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Infants recognize counting as numerically relevant

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Abstract

Children do not understand the meanings of count words like "two" and "three" until the preschool years. But even before knowing the meanings of these individual words, might they recognize that counting is "about" the dimension of number? Here in five experiments, we asked whether infants already associate counting with quantities. We measured 14- and 18-month olds' ability to remember different numbers of hidden objects that either were or were not counted by an experimenter before hiding. As in previous research, we found that infants failed to differentiate four hidden objects from two when the objects were not counted—suggesting an upper limit on the number of individual objects they could represent in working memory. However, infants succeeded when the objects were simply counted aloud before hiding. We found that counting also helped infants differentiate four hidden objects from six (a 2:3 ratio), but not three hidden objects from four (a 3:4 ratio), suggesting that counting helped infants represent the arrays' approximate cardinalities. Hence counting directs infants' attention to numerical aspects of the world, showing that they recognize counting as numerically relevant years before acquiring the meanings of number words.

KEYWORDS
approximate number system, counting, infants, number words, working memory

1 | INTRODUCTION

Infants and animals attend to quantities from the start of life (Izard, Sann, Spelke, & Streri, 2009; Rugani, Vallortigara, & Regolin, 2013). The primitive representations they use are imprecise, supporting the discrimination of quantities only when their ratio is sufficiently large. For example, 6-month olds can distinguish 8 dots from 16 on the basis of approximate numerosity, but not 8 from 12 (Xu & Spelke, 2000). The approximate number system (ANS) representations that underlie this performance are inexact, but support basic arithmetic operations even in infancy (McCrink & Wynn, 2004).

Numerate humans also have access to exact integer representations (Feigenson, Dehaene, & Spelke, 2004). Unlike ANS representations, integers allow observers to represent small numerical differences, like that between 100 and 101. Doing so relies on mastering the logic of linguistic counting (Carey, 2009)—a process that takes years. Wynn (1990, 1992) found that children start this process at around 2.5 years old, when they begin to recite the count list but do not yet know what the count words mean. Roughly 6 months later, children come to understand the meaning of "one;" 6 months after that they learn the meaning of "two," and another 6 months later, "three." After this piecemeal learning, at about age four, children come to understand the cardinal principle (Sarnecka & Carey, 2008; Wynn, 1990): that the last word in any count sequence represents the set's exact cardinality.

Integer representations and approximate number representations exhibit distinct phylogenetic and ontogenetic signatures (Carey, 2009). Yet, the two ultimately are mapped together, as shown by people's ability to verbally estimate the number of elements in an uncounted array- thereby using exact integer words to describe an approximate numerosity (Whalen, Gallistel, & Gelman, 1999). Moreover, integer-based symbolic math performance correlates with individual differences in numerical approximation abilities across the lifespan (Chen & Li, 2014; Feigenson, Libertus, & Halberda, 2013; Schneider, et al., 2017, for reviews).

How do these two numerical systems, with their distinct representational formats, first become linked? Many children in Western cultures begin experiencing integer words starting in infancy, in the form of hearing parents or caregivers engage in verbal counting (Goldstein, Cole, & Cordes, 2016). By 18 months, infants are sensitive to some procedural aspects of counting, preferring to watch correct counting over counting that violates the principles of one-to-one correspondence or stable order (Ip, Imuta, & Slaughter, 2018; Slaughter, Itakura, Kutsuki, & Siegal, 2011). Yet, children apparently do not map between individual number words in the counting sequence and particular approximate numerosities until age 4 years or later. Only then do they successfully produce uncounted arrays that are proportional to verbally requested numbers, produce number words proportional to the numerosity of briefly flashed arrays, or show electrophysiological signatures of the ANS when hearing spoken number words (Le Corre & Carey, 2007; Odic, Le Corre, & Halberda, 2015; Pinhas, Donohue, Woldorff, & Brannon, 2014; Wagner & Johnson, 2011). The relative lateness of this mapping between number words and ANS representations, plus the finding that children also lack exact meanings for number words until roughly the same age, raises a puzzle: What meaning, if any, do number words have for young children?

One possibility is that from infancy until the preschool years, count words have no meanings other than their memorized order (as in the case of sequences like "eeny, meeny, miney, mo") (Carey, 2009). But another possibility, as yet untested, is that number words have partial meanings even at these earliest stages. Early on, children may form a very general mapping between count words and the dimension of number in the world, long before learning the meanings of any particular number word. An analogy comes from the case of color words. Children do not reliably map color words to their referents until the preschool years. Yet up to a year before knowing that, for example, "red" refers to redness, children recognize that "red" refers to *some* color, without knowing which one (Wagner, Dobkins, & Barner, 2013). Similarly, young children may recognize that counting refers to quantities without knowing that, for example, "three" refers to exactly or approximately three.

Here we asked when children first recognize counting as being "about" number, by testing whether verbal counting would help infants represent arrays of hidden objects. In five experiments we tested 14- to 20-month olds in a manual search task that, in previous studies, reveals a strict upper limit on infants' ability to represent hidden objects. Infants watched varying numbers of identical objects hidden in a box. Next they saw either all or only a subset of these objects retrieved, and then their searching of the box was measured. In previous work, infants from 12- to 22-months successfully represented arrays of one, two, and three objects, continuing to search the box if any of the objects remained hidden. In contrast, infants failed with larger arrays; for example, infants who saw four objects hidden failed to keep searching the box after only one or two of them were retrieved (Feigenson & Carey, 2003, 2005). These findings show that infants in this task attempt to represent arrays using individual object representations—which are precise but subject to working memory limits, rather than approximate number representations—which are noisy but have no upper limit (Barner, Thalwitz, Wood, Yang, & Carey, 2007; Feigenson & Carey, 2003, 2005). In the present experiments we asked whether seeing objects counted prior to hiding would change this often-replicated pattern of performance. If infants recognize counting as "about" number, then observing counting might help them represent arrays exceeding working memory limits. Specifically, we hypothesized that counting might promote infants' use of approximate number representations in situations in which ANS representations are not otherwise deployed.

