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RESEARCH ARTICLE

What aspects of counting help infants attend to numerosity?

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Abstract

Recent work shows that 18-month old infants understand that counting is numerically relevant—infants who see objects counted are more likely to represent the approximate number of objects in the array than infants who see the objects labeled but not counted. Which aspects of counting signal infants to attend to numerosity in this way? Here we asked whether infants rely on familiarity with the count words in their native language, or on procedures instantiated by the counting routine, independent of specific tokens. In three experiments ($N = 48$), we found that 18-month old infants from English-speaking households successfully distinguished four hidden objects from two when the objects were counted correctly, regardless of their familiarity with the count words (i.e., when objects were counted in familiar English and in unfamiliar German). However, when the objects were counted using familiar English count words in ways that violated basic counting principles, infants no longer represented the arrays, failing to distinguish four hidden objects from two. Together with previous findings, these results suggest that children may link the procedure of counting with numerosity years before they learn the meanings of the count words.

1 | INTRODUCTION

One of the many learning challenges young children face is to understand how counting works (Carey, 2009). Intuitively, learning to count seems like part of learning to speak: Parents repeatedly say, "Let's count: one, two, three," and eventually children come to respond to the question "Can you count?" by saying "One, two, three" (Piaget, 1953). But what is children's initial understanding of this count sequence? Is early counting comprehension limited to recognizing a familiar list of meaningless words, or do children represent the counting routine in ways that are more abstract, and potentially more meaningful?

1.1 | Number word understanding emerges slowly

Decades of research suggest that although children first begin engaging in aspects of verbal counting quite early in development, typically at around 2 years of age, they initially fail to understand the meanings of the individual count words (e.g., Wynn, 1990, 1992). For example, new counters can recite the count list aloud but cannot reliably pick out one item in response to prompts like "Can I have *one*?" Roughly 6 months after they begin reciting the count list, children come to understand the meaning of "one"—they consistently pick one and only one item when asked for "one." Six months after that they learn the meaning of "two," and another 6 months later, "three." After this piecemeal learning, children come to understand the cardinal word principle: that the last word in any count sequence represents the set's exact cardinality—in typically developing English-learning children, this often happens at around 4 years of age (Wynn, 1990, 1992). This consistent learning pattern, observed across cultures (Le Corre et al., 2016; Piantadosi et al., 2014; Sarnecka & Carey, 2008; Sarnecka et al., 2007), has led to the hypothesis that children learn the meanings of the first few number words ("one," "two," and "three") by slowly coming to associate each word with a different small set (a set of one, a set of two, and a set of three, respectively). In this state of partial knowledge, young children do not seem to recognize the general relation that words that come later in the counting sequence map to greater numerosities (Condry & Spelke, 2008; Le Corre & Carey, 2007; Sarnecka & Wright, 2013; Slusser & Sarnecka, 2011). They also do not reliably establish one-to-one correspondence between the count words they produce and to-be-counted entities (Fuson et al., 1982), nor do they reliably identify other people's counting errors (e.g., Briars & Siegler, 1984; Frye et al., 1989; Fuson, 2012). Only after children have gradually constructed meanings for "one," "two," and "three" (and potentially also "four" and "five") do they come to understand the logic of the counting algorithm, and thereby acquire the meanings of larger number words (Carey, 2009; Carey & Barner, 2019; Le Corre & Carey, 2007; but see Dehaene, 2009; Gallistel & Gelman, 2000, Spaepen et al., 2011; Wagner & Johnson, 2011; for alternative views). This process unfolds over a period of several years.

1.2 | Sensitivity to counting in infancy

This evidence that children in the early stages of counting do not understand the meaning of individual count words is clear and compelling. However, recent work has begun to suggest that, surprisingly, a much more rudimentary recognition of counting may be in place even before children utter their first number words. Wang and Feigenson (2019) asked whether observing a set of objects being counted aloud would change the way 14- and 18-month old infants represented the array. When each of four objects was individually pointed out but not counted, and then the whole array was hidden, infants failed to remember how many objects were in the array. That is, after seeing just two of the four hidden objects retrieved, they failed to search for any remaining objects. This failure is consistent with the many previous findings of an upper limit of three individual items on infants' working memory (see Feigenson et al., 2004; Kibbe, 2015 for reviews). Although infants of this age can, under other circumstances, easily distinguish large quantities that differ by a 1:2 ratio (such as 8 vs. 16 dots), they often fail to deploy these approximate number representations when presented with small arrays of objects, instead attempting to represent each individual object in working memory. When there are more than three such objects, infants are unable to represent them, often exhibiting a pattern of “catastrophic” memory failure (Barner et al., 2007; Coubart et al., 2014; Feigenson & Carey, 2003, 2005; Hyde & Spelke, 2011; vanMarle, 2013; Zosh & Feigenson, 2015).

But counting appears to help. When infants in Wang and Feigenson's study observed objects counted aloud before they were hidden (e.g., “One, two, three, four… Four dogs!”), they successfully kept searching after only two of the four hidden objects had been retrieved. Rather than increasing working memory and allowing infants to remember that exactly four objects had been hidden, counting appeared to direct infants' attention to the approximate numerosity of the array. Infants successfully distinguished six counted objects from four, a distinction that clearly surpasses the three-item limit of working memory. However, infants failed to differentiate four counted objects from three, showing that their representation of the array's numerosity was imprecise (Wang & Feigenson, 2019). This imprecision contrasts with the performance pattern observed in studies of chunking, which finds that infants can make use of various perceptual and semantic cues (including the sharing of common labels) to bind representations of individual objects into higher-order sets (Feigenson & Halberda, 2008). Chunking preserves representations of individual items in memory, thereby allowing infants to precisely distinguish three hidden objects from four (Rosenberg & Feigenson, submitted). Because infants who saw objects counted successfully represented the distinction between two and four, but not between three and four, counting apparently did not trigger infants to chunk the objects into sets.

Instead, Wang and Feigenson's results suggest that counting cued infants to represent the approximate numerosity of the set, and thus that infants as young as 14-months already have linked counting to quantities. This finding has been recently replicated using an online looking time paradigm (Wang, 2023). Note that this very preliminary understanding of counting is quite different from the mature meaning that children slowly build over the preschool years. There is no evidence that infants hypothesize different meanings for each number word in the count sequence, nor that they entertain any notion of numerical exactness. But by 14- to 18-month, infants do seem to have related the activity of counting to the dimension of number out in the world.

1.3 | What's special about counting?

What properties of the counting routine trigger very young children to attend to number? One possibility is that, by 14- to 18-month, infants are already familiar with the count words in their native language, and have linked these familiar tokens to the dimension of number even without yet knowing their individual meanings. Observations of parent-infant interactions during picture book reading find that infants often begin to receive counting input from parents during the first year of life (Goldstein et al., 2016). The amount of “number talk” children hear increases between 14 and 30 months, and is related to children's later number knowledge at 3.5 years (Gunderson & Levine, 2011; Levine et al., 2010). This early experience of hearing people talk about number may provide infants with some recognition of the number words in their language, and the contexts in which they tend to be used.

