and the revised answers, and used the final answer to determine the next trial. Only participants who correctly moved four bouncy balls at least once proceeded to the one-to-one correspondence task (as determined in the pre-registration; although note that all participants who participated in the one-to-one correspondence were coded afterwards to test if they knew how to count; see Results).

Animal task. Participants were introduced to a non-numeric ordered list that consisted of eight animals ordered from left to right based on size (from smallest to largest; Figure 1a): ant, mouse, cat, pig, cow, bear, elephant, giraffe. Children were given a printed version of this list that they could consult at any time. To show how an agent would count using this list, the experimenter counted a line of four identical objects visible to the child using the list ("ant, mouse, cat, pig"), and then counted a line of eight visible objects using the list ("ant, mouse, …, elephant, giraffe"). The experimenter counted out loud while using their finger to touch each item as they pronounced each animal name in the non-numeric ordered list and emphasized the final word. The experimenter then restated the final word of the count list (e.g., "there are giraffe objects"). After the warm-up, children completed three test trials (order counterbalanced across participants). In each trial, participants watched a video of an agent counting the objects in two boxes. The boxes were visible, but their contents were not. Immediately after counting the items in the box, the agent placed a picture of the corresponding animal on each box and then stated how many items were in the box using the non-numeric animal list. The animals were scaled by size on the printed list that children received, and on the pictures attached to the boxes (see below).

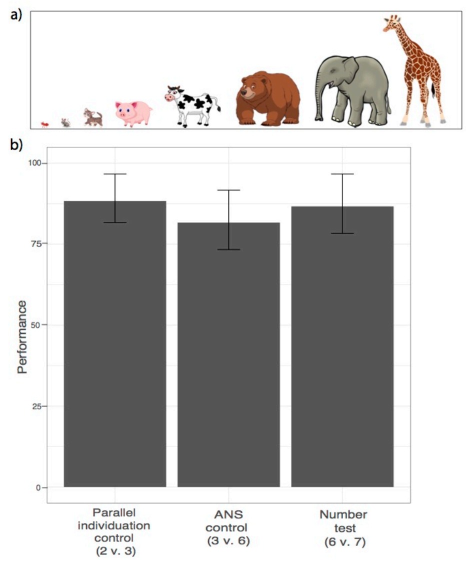

Figure 1. a) Animal list used in Experiment 1. b) Results from Experiment 1. The x axis shows the trial and the y axis shows the percentage of participants who correctly identified the box with more objects. Vertical lines show 95% bootstrapped confidence intervals. Overall, participants were able to identify which box had more objects in all three trials.

The three counterbalanced trials consisted of a 2 v. 3 trial, a 3 v. 6 trial, and a 6 v. 7 trial. In the 2 v. 3 trial the agent counted two objects in one box and then three objects in another box using the animal list (order in which boxes were counted counterbalanced). In the 3 v. 6 trial the agent counted three objects in one box and then the agent counted six objects in another box using the non-numeric ordered list (order counterbalanced). Finally, in the 6 v. 7 trial the agent counted six objects in one box and then seven objects in a second box using the non-numeric ordered list (order counterbalanced). The first two trials were control trials, as they could be solved by tracking number of words uttered via the parallel individuation system (2 v. 3 trial; Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002), or they could be distinguished through the approximate number system (3 v. 6 trial; Xu & Spelke, 2000; Xu, 2003; Lipton & Spelke, 2003; Wood & Spelke, 2005). The last trial (6 v. 7) was the critical one, as it can only be solved by understanding how the assignment of objects to animals reveals exact cardinality.

Trial order was counterbalanced across participants. In all videos, the agent counted out loud while using their finger to touch the inside of the box as they pronounced each animal name in the non-numeric ordered list. After each video, children were shown a picture of the two boxes, each labeled with the animal corresponding to the number of objects in the box, and they were asked which box has more blocks in it.

Results and Discussion

A coder blind to the experiment hypothesis coded whether children who participated in the one-to-one correspondence study knew how to count, based on their Give-N responses.

Participants who were not determined to be full counters by decision of a coder blind to hypothesis were excluded from the study and replaced (n = 10). An additional 3 participants were excluded and replaced because they did not want to complete the study.

Figure 1b shows the results from the experiment. Participants overwhelmingly succeeded in the 2 v. 3 and in the 3 v. 6 trials, showing that they understood the task. Of the 60 full counters included in the study, 88.3% (95% CI: 78.33-95.00; N=53 participants) correctly identified the box with more objects in the 2 versus 3 trial, and 81.7% of participants (N=49; 95% CI: 70.00-90.00) correctly identified the box with more objects in the 3 versus 6 trial.