Research Highlights

- Although children do not understand count words like "two" and "three" until 3–4 years, a more basic understanding of counting might be present much earlier.
- Here we found that 14- and 18-month-old infants remembered more hidden objects when objects were counted before hiding than when they were not.
- Infants' ability to remember counted objects was approximate and ratio-dependent.
- Counting directs infants' attention to the dimension of numerosity long before children understand the meanings of individual count words.

2 | EXPERIMENT 1

2.1 | Method

2.1.1 | Participants

Sixteen full-term infants between 17- and 20-month olds participated (mean age 19.42 months; *SD* = 0.92 months; eight girls). The sample size was chosen based on previous research using the manual search task (e.g., Barner *et al*., 2007; Feigenson & Carey, 2005; Feigenson & Halberda, 2008). Twelve infants were identified by their parents as White, and one as Black; parents of the remaining infants declined to report infants' racial or ethnic background. Four additional infants were excluded for fussiness (three) or equipment failure (one). All infants across Experiments 1–5 came from English-speaking households, and all received a small gift (e.g., t-shirt, book, or toy) to thank them for their participation.

2.1.2 | Stimuli

Infants watched objects being hidden in a black box (40.5 cm × 25 cm × 12 cm) whose front face had a spandex-covered

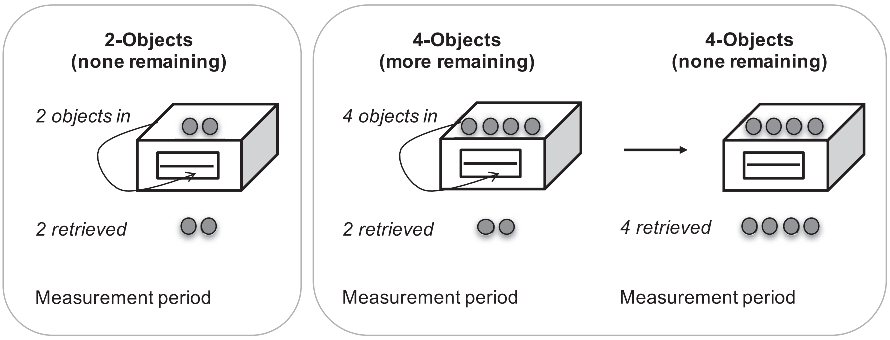

FIGURE 1 Schematic of the measurement periods in Experiment 1. Stimuli depicted as circles for ease of viewing

opening with a slit through which infants could reach without seeing inside. The box's rear face had a secret opening through which the experimenter could reach to withhold objects on critical trials. The stimulus objects were four identical beige toy dogs (6.3 cm tall) and four identical blue toy cars (7.2 cm long).

2.1.3 | Design and procedure

Infants started with a brief familiarization that gave them practice seeing objects hidden and retrieving them from the box, and then were administered two test blocks. In one, infants saw objects individually indicated before they were hidden, but without number words (No Counting block); in the other, infants saw objects counted (Counting block). Block order was counterbalanced across infants, as was whether the Counting block was paired with toy dogs or cars.

Within each block there were three measurement periods, presented twice each (Figure 1). *2-Objects (none remaining)* measurement periods measured infants' searching after two objects had been hidden and both of them retrieved. The experimenter showed infants two identical toys (dogs or cars) atop the box, and pointed to each either without counting (No Counting block), or with (Counting block). In the No Counting block the experimenter pointed to the objects in turn, producing a non-counting utterance for each ("Look! This, this!"), then indicated the array using a circular pointing motion ("These dogs/cars!"). In the Counting block the experimenter counted the objects aloud, then stated the array's cardinality while making the same circular pointing motion ("Look! One, two! Two dogs/ cars!"). The experimenter then picked up the toys and inserted them sequentially through the front of the box, again producing an utterance for each (i.e., either "One, two!" or "This, this!"). Infants subsequently were allowed to reach into the box and retrieve both toys. Almost all infants immediately did so, but if they failed to retrieve the toys within 5 s, the experimenter helped (this was true across all trial types, across all experiments). After both toys had been retrieved, the 10-s measurement period began. After these 10-s, the experimenter picked up the box and shook it to show that it was empty, saying "Shall we play again?"

4-Objects (more remaining) measurement periods measured searching after four objects had been hidden and just two of these retrieved. The experimenter showed infants four identical toys atop the box, and either pointed at each without counting (No Counting block: "This, this, this, this! These dogs/ cars!"), or with counting (Counting block: "One, two, three, four! Four dogs/ cars!"). The experimenter then picked up the toys and inserted them through the front face of the box while labeling each, either saying "This, this, this, this!" or "One, two, three, four!" Infants were allowed to reach into the box and retrieve two of the toys while the experimenter secretly held the remaining two out of reach in the back of the box. The 10-s measurement period then began. After it ended, the experimenter reached through the front of the box and showed infants as she retrieved the remaining two toys, saying, "What else is in there?"

4-Objects (none remaining) measurement periods immediately followed the 4-Objects (more remaining) sequence just described. After the experimenter had "helped" infants retrieve the two missing toys from the previous 4-Objects (more remaining) period, infants were allowed to search the (now empty) box for 10 more seconds.