But early observations of counting not only provide exposure to particular linguistic tokens—they also offer evidence of the procedures that are integral to counting. As highlighted by Gelman and Gallistel (1986), across languages, counting instantiates a set of core principles that differentiate it from other verbal sequences. In addition to the cardinal word principle (the last word in the count sequence denotes the cardinal value of the set), counting respects the stable order principle (count words are applied in a consistent order), and the one-to-one correspondence principle (every object in an array is paired with one and only one count word). It is possible, then, that young children are cued to instances of counting by the overall procedure of its deployment, either instead of or in addition to the individual words that comprise it.

When do children show sensitivity to these counting principles? In children's own counting, adherence to the counting principles is observed rather late; even by the end of kindergarten, children do not always count in ways that instantiate them (Stock et al., 2009). With tasks that focus on comprehension rather than production, preschool-age children show more sensitivity, pointing out instances when a puppet counted incorrectly (Gelman & Meck, 1983). Still, even in these easier tasks, other work finds that preschool children do not reliably detect others' counting errors (Briars & Siegler, 1984; Frye et al., 1989; Siegler, 1991).

However, recent studies using an even less demanding, more implicit task suggest that although they themselves cannot yet count, infants are already sensitive to at least some of the counting principles. Children as young as 18 months preferred to watch videos that depicted a correct counting sequence, compared to counting that violated either the stable order principle (Ip et al., 2018) or the one-to-one correspondence principle (Slaughter et al., 2011). In these studies, infants' cultural-linguistic experience influenced their performance: infants from monolingual English-speaking families detected violations of one-to-one correspondence and stable order when counting occurred in English, but not in Japanese (Ip et al., 2018; Slaughter et al., 2011). These results offer some evidence in favor of Gelman and colleagues' proposal that children have some knowledge of counting principles before starting to count themselves (Gelman & Gallistel, 1986. However, they leave open the question of whether this very early sensitivity has any numerical relevance for infants.

1.4 | The current study

Does observation of the counting principles play a role in directing infants' attention to number? Alternatively, or in addition, might infants already link familiar count words to approximate numerosity, regardless of whether the counting principles are respected? To address these questions, we conducted three experiments in which we separately manipulated these factors. The question was whether, under various conditions of counting, infants would remember an array that exceeded typical limits on working memory (i.e., contained four hidden objects)—that is, whether infants would attend to the approximate numerosity of an array that would otherwise activate only individual object representations. In Experiment 1 we asked whether infants required familiar count words for this. We first replicated the finding of Wang and Feigenson (2019) that correct English counting enables infants from English-speaking households to successfully represent a four-object array. Then we asked whether these infants would also succeed when the array was counted in unfamiliar German. Because we found that infants successfully represented 4-object arrays even when objects were counted in the unfamiliar language, in Experiment 2 we asked whether infants' attention to number required objects to be counted using sequences that obeyed the stable order and cardinal word principles. Finally, in Experiment 3, we asked whether infants' attention to number required objects to be counted using sequences that respected one-to-one correspondence between count words and objects.

Importantly, our aim was not to ask whether infants knew the meanings of individual words like "one," "two," or "three." Instead, we probed for a much more rudimentary understanding, asking simply whether infants were able to attend to an array's approximate numerosity when presented with unfamiliar count words, or when presented with incorrect counting sequences.

2 | EXPERIMENT 1

Our first question was whether counting propels infants to attend to numerosity only when it involves familiar count words, or whether counting can also exert this effect with unfamiliar words, if those words are deployed in ways that respect the basic counting principles. Wang and Feigenson (2019) found that when objects were each indicated with a proper noun instead of a count word ("Sophie, Katie, Annie, Mary… Look at this!"), 18-month old infants failed to remember the approximate numerosity of the array. But because this proper noun sequence uses words that infants have not experienced as part of the counting routine, and also violates the cardinal word principle (saying "Look at this" instead of labeling the whole set with the last word in the sequence), it is unclear which aspect caused them to treat the arrays differently than they did when they heard "One, two, three, four…Four dogs!" Furthermore, it is possible that some infants had previously heard one or more of the proper names used by Wang and Feigenson (e.g., as the name of a family member, friend, or pet); this could plausibly have blocked them as candidate count words. Therefore, in Experiment 1, we measured infants' attention to arrays that were counted using non-English count words, using a procedure that respected all of the counting principles.

We did this using a manual search task. Infants saw either two or four identical objects presented simultaneously and watched an experimenter count them in either familiar English or unfamiliar German. The objects were then hidden in a box, and then infants were allowed to retrieve either all or just a subset of them. If infants succeeded in surpassing their working memory limit (and remembering 4-object arrays as containing "approximately four," as in Wang & Feigenson, 2019), they should continue searching the box longer after seeing four objects hidden and retrieving just two of them, compared to when seeing two objects hidden and retrieving both, or seeing four objects hidden and retrieving all four. If, instead, counting using unfamiliar tokens is more like hearing the objects indicated using either proper names ("Sophie, Katie, Annie, Mary… Look at this!") or simple indexicals ("This, this, this, this… Look at these!"), then infants should stop searching after seeing four objects hidden and retrieving just two of them.

2.1 | Method

2.1.1 | Participants

Sixteen full-term 18-month-old infants participated (mean age 18.61 months; $SD = 0.72$ months; 12 girls). This was based on previous tasks using the manual search method that used samples of this size to probe infants' representations of object arrays (Barner et al., 2007; Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2004; Stahl & Feigenson, 2014, 2018; Taborda-Osorio & Cheries, 2018; Van de Walle et al., 2000; Wang & Feigenson, 2019; Xu et al., 2005; Zosh & Feigenson, 2015). Thirteen of the infants in our sample were identified by their parents as White and two as Black; parents of the remaining infants declined to report infants' racial or ethnic background. Four additional infants were excluded for fussiness. All infants across Experiments 1–3 were reported by their parents to live in households in which only English was spoken. All infants received a small gift (e.g., t-shirt, book, or toy) to thank them for their participation.

The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Homewood Institutional Review Board at the Johns Hopkins University.

2.1.2 | Stimuli

Infants watched objects being hidden in a black foam-core box (40.5 cm × 25 cm × 12 cm). The front face of the box was covered with spandex with a slit across its width, through which infants could reach without seeing inside. The box's rear face had a concealed opening through which the experimenter could reach to withhold objects without infants noticing. A toy bunny and a wooden block were used during familiarization, and four identical beige toy dogs (6.3 cm tall) and four identical blue toy cars (7.2 cm long) were used in the test trials.

2.1.3 | Design and procedure

The experiment began with a familiarization to give infants practice seeing objects hidden and retrieving them from the box. Infants sat in a high chair in front of a child-sized table, with the parent sitting out of view behind them and the experimenter kneeling to their left. The experimenter showed infants as she placed the toy bunny atop the box and then inserted through the slit in the box's front face, after which infants were encouraged to reach in and retrieve it. Once infants had retrieved the bunny, the experimenter said "Can I have the bunny?" and removed it from view. Infants next saw a wooden block being placed atop the box and then inserted inside, and were encouraged to reach in to retrieve it. This time the experimenter secretly held the block out of reach in the back of the box, so that infants had the experience of being unable to immediately retrieve something that should have been in the box. After 5 s, the experimenter said, "Can I help?," reached into front of the box, and retrieved the block, which she showed to infants and then removed from view.