Participants also succeeded in the critical 6 v. 7 trial. 86.6% of participants (N=52; 95% CI: 78.33-96.97) correctly identified the box with more objects in the 6 v. 7 trial. Together, these results suggest that children were able to understand that the number of recited animals revealed the quantity of objects in the set.

To test for any developmental change, we ran a mixed-effects logistic regression predicting children's response in the critical number trial (6 v. 7) as a function of age (as a continuous variable), with trial order as a random intercept. These results suggested that children's performance improved as a function of age ($\beta = 1.87$, $p < 0.01$; See Figure 2).

Children's ability to succeed in the 6 versus 7 trial of this experiment suggests that children understand how following the counting principles can reveal a set's cardinality. Critically, this understanding can happen without recognizing that the words themselves are names for different set sizes.

At the same time, it is possible that children's performance was facilitated by the use of an animal list ordered by size. Specifically, children may have simply followed a heuristic where they always pointed to the larger

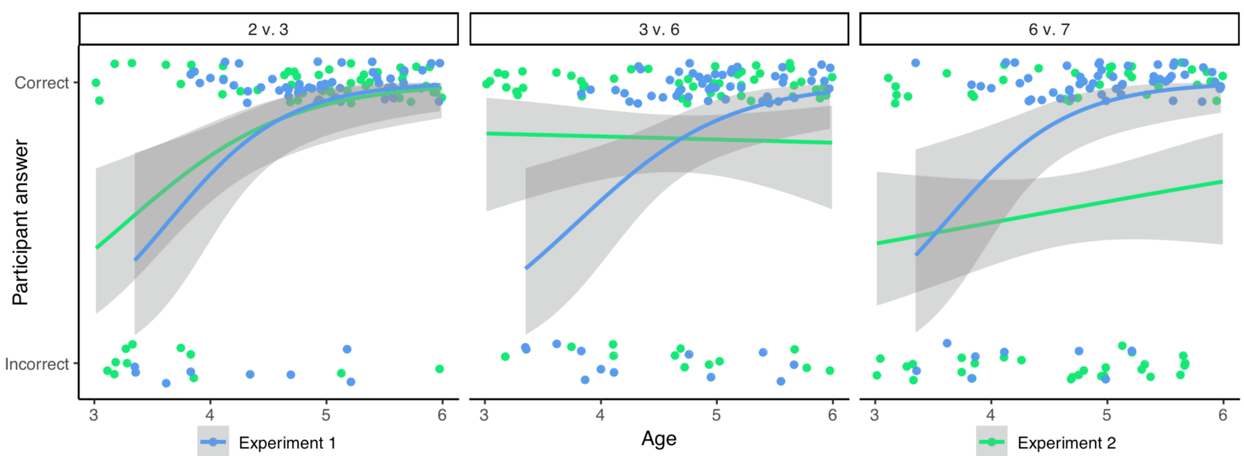

Figure 2. Participant responses in both experiments. Each dot represents a participant answer. The x-axis shows their age, and the y axis shows whether they identified the box with more objects. Data is minimally jittered on the y-axis for visibility purposes but was not jittered on the x-axis. Color indicates the experiment and the lines show logistic regressions.

animal without a deep understanding of how counting relates to cardinality. We test for this possibility in Experiment 2.

Experiment 2

Experiment 2 was conceptually identical to Experiment 1, with the difference that we used an animal list where the animals were no longer ordered on the basis of size, such that animals associated with larger quantities were not visually larger. Hypotheses, procedure, exclusion criteria, and analyses were pre-registered.

Methods

Participants. 60 full counters, as determined by the Give-N Task (Wynn, 1992; Carey, 2009, Sarnecka & Lee, 2009; Lee & Sarnecka, 2010) were recruited for this study (mean age: 4.67 years; range = 3.01-5.99). Nineteen additional children were recruited for the study, but not included because the experimenter determined they did not know how to count based on a pre-registered criterion (n=9; see Procedure); because a coder blind to hypothesis determined that the participant did not know how to count, as determined by a pre-registered coding procedure (n=8; see Results); or due to an error playing the experiment videos (n=2; see results).

Stimuli. Stimuli were identical to those in Experiment 1 with one exception. The counting list for this study consisted of eight different animals, ordered by color (Figure 3a).