Whether infants were first presented with a 2-Objects (none remaining) or 4-Objects (more remaining) trial was counterbalanced across infants. 4-Objects (none remaining) measurement periods always immediately followed 4-Objects (more remaining) measurement periods. Infants' searching was coded from video by two naïve observers (inter-coder reliability r = 98%).

2.2 | Results

Infants' search times first were averaged across the two repetitions of each measurement period within each block. Analyses were performed on these averaged search times.

A 2 (Block: No Counting vs. Counting) × 2 (Block Order: No Counting first vs. Counting first) × 3 (Measurement Period: 2-Objects (none remaining), 4-Objects (more remaining), 4-Objects (none remaining)) repeated-measures ANOVA found no effect of Block, $F(1,14) = 1.30$, $p = 0.27$, $\eta_p^2 = 0.09$; infants did not search longer overall after hearing objects counted versus not counted. There was neither effect of Block Order nor any interaction between Block, Block Order, and Measurement Period, $Fs < 0.88$, $ps > 0.39$. The analysis did reveal a significant effect of Measurement Period, $F(2,28) = 8.33$, $p = 0.001$, $\eta_p^2 = 0.59$, showing that infants' searching depended on how many objects had just been hidden and retrieved.

Critically, this was qualified by a significant Block × Measurement Period interaction, $F(2,28) = 3.92$, $p = 0.03$, $\eta_p^2 = 0.28$. Whether infants searched differentially across the three measurement periods depended on whether they had just heard the objects counted (Figure 2).

We had predicted that infants would search longer when more objects remained in the box, but only when the objects had been counted prior to hiding. To test this prediction, we examined the difference in infants' searching on 4-Objects (more remaining) measurement periods versus searching when the box was actually empty (i.e., averaged searching on 2-Objects (none remaining) and 4-Objects (none remaining) measurement periods). If the subtraction of these (here called Increased Searching) is above zero, this would indicate that infants successfully searched the box longer when it contained more objects than when it was empty. Planned *t*-tests revealed that infants' Increased Searching did not differ from zero in the No Counting Block (*M* Increased Searching = 0.41 s, *SD* = 1.84 s), $t(15) = 0.89$, $p = 0.39$. Hence, without counting, infants failed to differentiate four from two hidden objects. In contrast, infants' Increased Searching in the Counting block was significantly greater than zero (*M* Increased Searching = 1.78 s, *SD* = 1.80s), $t(15) = 3.96$, $p = 0.001$, and significantly greater than Increased Searching in the No Counting block, $t(15) = 2.09$, $p = 0.05$. This success was also observed when the two types of none remaining measurement periods were not averaged. Within the Counting block, infants searched longer in the 4-Objects (more remaining) measurement periods than either of the two none remaining measurement periods, *ts* > 3.6, *ps* < 0.003, whereas the two none remaining measurement periods did not differ, $t(15) = 0.03$, $p = 0.97$.

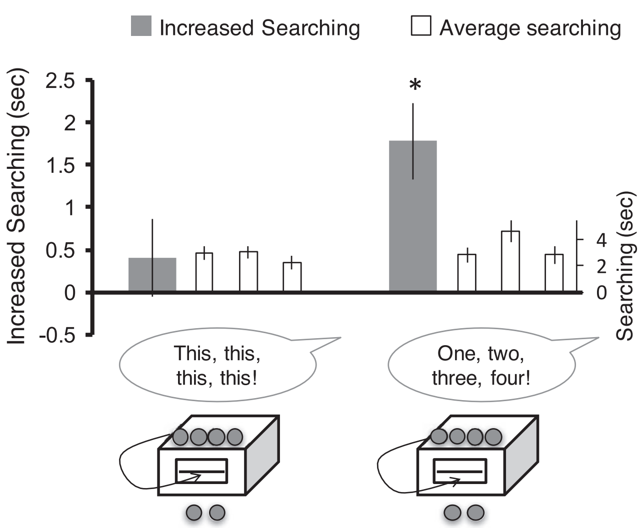

FIGURE 2 Results of Experiment 1. Average Increased Searching (searching when the box contained more objects minus searching when it was empty) (filled bars; left axis), and average searching during each measurement period (2-Objects (none remaining), 4-Objects (more remaining), 4-Objects (none remaining), respectively; open bars; right axis). Error bars: ±1 *SEM*

2.3 | Discussion

In previous studies, 12- to 22-month olds failed to represent four hidden objects concurrently (Barner *et al.*, 2007; Feigenson & Carey, 2003, 2005). This failure was replicated by the 19-month-old infants in the No Counting block of Experiment 1. But strikingly, when the same infants saw the arrays counted prior to hiding, they succeeded—continuing to search after seeing four objects hidden and only two of these retrieved. Despite being years from acquiring the meanings of individual number words, infants benefitted from observing counting.

How did counting help? One possibility is that counting highlighted the individual objects in the array, helping infants form and maintain representations of four items in working memory. Alternatively, counting may have triggered infants to represent the arrays' approximate cardinalities, effectively bypassing working memory limits by allowing infants to maintain a single summary representation of the array's numerosity. Experiment 2 tested these possibilities by asking whether counting helped infants represent the precise number of objects hidden. Infants' searching was measured after seeing four objects hidden and three (rather than two) of them retrieved. If counting helped infants maintain more individual object representations in memory, they should successfully represent the difference between three objects and four, and so should continue searching for the missing object. But if counting instead triggered infants to represent approximate cardinalities, then because children do not robustly discriminate a 3:4 ratio using the ANS until at least 3 years of age (Halberda & Feigenson, 2008; Odic, Libertus, Feigenson, & Halberda, 2013), the ANS's imprecision should prevent infants from continuing to search for the missing object.