After this familiarization, infants were administered two test blocks. In one, infants saw objects counted in English (English counting block); in the other, infants saw objects counted in German (German counting block). As in Wang and Feigenson (2019), prosody was equated across all presentations. Block order was counterbalanced across infants, as was whether dogs/cars were presented on the first or second block. Within each block there were three measurement periods, presented twice each, resulting in a total of 12 measurement periods for each infant (Figure 1).

2-Objects (none remaining) measurement periods measured infants' searching after they had seen two objects hidden and had retrieved both of them. These provided a direct comparison to the critical measurement periods in which infants had seen four objects hidden and retrieved just two of them (described below). In both cases searching was measured after infants had just retrieved two objects from the box, but on 2-Objects (none remaining) periods there was nothing else left to retrieve (and hence infants should now stop searching), whereas on 4-Objects (more remaining) periods there were still two objects expected inside (and hence infants should continue searching). The experimenter showed infants two identical toys (dogs or cars) placed atop the box, which she then counted either in English (English counting block), or in German (German counting block). In the English counting block the experimenter pointed to each object in turn, producing a familiar count word for

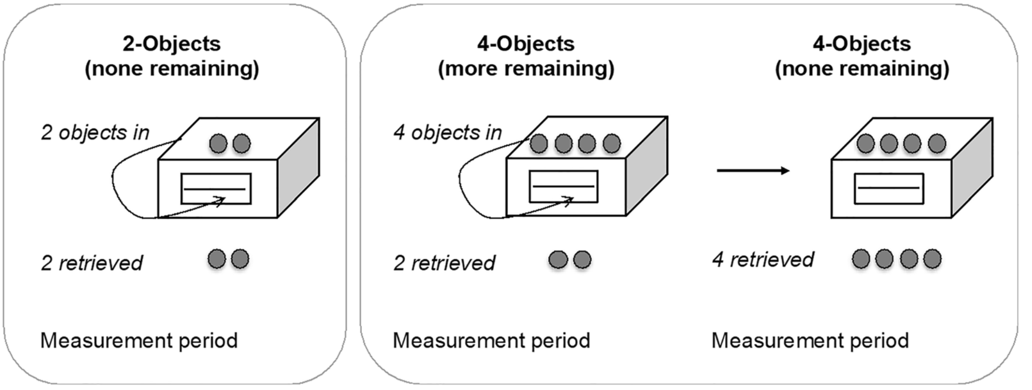

FIGURE 1 Schematic of the measurement periods in Experiments 1–3

each ("One, two!"). She then repeated this pointing and counting sequence ("One, two!"), and finally indicated the cardinality of the array using a circular pointing motion, and saying "Two dogs/cars!" In the German counting block the experimenter counted the objects in the same way, but used German count words ("Eins, zwei! Eins, zwei! Zwei dogs/cars!"). The experimenter then picked up the two toys and inserted them sequentially through the front of the box, again producing a count word with each object insertion (i.e., either "One, two!" or "Eins, zwei!"). 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 both toys within 5 s, the experimenter helped (this was true across all trial types, across all experiments). After both toys had been retrieved, the experimenter removed them from view and held the box in place for 10 s, during which any searching of the box was measured. After this 10-s measurement period, 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 them were retrieved. The experimenter showed infants four identical toys atop the box, and either counted the array twice in English—producing one number word per object, and then indicating the entire array while repeating the last word in the count sequence ("One, two, three, four! One, two, three, four! Four dogs/cars!"), or in German ("Eins, zwei, drei, vier! Eins, zwei, drei, vier! Vier dogs/cars!"). The experimenter then picked up the objects and inserted them through the front face of the box one at a time, producing a count word with each object insertion: "One, two, three, four!" or "Eins, zwei, drei, vier!" 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. After infants had retrieved them, the experimenter immediately removed the objects from view and the 10-s measurement period 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 and removed them from view, infants were allowed to search the (now empty) box for 10 more seconds. If infants successfully represented the four hidden objects (even approximately), they should stop searching during this measurement period.

Whether infants first were 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. During all measurement periods, the experimenter looked down to avoid giving infants any cues as to whether she believed anything was left in the box, only looking up again after the 10-s measurement period had ended. Infants were considered to be searching if either of their hands were inserted through the spandex at least to the second knuckle. If infants were still searching the box at the 10-s mark, the measurement period was allowed to continue until infants had removed their hand(s) from the box. Searching was coded from video by two experienced observers; inter-coder reliability was 0.93.

2.2 | Results

We examined infants' search performance using a 2 (Counting Type: English vs. German) × 2 (Counting Type Order: English first vs. German first) × 3 (Measurement Period: 2-Objects [none remaining], 4-Objects [more remaining], 4-Objects [none remaining]) × 2 (Trial: first vs. second instance of a given trial) repeated-measures ANOVA. This analysis revealed a significant effect of Measurement Period, $F(2, 28) = 11.63$, $p < .001$, $\eta_p^2 = 0.45$, indicating that infants' search duration depended on the number of objects that had been hidden/retrieved. There was a marginally significant effect of Counting Type Order, $F(1, 14) = 3.89$, $p = .07$, $\eta_p^2 = 0.22$, qualified by a significant non-predicted Counting Type × Counting Type Order interaction, $F(1, 14) = 23.84$, $p < .001$, $\eta_p^2 = 0.63$. Post hoc tests using Bonferroni correction revealed that infants searched more during the German block when they heard German counting first, $p = .02$, and searched more during the English block when they head English counting first, $p = .03$. There was no significant Counting Type × Measurement Period interaction, $F(2, 28) = 0.12$, $p = .85$, indicating that infants modulated their search based on the number of objects that had been hidden, regardless of whether the objects had been counted in English or in German. There were no other significant effects, $ps > .19$.

We more closely examined infants' performance with a series of planned *t*-tests. We had hypothesized that if infants were only able to use familiar English count words to better remember the hidden objects, they should continue searching longer when more objects remained in the box (relative to when nothing remained in the box) in the English counting block but not the German counting block. Therefore, we compared whether infants searched significantly longer on the 4-Objects more remaining measurement periods than on the two none remaining measurement periods. We calculated an Increased Searching score by subtracting the average search duration during the none remaining measurement periods[1] from the more remaining measurement periods, and asked whether this Increased Searching was significantly greater than zero. Planned *t*-tests revealed that Increased Searching was greater than zero for both the English counting block (*M* Increased Searching = 0.92 s, *SD* = 1.11 s), $t(15) = 3.32$, $p = .005$, Cohen's $d = 0.83$, and the German counting block (*M* Increased Searching = 1.22 s, *SD* = 1.54 s), $t(15) = 3.16$, $p = .007$, Cohen's $d = 0.78$ (Figure 2).

2.3 | Discussion

Experiment 1 replicated the findings of Wang and Feigenson (2019), in that 18-month-old infants from English-speaking households successfully discriminated four hidden objects from two after

[1]As in previous studies, we first checked that infants' searching did not differ across the two measurement periods when nothing remained the box (2-Objects none remaining vs. 4-Objects none remaining). We found that these did not differ for either the English counting block or the German counting block, $t(15) = 1.41$, $p = .18$, Cohen's $d = 0.71$; $t(15) = 0.99$, $p = .34$, Cohen's $d = 0.50$, respectively. Given this lack of difference, we collapsed across the two identical instances of each measurement period.