Procedure. Methods for this study were identical to those from Experiment 1 with one exception. Instead of ordering the list by size, we now used a list of animals ordered by color (green, blue, purple, magenta, pink, red, orange, yellow): alligator, frog, octopus, butterfly, flamingo, lobster, fox, duck (Figure 3a). The size of the animals was matched on the printed list that children received and on the pictures attached to the boxes. Children completed the Give-N task, and the warm-up, as described in the previous experiment, using this new ordered list.

Children then completed the same three counterbalanced trials from Experiment 1: a 2 v. 3 trial, a 3 v. 6 trial, and a 6 v. 7 trial. After each video, children were shown a picture of the two boxes, each labeled with the animal corresponding to the number of objects in the box, and asked which box has more blocks in it.

Results and Discussion

Results were coded in the same way as Experiment 1. Eight participants were excluded from the study because they had not yet learned how to count. Two additional children were excluded because the experimental videos did not load properly.

Figure 3b shows the results from the experiment. Overall, participants succeeded in the two control trials, confirming that participants understood that the agent who counted was placing the objects in one-to-one correspondence with the animal list, and that the uttered animals revealed the number of objects in the set. Of the 60 full counters included in the study, 81.7% of participants (N=49; 95% CI: 71.67-91.67) correctly identified the box with more objects in the 2 v. 3 trial, and 80.0% of participants (N=48; 95% CI: 70.00-90.00) correctly identified the box with more objects in the 3 versus 6 trial. By contrast, only half of participants were now able to solve the critical 6 v. 7 trial. In this critical trial, only 55.0% of participants (N=33; 95% CI: 41.67-68.33) identified the box with seven objects.

To test for any developmental change, we ran a mixed-effects logistic regression predicting children's response in the critical number trial (6 v. 7) as a function of age (as a continuous variable), with trial order as a random intercept. These results suggested that children's performance did not improve as a function of age ($\beta = 0.3$; $p = 0.29$; See Figure 3).

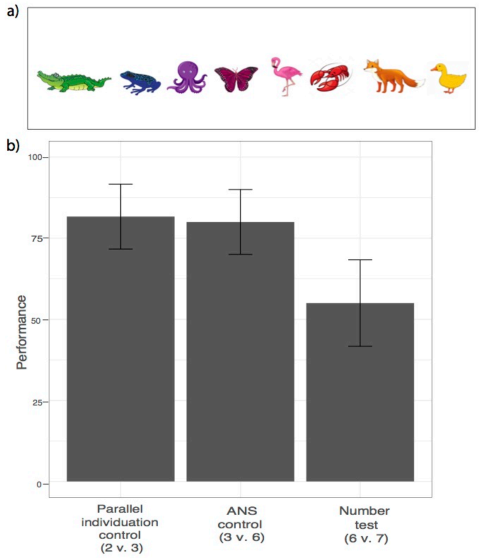

Figure 3. a) Animal list used in Experiment 2. b) Results from the experiment. The x axis shows the trial and the y axis shows the percentage of participants who correctly identified the box with more objects. Vertical lines show 95% bootstrapped confidence intervals. Overall, participants were able to identify box had more in the the 2 vs 3 and the 3 vs 6 trials. By contrast, only half of the participants succeeded in the critical 6 vs 7 trial.

These results conflict with those from Experiment 1, and they suggest that children did not recognize that the animal list could be used to determine exact cardinality. If they did, they could have solved the 6 v. 7 trial simply by consulting the list of animals and checking whether the set crocodile-lobster (six animals) was smaller or larger than the set alligator-fox (seven animals) were farther along the list. Note also that children always had a printed version of the list in front of them, and that pictures of the corresponding animals were placed in front of each box, minimizing concerns explainable by memory constraints.

These results suggest that children's success in Experiment 1 was supported by the use of animals ordered by size. Similarly, their overall failure in this experiment suggests that children understood that animals were being placed in one-to-one correspondence with the animal list, as they were able to solve the two control trials, but that they did not recognize that, through this process, children could determine the exact number of objects in the set.

General Discussion

Here we tested whether children who can count understand how the counting principles can be used to determine a set's exact cardinality, even without knowing the cardinal-principle—the understanding that the last word during counting refers to the size of the entire set. In Experiment 1 children watched an agent count the number of objects in two opaque boxes via one-to-one correspondence with a non-numerical animal list ordered by size (Figure 1a). Children were able to identify which box had more objects when the agent counted two objects in one box and three objects in the other, when the agent counted three objects in one box and six objects in the other, and when the agent counted six objects in one box and seven objects in the other (Figure 1b). Experiment 2 replicated this study using an animal list where the size of the animals was kept constant (Figure 3a). While children continued to successfully identify the larger set in the two control trials, their performance was drastically lower in the critical trial (Figure 3b).