3 | EXPERIMENT 2

3.1 | Method

3.1.1 | Participants

Sixteen full-term infants between 17- and 19-month olds participated (mean age 18.68 months; *SD* = 0.59 months; nine girls). Twelve were identified as White, one as Black, and the parents of the remaining infants declined to report their racial or ethnic background. Six additional infants were excluded for fussiness (four), parental interference (one), and equipment failure (one).

3.1.2 | Design, stimuli, and procedure

Infants were administered two test blocks in which objects were always counted prior to hiding. In one block, when four objects were hidden, infants retrieved two of them before their searching was measured (2- vs. 4-Objects Block). This block was identical to the Counting block of Experiment 1, and contained the following measurement periods, presented twice each: 2-Objects (none remaining), 4-Objects (more remaining), and 4-Objects (none remaining). In the other block, when four objects were hidden, infants were able to retrieve three of them before their searching was measured (3- vs. 4-Objects Block). This block contained the following measurement periods, presented twice each: 3-Objects (none remaining), 4-Objects (more remaining), and 4-Objects (none remaining). Stimuli and procedure were as in Experiment 1, and block order was counterbalanced across infants.

3.2 | Results

A 2 (Block: 2- vs. 4-Objects or 3- vs. 4-Objects) × 2 (Block Order: 2 vs. 4 first or 3 vs. 4 first) × 3 (Measurement Period: 2- or 3-Objects (none remaining), 4-Objects (more remaining), 4-Objects (none remaining) repeated-measures ANOVA revealed no effect of Block, $F(1,14) = 0.005$, $p = 0.95$, $\eta_p^2 < 0.001$. There was also no significant effect of Measurement Period, $F(2,28) = 1.16$, $p = 0.33$, $\eta_p^2 = 0.08$, and no significant Block x Measurement Period interaction, $F(2,28) = 1.80$, $p = 0.18$, $\eta_p^2 = 0.13$. There was neither effect of Block Order nor interaction between Block, Block Order, and Measurement Period, $Fs < 1.53$, $ps > 0.23$.

Despite the lack of a Block × Measurement Period interaction, planned *t*-tests revealed that when objects were counted prior to hiding, infants successfully differentiated two objects from four, but not three objects from four (Figure 3). As in Experiment 1, we averaged infants' searching on the two measurement periods when the box was empty and subtracted this baseline from searching when there were more objects in the box (4-Objects (more remaining)−((2 or 3-Objects (none remaining)+4-Objects (none remaining))/2). This Increased Searching was significantly greater than zero when four objects had been hidden and two retrieved (*M* Increased Searching = 1.09s, *SD* = 1.93s), $t(15) = 2.26$, $p = 0.04$, but not when four objects were hidden and three retrieved (*M* Increased Searching = −0.21s, *SD* = 1.99s), $t(15) = -0.42$, $p = 0.68$. Infants' Increased Searching was marginally greater in the 2- vs. 4-Objects Block than the 3- vs. 4-Objects Block, $t(15) = 1.74$, $p = 0.10$.

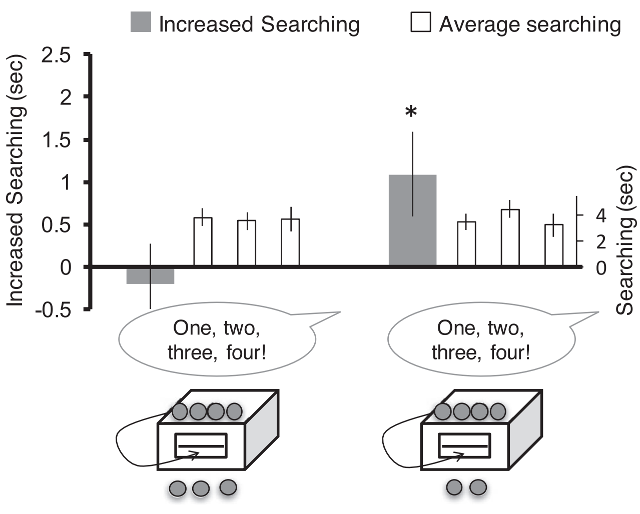

FIGURE 3 Results of Experiment 2. Error bars: ±1 *SEM*

As an additional check to confirm infants' success at discriminating 2 from 4 counted objects, we compared their performance in the 2- vs. 4-Objects block in Experiment 2 with that in the Counting block of Experiment 1. A 2 (Experiment 1 or Experiment 2) × 3 (Measurement Period: 2-Objects (none remaining), 4-Objects (more remaining), 4-Objects (none remaining) repeated-measures ANOVA with searching as the dependent measure revealed a significant effect of Measurement Period, $F(2,60) = 12.24$, $p < 0.001$, $\eta_p^2 = 0.29$, and neither effect of Experiment, $F(1,30) = 0.089$, $p = 0.77$, $\eta_p^2 = 0.003$, nor any Block × Measurement Period interaction, $F(2,60) = 0.77$, $p = 0.46$, $\eta_p^2 = 0.025$. Across Experiments 1 and 2, infants' who saw objects counted prior to hiding successfully differentiated four from two.

3.3 | Discussion

Experiment 2 replicated the surprising finding that infants represented 4-object arrays that were counted prior to hiding. Furthermore, it revealed that counting did not allow infants to differentiate four hidden objects from three, suggesting that infants represented the counted arrays imprecisely. This is consistent with the "noisy" representations of the ANS.