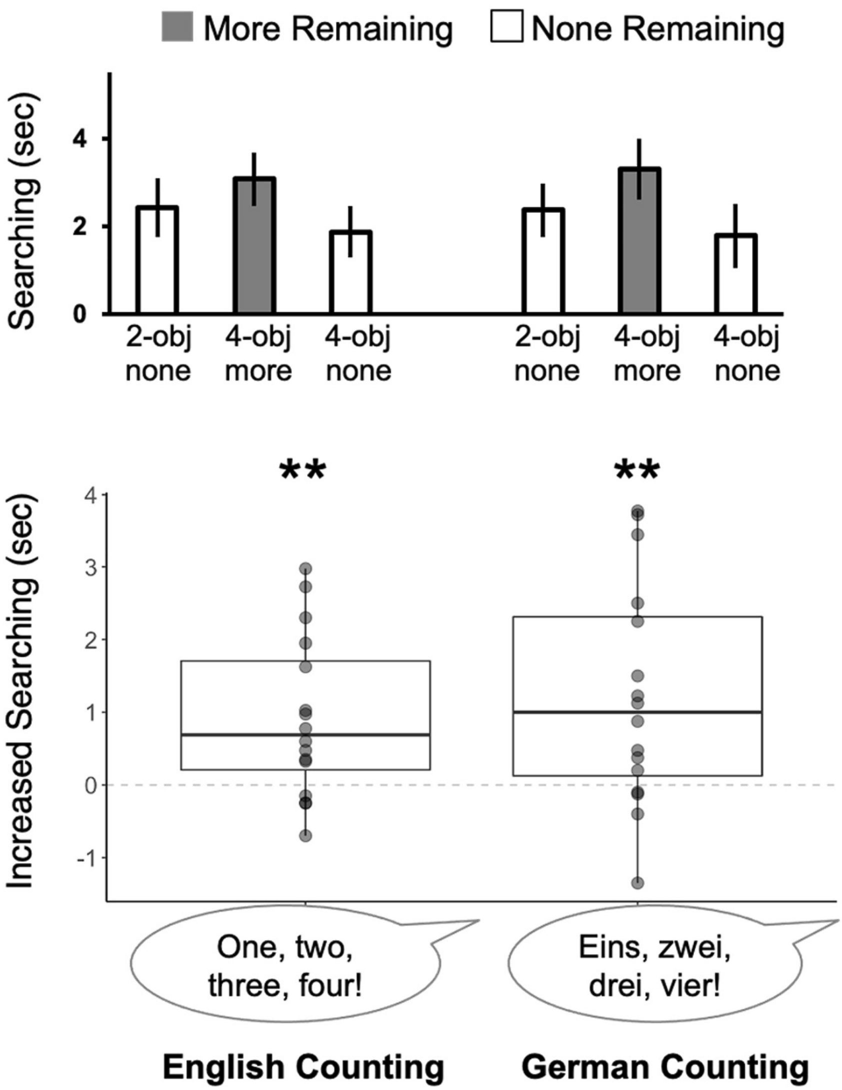

FIGURE 2 Results of Experiment 1. Top panel: Average searching during each measurement period (2-Objects [none remaining], 4-Objects [more remaining], 4-Objects [none remaining], respectively). Bottom panel: Increased Searching (searching when the box contained more objects minus searching when it was empty). Boxplot middle line = median, hinges = 25% and 75% quantiles. $^{**}p < .01$.

seeing the objects counted in English. Surprisingly, infants also succeeded when the objects were counted in German, despite parents reporting that infants had no prior German exposure. This success contrasts with infants' performance with uncounted arrays containing four or more objects in many previous studies (Barner et al., 2007; Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2008; Stahl & Feigenson, 2014, 2018; Wang & Feigenson, 2019).

These results are consistent with the interpretation that because German counting instantiated the same set of abstract counting principles as English counting, infants recognized the German routine as an instance of counting, or at least as relevant to counting. Unlike the individual labeling of objects with proper nouns, as in "Sophie, Katie, Annie, Mary… Look at this!" (which did not help infants attend to numerosity; Wang & Feigenson, 2019), counting in German respected not only the one-to-one correspondence and stable order principles, but also the cardinal word principle. If infants' recognition of counting relies on such principles, rather than on specific familiar words, then infants' performance should be disrupted when objects are counted in ways that violate those counting principles, even when familiar count words are used. To test this possibility, and to begin to ask which counting principles infants might be sensitive to, in Experiment 2 we asked whether infants could remember (approximately) four hidden objects that either were correctly counted in German (in an effort to replicate the results of Experiment 1), or were counted in English using a sequence that violated the stable order and cardinal word principles.

3 | EXPERIMENT 2

3.1 | Method

3.1.1 | Participants

Sixteen full-term 18-month-old infants participated (mean age 18.39 months; *SD* = 0.65 months; nine girls). Twelve infants were identified by their parents as White, two as Black, and the parents of the remaining infants declined to report their racial or ethnic background. Three additional infants were excluded for fussiness, and one for parental interference.

3.1.2 | Design, stimuli, and procedure

Infants were administered two test blocks: a German counting block and a Scrambled English counting block. As in Experiment 1, each test block contained two 2-Objects none remaining measurement periods, two 4-Objects more remaining measurement periods, and two 4-Objects none remaining measurement periods, resulting in a total of 12 measurement periods.

The German counting block was identical to the German counting block in Experiment 1: Infants saw arrays of two and four objects that were counted in German (e.g., “Eins, zwei, drei, vier! Eins, zwei, drei, vier! Vier dogs!”) and then hidden in the box. In the Scrambled English block, the experimenter counted aloud in English, but each time she counted she uttered the count words in a different order. On the initial presentation of an array she counted the objects in a scrambled order (e.g., “Three, one, four, two!”), while also pointing at the toys in a non-canonical order (e.g., pointing at the 2nd, 1st, 4th, and then the 3rd toy, from left to right in the array). After a brief pause, the experimenter counted again using a different order (e.g., “Two, one, three four!”), while pointing at the toys in a different order (e.g., 4th, 2nd, 3rd, 1st). This guaranteed that all infants heard a count sequence that lacked stable order, even if they had no prior established knowledge of the correct English sequence. After counting, the experimenter indicated the array using a circular pointing motion while saying “These dogs!” Thus, counting in the German block used unfamiliar words but respected the stable order and cardinal word principles, whereas counting in the Scrambled English block used familiar words but violated these principles (with counting in both sequences matched for prosody). Except for the differences noted above, the stimuli, procedure, and coding were as in Experiment 1. Inter-coder reliability was 0.94.

3.2 | Results

We examined infants' searching using a 2 (Counting Type: German vs. Scrambled English) × 2 (Counting Type Order: German first vs. Scrambled English first) × 3 (Measurement Period: 2-Objects [none remaining], 4-Objects [more remaining], 4-Objects [none remaining]) × 2 (Trial: first vs. second instance of a given trial) repeated-measures ANOVA. This analysis revealed a significant Counting Type × Measurement Period interaction, $F(2, 28) = 4.95$, $p = .015$, $\eta_p^2 = 0.26$, suggesting that infants' search patterns depended on the type of counting they observed. The ANOVA also revealed a significant Counting Type × Counting Type Order interaction, $F(1, 14) = 7.87$, $p = .014$, $\eta_p^2 = 0.36$. We found no other significant effects, *p*s > .11.