Children's success in the two versus three trial, and in the three versus six trial in both experiments shows they understood that the number of words the agent uttered revealed the quantity of objects (Note also that children completed two warm-up trials where they saw the agent place two visible sets of objects in one-to-one correspondence with the animal list). However, success in these trials does not imply a mature understanding of how the counting procedure reveals exact cardinality. Past research has shown that children can distinguish between two and three sounds via the parallel individuation system (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002) and that they can distinguish between three and six sounds via the approximate number system (Xu & Spelke, 2000; Xu, 2003; Lipton & Spelke, 2003; Wood & Spelke, 2005). By contrast, because children cannot perceptually distinguish between six and seven sounds, they could only solve this by understanding how the counting procedure reveals exact cardinality.

Critically, in our study, children did not need to understand the cardinal principle to succeed. If children recognized that the agent was placing the hidden objects in one-to-one correspondence with the animal list, they could have solved the task through at least two strategies. A first strategy is through awareness that, when counting principles are applied, later items reveal greater quantities. If children understood this, they would need to only find which animal comes later in the list to perform at ceiling. However, even if children did not recognize that later symbols in a count list reveal greater quantities, they could have solved the task through a second strategy: When the agent counted up to a certain animal, children could consult their list and see a set of animals that is numerically identical to the set of hidden objects (e.g., when the agent counted to butterfly in Experiment 1, children could see their list and recognize that the set of animals starting in crocodile and ending in butterfly is a set of the same size than the set of hidden objects that was counted). Through this strategy, children could recognize that one of the sets of animals is a subset of the other, making it trivial to identify which bowl had more objects.

The results from Experiment 1 are consistent with two possibilities. A first possibility is that children's ability to determine which of two sets had more objects improves when we the list includes a cue to number (by ordering the animal's based on size; Figure 1a). However, it is also possible that varying the size of the animals did not help children link the animal list to cardinalities. Instead, children may have simply selected the larger animal without conceptually understanding why this would be the correct answer. Note, however, that children's performance in the 2 v. 3 and the 3 v. 6 trials was near-identical in Experiment 1 and Experiment 2. If children were simply pointing to the larger animal in Experiment 1, one might expect better performance relative to Experiment 2. In addition, older children were more likely to succeed in the 6 v.7 trial in Experiment 1. Intuitively, if children were relying on a size heuristic, younger children should have succeeded as well. Future work will test if this alternative can explain children's improved performance in Experiment 1.

In this study we recruited three-, four-, and five-year-olds and only tested children who were able to count. Because, in the US, children usually learn to count at around age four (Piantadosi, Jara-Ettinger, & Gibson, 2014; Wynn 1990, 1992), it is likely that most of our participants had just learned how to count. However, older participants are more likely to have known how to count for a longer time such that experience with counting and age were likely correlated in our sample. Thus, our finding that children improved in the 6 v. 7 trial in Experiment 1 does not reveal whether this improvement was due to age, or due to experience with counting. Future work will disambiguate between these possibilities.

Altogether, our results suggest that children who know how to count have yet to reach a mature understanding of how the counting principles reveal exact cardinalities. Our results add to a body of work that suggests that children's mastery of the counting procedure is not a final milestone in children's mastery of number words. Related work has also shown that young counters may also lack the cardinal principle (Davidson, Eng, & Barner, 2012; see introduction for review). Combined, this work suggests that when children learn to count, they master a set of procedural rules with only a partial understanding of how these rules relate to cardinality. Under this view, children's ability to count may be a building block towards their understanding of number words and cardinality rather than an endpoint. By learning to count, children may begin to notice a relationship between the set size and the final number word when counting, helping them realize that counting computes cardinality. Future work will test this hypothesis. What our findings do show, is that children's mastery of counting is an intermediate step in children's path to knowledge, and we add to a growing body of work suggesting that children's acquisition of procedural number knowledge may precede a mature understanding of the meaning of number words and counting (Jara-Ettinger, Piantadosi, Spelke, Levy, & Gibson, 2017; Davidson, Eng, & Barner, 2012; Cheung & LeCorre, 2015).

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