However, a further test of the hypothesis that counting triggered infants to deploy the ANS is to present infants with larger arrays. Because the ANS is not subject to an upper representational limit, it should allow infants to represent arrays that exceed working memory capacity—arrays that fail to activate the ANS in the absence of counting (Barner *et al.*, 2007; Feigenson *et al.*, 2004; Feigenson & Carey, 2003, 2005). In addition, presenting infants with larger arrays can address an alternative interpretation of infants' performance. Zosh and Feigenson (2015) found that infants' ability to track hidden objects was affected by the heterogeneity of the arrays. With identical objects, infants shown arrays that exceed working memory capacity (e.g., four objects) fail to represent even a subset of the array. That is, they fail to represent three of the four presented objects, even though doing so would seem to be within working memory limits (Feigenson & Carey, 2003, 2005; Feigenson, Carey, & Hauser, 2002). Yet this "catastrophic failure" is prevented when objects contrast with each other (e.g., a brush, bottle, duck, spoon, rather than ball, ball, ball, ball). Such heterogeneity allows infants to maintain representations of a subset of a supra-capacity array, so that infants represent four as three. Might counting similarly have served to make objects more distinct, thereby allowing infants in Experiments 1 and 2 to represent three of the four presented objects? This account would not implicate an understanding of the link between counting and number, but would instead show an effect of highlighting individuals on working memory encoding and/ or storage.

To test this, in Experiment 3 we presented infants with arrays containing four versus six objects, well beyond working memory limits (Barner & Carey, 2007; Feigenson & Carey, 2004; Feigenson & Carey, 2003, 2005; Ross-Sheehy, Oakes, & Luck, 2003). If counting merely amplifies the contrast between objects, thereby allowing infants to represent just three of the objects in these arrays, then

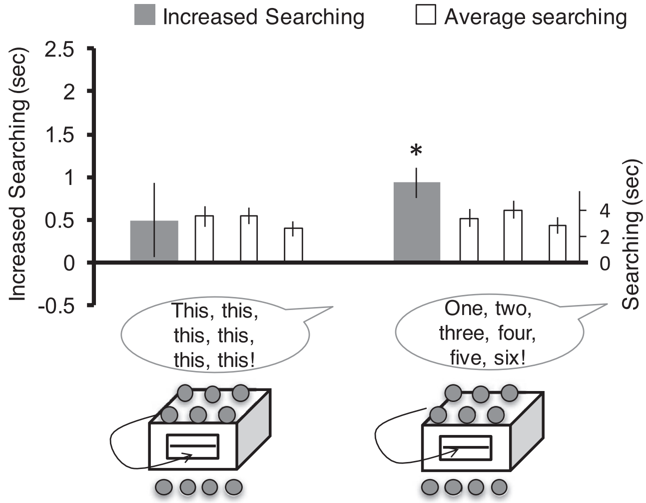

FIGURE 4 Results of Experiment 3. Error bars: ±1 *SEM*

infants should represent 4- and 6-object arrays similarly and so should not continue searching after seeing six objects hidden and four of these retrieved. But if counting triggers infants to deploy the ANS to represent the approximate number of objects present, they should succeed, given that infants can differentiate the ratio between 4 and 6 objects (2:3) by 9 months (Lipton & Spelke, 2003).

4 | EXPERIMENT 3

4.1 | Method

4.1.1 | Participants

Sixteen full-term infants between 17- and 19-month olds participated (mean age 18.84 months; *SD* = 0.72 months; seven girls); 15 were identified by their parents as White, and one as Black. Four additional infants were excluded for fussiness.

4.1.2 | Stimuli

Stimuli were as in Experiments 1 and 2.

4.1.3 | Procedure

The design and procedure paralleled those of Experiment 1. Infants were tested in one block in which objects were individually labeled without counting prior to hiding (No Counting block), and one block in which objects were counted (Counting block). For both blocks the three measurement periods were 4-Objects (none remaining), 6-Objects (more remaining), and 6-Objects (none remaining).

4-Objects (none remaining) measurement periods measured infants' searching after four objects were hidden and all of them retrieved. The experimenter showed infants four identical toys (dogs or cars) atop the box, and either referred to each without counting (No Counting block: "Look! This, this, this, this! These dogs/cars!"), or with counting (Counting block: "Look! One, two, three, four! Four dogs/cars!"). Infants then saw the experimenter pick up the toys and insert them sequentially into the box, again referring to each either with or without counting. Infants then retrieved all four objects and their searching of the empty box was measured for 10 s.

6-Objects (more remaining) measurement periods measured infants' searching after six objects had been hidden and four of them retrieved. The experimenter showed infants six identical toys atop of the box (in two rows of three, as in Feigenson & Halberda, 2008) and referred to each either without counting (No Counting block: "Look! This, this, this, this, this, this! These dogs/ cars!") or with counting (Counting block: Look! One, two, three, four, five, six! Six dogs/ cars!"). Infants then saw the experimenter pick up the toys and insert them into the box while referring to each either with or without counting. Infants were next allowed to reach into the box and retrieve four of the toys; the experimenter secretly withheld the remaining two in the back of the box. A 10-s measurement period then began during which infants' searching was measured. After these 10 s, the experimenter reached through the front of the box and showed infants as she retrieved the remaining two toys, saying, "What else is in there?"

6-Objects (none remaining) measurement periods immediately followed 6-Objects (more remaining) measurement periods, and measured infants' searching for 10 s after all six objects had been retrieved.

Counterbalancing was as in Experiment 1.