We more closely examined infants' performance with a series of planned *t*-tests on Increased Searching (which, as in Experiment 1, reflected the difference between searching on the more remaining measurement periods and the none remaining measurement periods).[2] Increased Searching was significantly greater than zero for the German counting block: *M* Increased Searching = 0.80 s, *SD* = 1.10 s, $t(15) = 2.90$, $p = .01$, Cohen's $d = 0.72$. In contrast, Increased Searching was not significantly different from zero for the Scrambled English counting block: *M* Increased Searching = −0.30 s, *SD* = 1.20 s, $t(15) = -0.99$, $p = .34$. Cohen's $d = -0.25$ (Figure 3).

3.3 | Discussion

Experiment 2 replicated the finding that monolingual English-speaking infants successfully discriminated four hidden objects from two after experiencing German counting. Critically, when the same infants heard objects counted using familiar English count words, but in a scrambled order and without the cardinal word principle applied, infants failed to represent four hidden objects, despite the fact that the counting sequences were matched for duration and prosody. These results suggest that infants are at least somewhat sensitive to procedures that respect abstract properties of counting (specifically, the stable order and/or cardinal word principles), rather than relying on knowledge of specific count words.[3] To confirm and extend this finding, we next asked whether infants are sensitive to the one-to-one correspondence between count words and counted objects.

Many studies have shown that much older children, up to 5 years of age, sometimes fail to explicitly apply one-to-one correspondence to object arrays to establish exact equality, even after having acquired the cardinal word principle (e.g., Cowan, 1987; Schneider et al., 2022). When asked to judge the accuracy of someone else's counting, preschool children often have trouble rejecting counting sequences containing violations of one-to-one correspondence (e.g., Briars & Siegler, 1984). However, other evidence suggests that by age 3 years (well before they are proficient counters), children are significantly above chance at respecting one-to-one correspondence when attempting to count objects, although they still make errors (Cheung et al., 2021). In addition, research with both children and non-human primates has demonstrated some implicit sensitivity to one-to-one correspondence. When one-to-one correspondence between object arrays is highlighted via explicit counting, 3- and 4-year-old children show improved performance on a Piagetian number conservation task (Gelman, 1982). And baboons are better at numerically discriminating two sets of objects when the sets are presented

[2]Searching did not differ between the two types of none remaining measurement periods, for either the German counting block or the Scrambled English counting block, $t(15) = 1.83$, $p = .09$, Cohen's $d = 0.91$; $t(15) = -0.68$, $p = .51$, Cohen's $d = -0.33$, respectively.

[3]On some definitions of one-to-one correspondence, infants in Experiment 2 also observed a violation of this principle because a *unique* number word was not applied to each object; when infants saw an array counted for the second time, a different word was applied to each object compared to the first count. However, other definitions of one-to-one correspondence require only that one word be applied to each object, without reference to uniqueness (Slaughter et al., 2011; Sophian, 1988; Wynn, 1990). The counting sequences in Experiment 2 respected this broader definition of one-to-one correspondence.

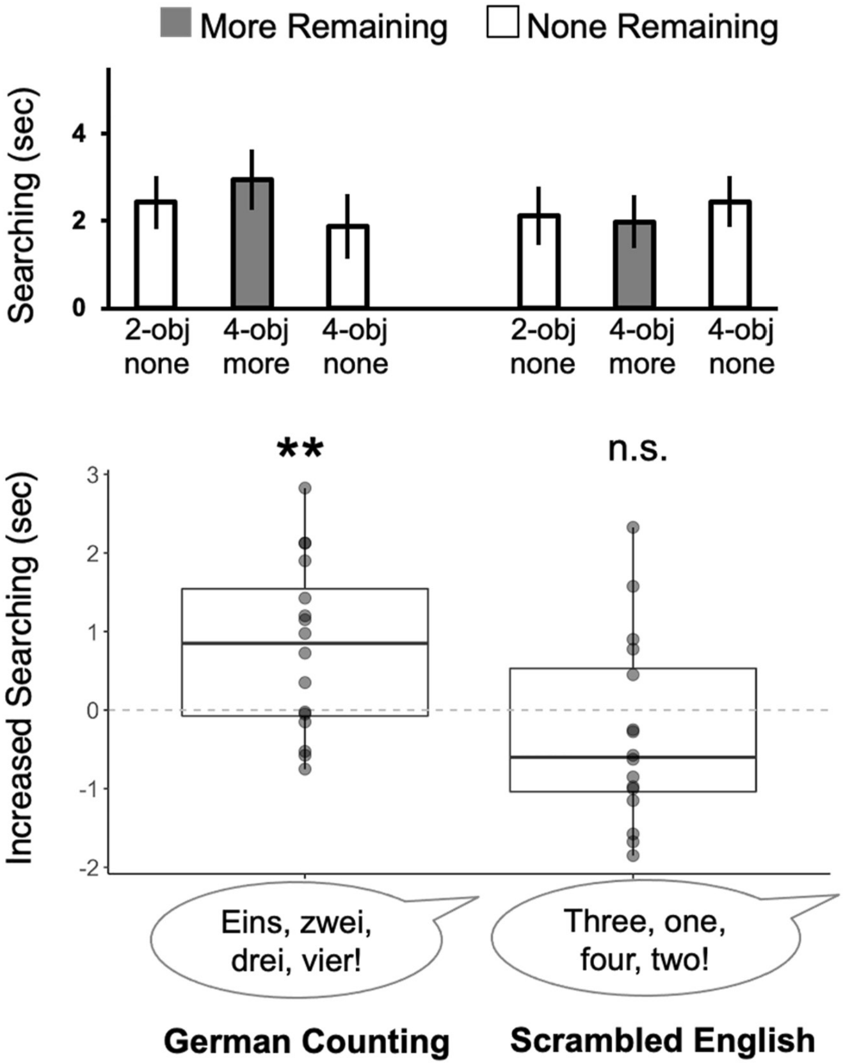

FIGURE 3 Results of Experiment 2. Top panel: Average searching during each measurement period (2-Objects [none remaining], 4-Objects [more remaining], 4-Objects [none remaining], respectively). Bottom panel: Increased Searching (searching when the box contained more objects minus searching when it was empty). Boxplot middle line = median, hinges = 25% and 75% quantiles. $^{**}p = .01$.

with one-to-one correspondence between their elements, compared to sequential presentation without highlighting one-to-one correspondence (Koopman et al., 2019). Finally, looking time studies have demonstrated that 18-month-old infants prefer to look at correct counting sequences over otherwise identical sequences that violate one-to-one correspondence (Slaughter et al., 2011). Overall, this past research suggests that children may be sensitive to one-to-one correspondence from early in life; however, it is unknown whether this very early sensitivity has any effect on infants' representation of object arrays.