4.2 | Results

A 2 (Block: No Counting vs. Counting) × 2 (Block Order: No Counting first vs. Counting first) × 3 (Measurement Period: 4-Objects (none remaining), 6-Objects (more remaining), 6-Objects (none remaining) repeated-measures ANOVA revealed no effect of Block, $F(1,14) = 0.13$, $p = 0.73$, $\eta_p^2 = 0.009$. There was a significant effect of Measurement Period, $F(2,28) = 7.22$, $p = 0.003$, $\eta_p^2 = 0.52$, but no Block x Measurement Period interaction, $F(2,28) = 0.57$, $p = 0.57$, $\eta_p^2 = 0.04$. There was neither effect of Block Order nor interaction between Block, Block Order, and Measurement Period, $Fs < 0.26$, $ps > 0.66$.

As in our previous experiments, we averaged infants' searching on the two measurement periods when the box was empty and subtracted this baseline from searching when more objects remained (6-Objects (more remaining)−(4-Objects (none remaining)+6-Objects (none remaining))/2). Planned *t*-tests tests showed that infants failed in the No Counting block: Increased Searching was not different from zero (*M* Increased Searching = 0.50s, *SD* = 1.71s), $t(15) = 1.16$, $p = 0.26$. In contrast, infants successfully differentiated six from four in the Counting block (*M* Increased Searching = 0.94s, *SD* = 0.70s), $t(15) = 5.37$, $p < 0.001$ (Figure 4).

As a further check of infants' ability to represent these larger arrays, we compared their performance with 4 versus 6 objects in Experiment 3 with their performance with 2 versus 4 objects in Experiment 1. A 2 (Experiment 1 vs. 3) × 2 (Block: No Counting vs. Counting) repeated-measures ANOVA on Increased Searching revealed a significant effect of Block, $F(1,30) = 4.60$, $p = 0.04$, $\eta_p^2 = 0.15$, with greater Increased

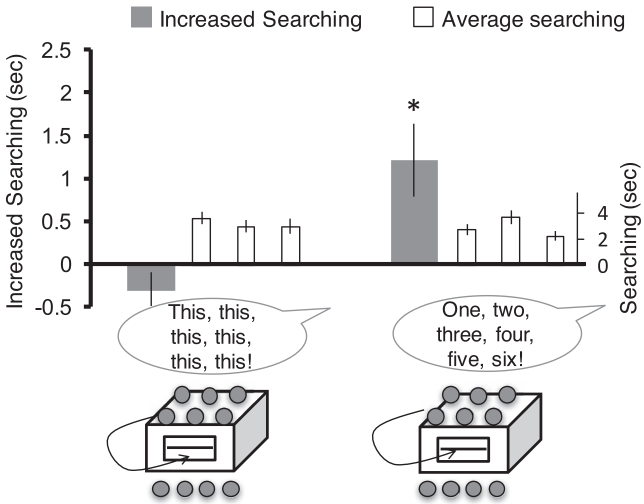

FIGURE 5 Results of Experiment 4. Error bars: ±1 *SEM*

Searching in the Counting than the No Counting block. There was neither effect of Experiment, $F(1,30) = 1.04$, $p = 0.32$, $\eta_p^2 = 0.03$, nor any Block × Experiment interaction, $F(1,30) = 1.22$, $p = 0.28$, $\eta_p^2 = 0.04$, suggesting that infants experienced similar benefits from counting when remembering 4-object and 6-object arrays.

4.3 | Discussion

Infants in Experiment 3 failed to represent either the exact or approximate number of uncounted objects in 6-object arrays, but succeeded when these same arrays were verbally counted. Because the arrays exceeded working memory limits, infants appear to have used the ANS to represent the arrays' approximate cardinalities.

However, this conclusion is tempered by the lack of a significant Block by Measurement Period interaction in Experiment 3. As predicted, in the absence of counting infants did not search statistically longer after seeing six objects hidden and only four retrieved; however, their search pattern bore some resemblance to that in the Counting block. One possible interpretation of these findings is that by 18 months, infants had begun to spontaneously represent large numbers of objects as approximate numerosities; hearing objects counted prior to hiding may have bolstered this fragile success. To test this interpretation, we next replicated Experiment 3 with younger, 14-month-old infants—an age group previously shown to robustly fail to remember six hidden objects, even approximately (Feigenson & Halberda, 2008).

5 | EXPERIMENT 4

5.1 | Method

5.1.1 | Participants

Sixteen full-term infants between 13- and 14-month olds participated (mean age = 13.93 months; *SD* = 0.27 months; seven girls). Eleven were identified by their parents as White, one as Black, and the parents of four infants declined to report their racial or ethnic background. Three additional infants were excluded for fussiness.

5.1.2 | Stimuli, design, and procedure

The design, stimuli, and procedure were as in Experiment 3.

5.2 | Results

A 2 (Block: No Counting vs. Counting) × 2 (Block Order: No Counting first vs. Counting first) × 3 (Measurement Period: 4-Objects (none remaining), 6-Objects (more remaining), 6-Objects (none remaining) repeated-measures ANOVA revealed no effect of Block, $F(1,14) = 0.47$, $p = 0.50$, $\eta_p^2 = 0.03$. The analysis did reveal a significant effect of Measurement Period, $F(2,28) = 3.51$, $p = 0.04$, $\eta_p^2 = 0.25$, and a significant Block × Measurement Period interaction, $F(2,28) = 4.36$, $p = 0.02$, $\eta_p^2 = 0.31$. Whether infants searched differentially across the three measurement periods depended on whether they had just heard the objects counted (Figure 5). There was neither effect of Block Order nor any interaction between Block, Block Order, and Measurement Period, *Fs* < 1.31, *ps* > 0.28.