Before attempting to answer this question, it is important to note that counting can violate one-to-one correspondence in a variety of ways. In some instances, a counter begins by applying one and only one count word to each to-be-counted object, but then may skip an object in an array while still producing a number word, or may produce two number words for a single object (i.e., double-counts). These cases are often interpreted as counting errors. Other one-to-one correspondence violations are more ambiguous, as when a counter recites the count list while pointing at the array in its entirety, rather than at individual objects within it. Although this latter type of violation is more extreme (in the sense that there is less overall alignment between count words and individual objects), it often is interpreted as a correct but non-canonical form of counting-- with the understanding that the counter is mentally pairing off count words and objects, rather than actually pointing to or touching each object in the array. For example, when a counter wants to enumerate items that are out of reach, like birds in a tree, this type of counting may be the only available option.

In Experiment 3 we tested infants' sensitivity to the above two types of one-to-one correspondence violations. If infants require perfect one-to-one correspondence to attend to numerosity, they should fail to remember four objects when observing any instance of counting in which one word is not produced in correspondence with each object. If infants recognize instances of counting in which the entire array is indicated, but objects are not pointed to individually, they should, perhaps counterintuitively, succeed at remembering four objects following more extreme violations of one-to-one correspondence, but fail when counting merely contains skips or double-counts. And if one-to-one correspondence is simply not a necessary cue for infants to attend to numerosity, then as long as counting respects the stable order and cardinal word principles, infants should successfully represent four hidden objects regardless of any correspondence disruptions.

4 | EXPERIMENT 3

4.1 | Method

4.1.1 | Participants

Sixteen full-term 18-month-old infants participated (mean age = 18.09 months; *SD* = 0.27 months; seven girls). Fourteen infants were identified by their parents as White, and the parents of the remaining infants declined to report their racial or ethnic background. Three additional infants were excluded for fussiness.

4.1.2 | Design, stimuli, and procedure

As in Experiments 1 and 2, infants were administered two test blocks in which objects were always counted aloud by the experimenter prior to hiding. Each test block contained two 2-Objects none remaining measurement periods, two 4-Objects more remaining measurement periods, and two 4-Objects none remaining measurement periods, resulting in a total of 12 measurement periods.

One of the blocks was identical to the English counting block in Experiment 1 (e.g., "One, two, three, four! One, two, three, four! Four dogs!"). In the other, infants saw the experimenter counting in the correct order in English. However, the counting sequence violated the principle of one-to-one correspondence between count words and objects (No One-to-One Correspondence block). We tested infants' performance with two types of correspondence violations: In one set of measurement periods, each counting instance involved a Single-Skip violation (one object was skipped during counting, and a different object was double counted), and in another set of measurement periods, each counting instance involved a Global Point (all of the count words in the sequence were applied while the experimenter pointed towards the middle of the array). For the Single-Skip violation, when presenting a 4-Object array the experimenter counted "One, two" while pointing at the first object, skipped the second object entirely, pointed to and counted the third object ("three"), and pointed to and counted the fourth object ("four!"). After a brief pause, the experimenter counted "one" while pointing at the first object, counted "two, three" while pointing at the second object, skipped the third object, and counted "four" while pointing at the last object. For the Global Point presentation, when presenting a 4-Object array the experimenter pointed to the middle of the array and counted, "One, two, three, four!" After a brief pause, the experimenter pointed again and counted, "One, two, three, four!" After counting, for both the Single-Skip and the Global Point presentations, the experimenter indicated the cardinality of the array using a circular pointing motion while saying "Four dogs!" Prosody was identical across all presentations. Except for the differences noted above, the stimuli, procedure, and coding were as in Experiments 1 and 2. Inter-coder reliability was 0.92.

4.2 | Results

We examined infants' searching using a 2 (Counting Type: English counting vs. No One-to-One Correspondence) × 2 (Trial: first vs. second instance of a given trial, which also captured the distinction between Single Skip and Global Point presentations in the No One-to-One Correspondence block) × 2 (Counting Type Order: English counting first vs. No One-to-One Correspondence first) × 3 (Measurement Period: 2-Objects [none remaining], 4-Objects [more remaining], 4-Objects [none remaining]) repeated-measures ANOVA. This analysis revealed a marginally significant effect of Measurement Period, $F(2, 28) = 3.57$, $p = .059$, $\eta_p^2 = 0.20$, and a significant effect of Trial, $F(1, 14) = 6.13$, $p = .027$, $\eta_p^2 = 0.31$. There was also a significant Counting Type × Counting Type Order interaction, $F(1, 14) = 7.99$, $p = .013$, $\eta_p^2 = 0.36$. There was no significant Counting Type × Measurement Period interaction, nor any other interaction, ps > .11.

As in Experiments 1 and 2, we conducted a series of planned analyses to more closely examine infants' searching, comparing searching on trials when more objects remained in the box versus when none remained.[4] Consistent with our previous experiments, we found that this Increased Searching was significantly greater than zero on the English counting block, M Increased Searching = 0.96 s, $SD = 1.22$ s, $t(15) = 3.13$, $p = .007$, Cohen's $d = 0.78$. Within the No One-to-One Correspondence block, Increased Searching did not differ from zero on the Single Skip trials, M Increased Searching = −0.15 s, $SD = 1.84$ s, $t(15) = -0.33$, $p = .74$, Cohen's $d =$ = 0.08. In contrast, Increased Searching was significantly greater than zero on Global Point trials, M Increased Searching = 1.36 s, $SD = 2.26$ s, $t(15) = 2.40$, $p = .029$, Cohen's $d = 0.60$ (Figure 4).

Our experiments were designed to allow us to ask whether infants would successfully represent four-object arrays under various conditions of counting, but they were not sufficiently powered to enable us to directly compare infants' performance across different counting conditions (e.g., to ask whether infants performed significantly better with correct English counting than with English counting lacking one-to-one correspondence). A power analysis using G*Power (Faul et al., 2007) for a 2 (Counting Type: English counting vs. No One-to-One Correspondence) × 3 (Measurement Period) repeated-measures interaction with $\alpha = .05$ and a medium effect size ($f = 0.25$) yielded $N = 28$ for 80% power. However, our sample sizes did afford sufficient power to ask whether, across experiments, any form of disruption to conventional counting (as in the Scrambled English and No One-to-One Correspondence blocks

[4]Searching did not differ between the two instances of none remaining measurement periods for either the English counting block or the No One-to-One Correspondence block, $t(15) = 0.37$, $p = .72$, Cohen's $d = 0.18$; $t(15) = -0.57$, $p = .58$, Cohen's $d = -0.28$, respectively.

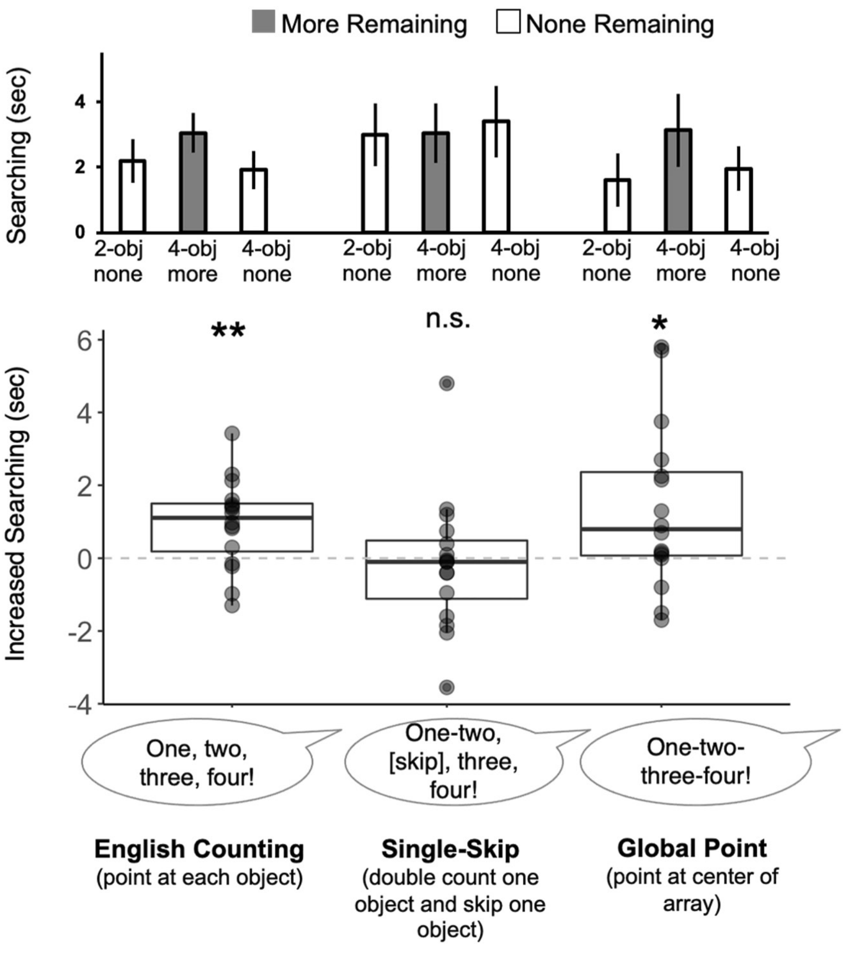

FIGURE 4 Results of Experiment 3. Top panel: Average searching during each measurement period (2-Objects [none remaining], 4-Objects [more remaining], 4-Objects [none remaining], respectively). Bottom panel: Increased Searching (searching when the box contained more objects minus searching when it was empty). Boxplot middle line = median, hinges = 25% and 75% quantiles. *$p < .05$. **$p < .01$.

of Experiments 2 and 3) influenced infants' ability to track four objects, relative to correct counting. A 2 (Counting Type: Correct vs. Disrupted Counting) × 3 (Measurement Period: 2-Objects [none remaining], 4-Objects [more remaining], 4-Objects [none remaining]) repeated-measures ANOVA on the data from Experiments 2 and 3 ($N = 32$) revealed a significant effect of Measurement Period, $F(2, 62) = 3.93$, $p = .025$, $\eta_p^2 = 0.11$, and no significant effect of Counting Type, $F(1, 31) = 0.33$, $p = .57$, $\eta_p^2 = 0.01$. Critically, there was a significant Counting Type × Measurement Period interaction, $F(2, 62) = 5.00$, $p = .010$, $\eta_p^2 = 0.14$. Infants were worse at remembering four-object arrays when the arrays were incorrectly counted, compared to when they were correctly counted.

4.3 | Discussion

Experiment 3 replicated our previous finding that infants successfully distinguish four hidden objects from two after experiencing correct English counting (see Wang & Feigenson, 2019, and Experiment

1 in the present series). Notably, infants also succeeded when the arrays were counted in English, but in a way that violated one-to-one correspondence—after seeing the experimenter point towards the center of the array while counting, infants again successfully continued searching after seeing four objects hidden and only two of them retrieved. In contrast, when the counting routine used familiar English words but clearly violated the one-to-one correspondence principle by skipping one of the objects in the array and double-counting another, infants no longer succeeded.

We view infants' failure in the Single Skip condition and their success in the Global Point condition as suggestive rather than definitive, due to our limited sample size and number of trials per infant. However, our findings are consistent with the possibility that, while one-to-one correspondence is an important feature of counting, infants do not treat all one-to-one violations as equivalent. Infants attended to the numerosity of arrays that were merely pointed to while counting occurred—this type of counting, which lacks the tagging of individual items, does appear to occur in early childhood. Work by Briars and Secada (1988) found that in a sample of preschool-aged children who were asked to count arrays, up to 15% of children's counts were cases in which children did not skip or double-count, but rather "skimmed" (whereby, according to Briars and Secada, a "finger skims over the array with no specific points"). Similarly, Saxe (1977) found that 32% of 3-year olds' counts of object arrays were of this type. In addition, Graham (1999) found that 3- and 4-year olds were more likely to accept such instances (i.e., a puppet counting an array without gesturing at each object) as correct, compared to some kinds of "milder" correspondence errors (e.g., instances in which an object was double counted). These findings begin to suggest that counting without indicating the individual component objects in the array is not so rare in children's experience, and that at least under some conditions they can consider such counting to be acceptable.

5 | GENERAL DISCUSSION

Previous research suggests that pre-counting infants recognize counting as quantity-relevant (Wang & Feigenson, 2019). In the current study, we asked which aspects of counting cue infants to attend to numerosity—whether familiarity with individual count words, correct counting procedures, or both, are required. In three experiments, we showed that 18-month-old infants from monolingual English-speaking households were able to keep track of four-object arrays that had been counted correctly, whether in English or in German, in contrast to their performance with uncounted four-object arrays in many previous studies (Barner et al., 2007; Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2008; Stahl & Feigenson, 2014, 2018; Wang & Feigenson, 2019). However, when the counting routine was disrupted, either by violating the stable order and cardinal principles of counting, or by violating one-to-one correspondence, infants showed the same failure to remember four objects that they show with uncounted arrays, despite hearing familiar English count words. Together with previous studies on infants' recognition of counting (Wang & Feigenson, 2019), these results suggest that infants are already sensitive to some of the principles that counting instantiates (as in the work by Ip et al., 2018; Slaughter et al., 2011), and that this sensitivity impacts infants' representations of counted arrays.

Among the principles we examined, our findings hint that the cardinal word principle might play an especially special role in facilitating infants' object tracking performance.[5] In previous experiments (Wang & Feigenson, 2019) and in Experiments 1–3 here, each condition in which infants successfully represented the hidden arrays involved the experimenter applying the cardinal word principle ("One, two, three, four… Four dogs!" or "Ein, zwei, drei, vier… Vier dogs!"). As she uttered the

[5]We thank an anonymous reviewer for this suggestion.

number word that signified the cardinality of the array, the experimenter used her finger to point at all of the objects in the array in a circular motion. Infants in the proper noun experiment by Wang and Feigenson (2019; “Sophie, Katie, Annie, Mary. Look at this!”) and the Scrambled English condition of the current Experiment 2 experienced instances of counting that omitted this highlighting of cardinality, and failed to represent the approximate cardinality of the array. We observed a more mixed pattern of performance in Experiment 3—even though infants heard counting that respected the cardinal word principle in both the Global Point and Single Skip presentations, *t*-tests showed that infants succeeded at representing four-object arrays following Global Point counting but not Single-Skip counting. It might be, then, that the cardinal word principle promoted some degree of success even when other counting principles were violated. The finding that infants in the studies by Slaughter et al. (2011) and Ip et al. (2018) differentiated correct from incorrect English counting even when cardinality was not highlighted suggests that the cardinal word principle is not required for infants to recognize counting when it occurs in a familiar language. However, future work should test whether inclusion of the cardinal word principle is needed for infants to recognize counting in an unfamiliar language, and for counting to most efficiently direct infants' attention towards numerosity.