As in our previous experiments, we averaged infants' searching on the two measurement periods when the box was empty and subtracted this baseline from searching when there were more objects in the box (6-Objects (more remaining)−(4-Objects (none remaining)+6-Objects (none remaining))/2). Planned *t*-tests on this Increased Searching revealed that infants failed to differentiate six from four hidden objects in the No Counting block (*M* Increased Searching = −0.32s, *SD* = 0.90s), $t(15) = -1.41$, $p = 0.18$, but succeeded in the Counting block (*M* Increased Searching = 1.21s, *SD* = 1.69s), $t(15) = 2.85$, $p = 0.01$. Increased Searching was greater in the Counting than the No Counting block, $t(15) = 2.85$, $p = 0.01$.

These results suggest that like 18-month-old infants, 14-month-old infants are better able to represent the approximate numerical information in an object array after experiencing the objects being counted, even for arrays well exceeding working memory limits.

5.3 | Discussion

Experiments 1–4 suggest that counting helps infants represent the approximate cardinality of object arrays. Which aspects of the counting routine promote infants' attention to number? Counting contains a variety of cues that infants might use to identify it as distinct from other verbal acts (Gelman & Gallistel, 1986; Ip *et al.*, 2018; Slaughter *et al.*, 2011). Alternatively, simply hearing each objects indicated with a distinct verbal label might have influenced infants' performance, given that hearing distinctive labels has been found to help infants individuate objects (Xu, Cote, & Baker, 2005), and chunk objects into groups (Feigenson & Halberda, 2008). Does counting change infants' performance over and above the mere act of distinctive labeling?

In Experiment 5 we asked whether infants would successfully represent 4-object arrays when the objects were verbally indicated aloud without counting. Infants saw four identical objects, but instead of hearing them counted infants heard them labeled with unique proper names. Proper names are among infants' earliest comprehended words (Tincoff & Jusczyk, 1999), and infants treat them differently from count nouns by 16- to 20-months (Bélanger & Hall, 2006). If infants' success in Experiments 1–4 relied on recognition of counting, as distinct from unique verbal labeling, infants should fail to remember the uncounted 4-object arrays in Experiment 5. To ensure that any such failure was not caused by the potentially less pragmatically familiar situation of hearing objects labeled with proper names, we also included a control condition in which proper names were used to refer to smaller arrays that were easily within infants' working memory capacity (1 vs. 2 objects).

6 | EXPERIMENT 5

6.1 | Method

6.2 | Participants

Sixteen full-term infants between 17- and 18-month olds participated (mean age = 17.85 months; *SD* = 0.66 months; six girls). Fourteen were identified by their parents as White, and two as Black. Five additional infants were excluded for fussiness (three) and experimenter error (two).

6.2.1 | Stimuli, design, and procedure

Infants were tested in a Within Capacity block in which we compared their searching for 1 versus 2 hidden objects, and a Beyond Capacity block in which we compared their searching for 2 versus 4 objects (with block order counterbalanced across infants). In both blocks, infants heard objects labeled with proper names before hiding. Stimuli were as in Experiment 1.

The Within Capacity block contained three measurement periods presented twice each. *1-Object (none remaining)* periods measured infants' searching after one object was hidden and retrieved. The experimenter showed infants a toy car atop the box, labeled it with a proper name ("Look! This is Bobby!"), indicated it again, saying "Look at this!", then inserted the object into the box while again labeling it with the proper name (i.e., "Bobby!"). Infants then retrieved the toy and their searching was measured.

2-Objects (more remaining) measurement periods measured infants' searching after two objects had been hidden and just one of them retrieved. The experimenter showed infants two identical cars atop the box and labeled each with a proper name ("Look! This is Bobby, Eddie!"), then pointed to the array using a circular motion and said, "Look at this!" Infants then saw the experimenter pick up both toys and insert them into the box, again labeling each ("Bobby, Eddie!"). Infants were allowed to reach into the box and retrieve one of the toys; the experimenter secretly withheld the other one. The 10-s measurement period then began. After 10 s, the experimenter reached into the box and showed infants as she retrieved the remaining object, saying, "What else is in there?"

2-Objects (none remaining) measurement periods immediately followed 2-Objects (more remaining) measurement periods, and measured infants' searching for 10 s after both objects had been retrieved.

The Beyond Capacity block was identical to the Counting block in Experiment 1, except that infants heard objects labeled with proper names instead of count words. For example, on 4-Objects (more remaining) measurement periods, the experimenter pointed to the objects and said, "Look! This is Sophie, Katie, Annie, Mary!" Then instead of circling all the toys and labeling their cardinality, the experimenter said, "Look at this!" Infants then saw the experimenter pick up the four toys and insert them sequentially into the box, again referring to each with the same proper name (i.e., "Sophie, Katie, Annie, Mary!").

6.3 | Results

A 2 (Block: Within Capacity vs. Beyond Capacity) × 2 (Block Order: Within first vs. Beyond first) × 3 (Measurement Period: 1- or 2-Objects (none remaining), 2- or 4-Objects (more remaining), 2- or 4-Objects (none remaining) repeated-measures ANOVA revealed no effect of Block, $F(1,14) = 0.04$, $p = 0.85$, $\eta_p^2 = 0.003$. There was a marginally significant effect of Measurement Period, $F(2,28) = 3.08$, $p = 0.06$, $\eta_p^2 = 0.22$, qualified by a significant Block × Measurement Period interaction, $F(2,28) = 4.29$, $p = 0.02$, $\eta_p^2 = 0.31$. Whether infants searched differentially across the three measurement periods depended on array size (Figure 6). There was neither effect of Block Order nor any interaction between Block, Block Order, and Measurement Period, $Fs < 1.83$, $ps > 0.18$.