Indeed, we note that the effects conferred by counting may not be all or none. It is possible that infants might experience the strongest effects from correct counting in a familiar language, and exhibit more modest improvements for counting containing one or more kinds of violations, and/or for counting using unfamiliar words. For example, while infants in Experiment 1 succeeded at remembering four objects counted in either English or in German, and their performance in the two conditions did not statistically differ, our experiment was not in fact designed to probe for such a difference. Rather, our question was whether familiar count words were required for infants to successfully represent four-object arrays. Given this limitation of the current study, whereby our smaller sample sizes ($N = 16$ in each experiment) did not empower us to probe for graded performance across conditions, future work with larger samples will be key to addressing this issue.

In addition, while the results of the current study demonstrate some early sensitivity to the principles instantiated by canonical counting, a mature understanding of counting also involves recognizing that counting can occur in non-canonical ways and still be correct. For example, it is possible to touch or point to objects in a different order each time (e.g., from left to right vs. from right to left)—that is, while number words must be deployed in a stable order, entities in the world can be indicated in any order at all. It is even permissible to violate one-to-one correspondence and yet count correctly by twos (or other multi-item chunks). This distinction between counting principles and counting conventions appears difficult even for children ages 5 and older (e.g., Briars & Siegler, 1984; Kamawar et al., 2010; LeFevre et al., 2006), so it is unlikely that much younger infants can distinguish between them. However, it may be that consistent, conventional counting is particularly effective in drawing children's attention to number very early in life.

Alongside the richer interpretation that by 18-month, infants recognize that instances of incorrect counting are less likely to be number-relevant, there are several other available accounts of infants' differential responses to correct versus incorrect counting that merit consideration. One is that infants were surprised by experiencing counting violations, such that observing objects incorrectly counted drew their attention away from the objects and towards the unusual sequence itself, or towards the person who performed the count. This might have made infants less likely to attend to the actual arrays (but note that, in the absence of any counting at all, infants typically fail to represent four-object arrays-so the unusual counting was not itself the root cause of infants' failure to represent the arrays; Barner et al., 2007; Coubart et al., 2014; Feigenson & Carey, 2003, 2005; Hyde & Spelke, 2011; vanMarle, 2013; Zosh & Feigenson, 2015). A related possibility is that incorrect counting, at least in the way we presented it, was distracting to infants because the incorrect sequences were more variable than the correct ones. For example, when infants in Experiment 2 observed counting that violated the stable order principle, they heard different sequences of number words across trials (e.g., "Three, two, one, four!" "Two, four, one, three!"), and saw objects pointed to in varying orders. We used these more variable counting presentations so that pre-counting infants would have ample evidence that the stable order principle was being violated (similar to Ip et al., 2018). But future work may want to ask whether, holding variability constant across instances of correct and incorrect counting, infants still distinguish the two. We note, however, that the deployment of count words in the same invariant order across all counting instances (at least for canonical counting, as opposed to less conventional forms of counting, like counting by twos) is likely a feature that differentiates counting from other acts of serial labeling, and may be important for promoting infants' attention to numerosity. For example, color words and lists of proper nouns are not uttered in any specific sequence. As such, the reduced variability involved in counting might be thought of as a feature, rather than an experimental confound.

In previous work, Slaughter and colleagues (Ip et al., 2018; Slaughter et al., 2011) found that 18-month old monolingual English-speaking infants discriminated correct from incorrect English counting, preferring to watch someone counting objects using a sequence that respected one-to-one correspondence and the stable order principle than counting in which these were violated. However, infants failed to discriminate correct from incorrect counting when the counting occurred in unfamiliar Japanese. These results might seem at odds with our findings that, in two separate experiments, infants of the same age from monolingual English-speaking households successfully represented four-object arrays after hearing objects counted in German. It is possible that this contrast stems from the difference in measures. Infants hearing objects correctly counted in an unfamiliar language might be pushed to attend to the dimension of numerosity, but still not show a significant *preference* between correct and incorrect counting in that language. For example, hearing novel count words might be interesting for monolingual infants, such that both correct and incorrect counting sequences attract their attention. It is also possible that linguistic differences between the languages presented to infants (English vs. Japanese in the studies by Slaughter et al., 2011 and Ip et al., 2018; English vs. German in the present study) contributed to the difference in findings.

Why might infants in the current study and in the work by Slaughter and colleagues have demonstrated such early sensitivity to counting principles, whereas previous research finds that much older, preschool-aged children sometimes fail to recognize counting errors (Briars & Siegler, 1984; Frye et al., 1989; Siegler, 1991)? Differences in the measures employed with infants versus older children may be part of the story. Whereas studies with infants measured infants' interest in the counting act (e.g., looking time in Slaughter et al., 2011; button pressing in Ip et al., 2018), or infants' representation of counted versus uncounted arrays (via manual search in the current study), studies with preschoolers required children to make explicit verbal judgments about counting (e.g., measuring children's ability to catch an experimenter playing a trick on them by making a counting error; Frye et al., 1989). Spontaneous behavioral responses to counting (looking, searching) might reveal sensitivity that is not always apparent in tasks requiring explicit verbal responses (see Greeno et al., 1984, for discussion of competence vs. performance in children's counting).

Finally, although our results replicate previous findings that infants represent counted arrays differently from uncounted arrays, the experiments we present here are not able to pinpoint the mechanism driving infants' performance. For example, infants could have succeeded either by representing the four presented objects as "approximately four," distinct from the "approximately two" objects later retrieved, or by chunking the four objects into two sets of two (as in studies by, e.g., Feigenson & Halberda, 2008), or by avoiding catastrophic forgetting and simply representing three of the four hidden objects (as in Zosh et al., 2011). Previous research found that counting triggers approximate number representations—infants represented up to six objects (surpassing typical working memory limits), but imprecisely (in that they failed to differentiate four hidden objects from three) (Wang &

Feigenson, 2019). Future research should test the hypothesis that counting with unfamiliar tokens (like the German words used in Experiments 1 and 2) also yields this pattern. At present, with appeal to parsimony, we cautiously interpret our findings as suggesting that sensitivity to the procedure of counting, independent of infants' knowledge of the count words themselves, also promotes infants' attention to the approximate numerosity of the counted array. Similar to the way young children recognize that color words like "red" refer to *some* color up to a year before they know that "red" refers to redness but not blueness, greenness, or yellowness (Wagner et al., 2013), and the way preschoolers know that time words like "minute" and "year" refer to temporal durations long before knowing which ones (Shatz et al., 2010), infants may recognize at least some aspects of the verbal counting procedures as referring to quantities, without yet knowing the actual meanings of "one," "two," or "three."

In sum, in the present experiments we found that 18-month old infants successfully represented four-object arrays after watching the objects counted correctly in both a familiar language and a foreign language. However, infants failed when the counting routine was applied in ways that did not respect typical counting principles. Together with previous findings, these results suggest that pre-counting infants are sensitive to some of the principles instantiated by counting years before they understand the meanings of count words, and this sensitivity impacts their representation of the counted arrays.

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