We next averaged infants' searching on the two measurement periods when the box was empty and subtracted this baseline from searching when there were more objects in the box (2- or 4-Objects (more remaining)−(1- or 2-Objects (none remaining)+2- or 4-Objects (none remaining))/2). Planned *t*-tests on this Increased Searching revealed that infants successfully differentiated one from two hidden objects (*M* Increased Searching = 1.15s, *SD* = 1.78s), $t(15) = 2.57$, $p = 0.02$, whereas they failed to differentiate two from four hidden objects (*M* Increased Searching = 0.31s, *SD* = 1.01s), $t(15) = 1.14$, $p = 0.27$. Increased Searching was greater in the Within Capacity than the Beyond Capacity block $t(15) = 2.59$, $p = 0.02$. These results suggest that hearing objects being labeled by a list of distinct proper names does not help infants differentiate four hidden objects from two.

7 | GENERAL DISCUSSION

The present experiments asked whether infants recognize the link between counting and numerical quantities. Using a manual search task, we first replicated previous findings that in the absence of counting,

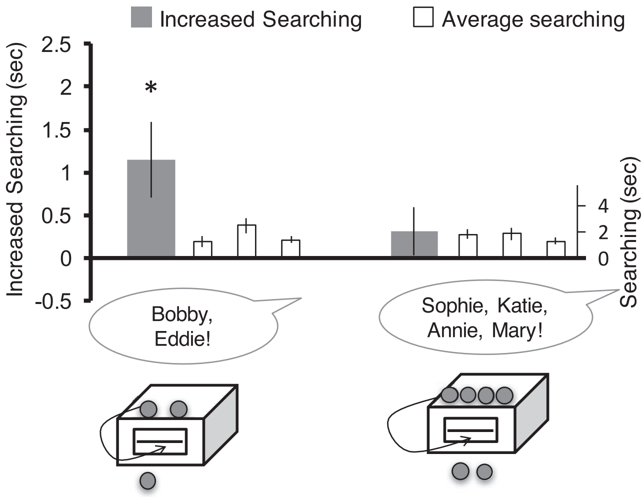

FIGURE 6 Results of Experiment 5. Error bars: ±1 *SEM*

18-month olds fail to differentiate four hidden objects from two. Our new finding was that simply watching the objects being counted caused these same infants to succeed—infants continued searching after seeing four objects counted, then hidden, and two of these retrieved (Experiment 1). We next probed the source of this success, and found two pieces of evidence that counting caused infants to represent the approximate cardinality of the arrays. First, counting did not help infants represent the arrays precisely, as infants failed to differentiate four hidden objects from three (Experiment 2). Second, counting helped infants represent arrays that exceeded the limits on individual object representation: both 14- and 18-month olds failed to differentiate six uncounted objects from four, but succeeded after seeing the objects counted (Experiments 3 and 4). Finally, we asked whether counting affects infants differently from other acts of verbal labeling. We found that although infants who heard objects labeled with proper names successfully represented arrays of one and two objects, proper names did not help them represent arrays of four objects (Experiment 5). Thus, counting affects infants' representation of object arrays years before children understand the meaning of individual count words, showing infants recognize a link between counting and approximate numerosity.

The counting experience that many infants receive from early in life (Goldstein *et al.*, 2016) may provide an opportunity to notice that counting often occurs in the presence of quantities—a co-occurrence that could lead infants to link the two. For such a link to form, infants must recognize instances of counting as distinct from other utterances. Which aspects of counting do infants recognize, such that they deploy the ANS? By 18 months, infants detect violations of one-to-one correspondence and stable order in counting (Ip *et al.*, 2018; Slaughter *et al.*, 2011)—one or both of these might need to be instantiated in a counting event for infants to activate the ANS. Alternatively, familiarity with actual count words in the sequence might be critical, rather than recognition of abstract counting principles. Previous research finds that children do not know the precise meanings of "one" and "two" until 2.5–3 year olds (Wynn, 1990). However, even if children lack *exact* meanings, they may have linked number words to the general dimension of numerosity. Note that the results of Experiment 5 do not distinguish these accounts, because infants heard instances of labeling that both failed to instantiate key counting principles (like the cardinal word principle; Gelman & Gallistel, 1986), and that were clearly not count words. To test whether counting principles or familiar number word tokens underlie infants' performance, infants might be shown arrays that are counted correctly in a foreign language, or arrays that are counted with familiar number words in a sequence that violates counting principles. Such investigations are an important step for future work.

These results provide evidence for the earliest known link between nonverbal approximate numerical representations and counting– an important component of symbolic mathematics. Of course, the link demonstrated here is a primitive one: the simple recognition that counting has something to do with the dimension of numerosity. Still, this very basic link could plausibly serve as a partial foundation for children's later learning of counting and construction of exact integer representations, although this possibility remains speculative (see also Wagner, Chu, & Barner, 2018). Some evidence suggests that early exposure to certain counting activities significantly contributes to children's later number knowledge (Gunderson & Levine, 2011). Consistent exposure to counting may help direct infants' attention to the duel possibility of representing arrays both as sets of individual objects (i.e., distinct individuals that can be precisely represented), and as a collection with an approximate cardinality; this may in turn facilitate children's eventual learning of the meanings of count words. Future research should test the relationship between early numerical experience in infancy, infants' recognition of counting, and children's later number skills. Given our finding that experiencing counting modulates infants' attention to number even in infancy, counting may play an earlier role in emerging number representations than previously thought.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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