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On the limits of infants' quantification of small object arrays

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Abstract

Recent work suggests that infants rely on mechanisms of object-based attention and short-term memory to represent small numbers of objects. Such work shows that infants discriminate arrays containing 1, 2, or 3 objects, but fail with arrays greater than 3 [Feigenson, L., & Carey, S. (2003). Tracking individuals via object-files: Evidence from infants' manual search. *Developmental Science*, *6*, 568–584; Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object files versus analog magnitudes. *Psychological Science*, *13*(2), 150–156]. However, little is known about how infants represent arrays exceeding the 3-item limit of parallel representation. We explored possible formats by which infants might represent a 4-object array. Experiment 1 used a manual search paradigm to show that infants successfully discriminated between arrays of 1 vs. 2, 2 vs. 3, and 1 vs. 3 objects. However, infants failed to discriminate 1 vs. 4 despite the highly discriminable ratio, providing the strongest evidence to date for object-file representations underlying performance in this task. Experiment 2 replicated this dramatic failure to discriminate 1 from 4 in a second paradigm, a cracker choice task. We then showed that infants in the choice task succeeded at choosing the larger quantity with 0 vs. 4 crackers and with 1 small vs. 4 large crackers. These results suggest that while infants failed to represent 4 as "exactly 4", "approximately 4", "3", or as even as "a plurality", they did represent information about the array, including the existence of a cracker or cracker-material and the size of the individual objects in the array.

Keywords: Number; Numerosity; Singular; Plural; Object-files; Short-term memory limits

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1. Introduction

Data from a variety of paradigms suggest that long before learning their first words, infants represent the quantity information inherent in small object arrays. Infants between 0 and 10 months discriminate between 1 vs. 2 and 2 vs. 3 dots, objects, puppet jumps, moving shapes, or syllables (Antell & Keating, 1983; Bijeljac-Babic, Bertoncini, & Mehler, 1993; Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Van Loosbroek & Smitsman, 1990; Wynn, 1996). Infants also represent the outcomes of simple arithmetic transformations on object arrays. For example, 5- to 7-month olds look longer at unexpected outcomes of $1+1=2$ or 1 events and of $2-1=2$ or 1 events in violation-of-expectation tasks (Feigenson, Carey, & Spelke, 2002; Koechlin, Dehaene, & Mehler, 1998; Simon, Hespos, & Rochat, 1995; Uller, Huntley-Fenner, Carey, & Klatt, 1999; Wynn, 1992). In a third paradigm, 10- to 12-month-old infants who saw crackers hidden in opaque buckets spontaneously preferred to obtain the larger quantity with choices of 1 vs. $1+1=2$ crackers, and of $1+1=2$ vs. $1+1+1=3$ crackers (Feigenson, Carey, & Hauser, 2002). Finally, in a manual search task, 12- to 14-month-old infants reached into an opaque box according to the precise number of objects they saw hidden. If shown 2 objects hidden in the box, infants' patterns of search demonstrated that they expected to retrieve exactly 2 objects; if shown 3 objects hidden, infants expected to retrieve exactly 3 (Feigenson & Carey, 2003).

Strikingly, although infants track quantity across many kinds of tasks, they show an abrupt upper limit to the number of individual items they can represent at any given time. This upper limit appears to be 3.[1] Consider the cracker choice task by Feigenson, Carey, and Hauser (2002). After seeing crackers sequentially hidden in two buckets, infants reliably chose the larger quantity with choices of 1 vs. 2 and 2 vs. 3 crackers. However, infants failed with choices of 2 vs. 4, 3 vs. 4, and 3 vs. 6, despite the highly discriminable ratios between these arrays. Indeed, infants chose at chance whenever there were more than 3 crackers in either bucket. An identical pattern was obtained in the manual search paradigm, in which 14-month-old infants searched a box according to the number of objects they saw hidden, but only for the numerosities 1, 2, and 3 (Feigenson & Carey, 2003). For example, infants who saw 3 objects hidden and initially retrieved just 2 of them continued searching for the third object. By contrast, if infants had seen only 2 objects hidden and retrieved both, they correctly stopped searching, illustrating that they successfully discriminated the hiding of 2 objects from the hiding of 3 (a 2 vs. 3 comparison). In addition, infants succeeded on comparable 1 vs. 2 comparisons.

[1] Infants can also discriminate large numerosities, such as 8 vs. 16 dots or sounds (Lipton & Spelke, 2003; Xu & Spelke, 2000). However, in these cases, infants do not appear to be representing the individual items comprising the array, but are instead representing cardinality as a summary property of the array as a whole. Infants' hallmark performance signature with such large arrays is sensitivity to the ratio between quantities (for example, the 1:2 ratio between 8 and 16 dots). This performance signature implicates a system distinct from the system for representing small numbers of discrete objects that is our focus here (for discussion of these two representational systems, see Feigenson et al. (2004)).

But infants failed with 2 vs. 4, again showing that they were unable to represent more than 3 objects at a time.

This dramatic upper limit on infants' abilities replicates the 3–4 item representational limit exhibited by adults in a range of tasks (for review, see Cowan (2001)). For example, adults can track up to about 4 moving objects at a time (Pylyshyn & Storm, 1988), and can encode properties from up to 4 items in parallel (Halberda, Simons, & Wetherhold, submitted; Luck & Vogel, 1997). This suggests that the same representations that subserve mid-level attention and working memory in adults also underlie infants' tracking of small numbers of individuals (Carey & Xu, 2001; Feigenson, Carey, & Hauser, 2002; Scholl, 2001; Scholl & Leslie, 1999; Simon, 1997; Uller et al., 1999). This system of representations allows an object in an array to attract a visual index (Pylyshyn & Storm, 1988; Trick & Pylyshyn, 1994), which provides that object with a spatio-temporal address. Once attentionally indexed in this way, the object can be represented in working memory by a mental token such as an object-file (Kahneman, Treisman, & Gibbs, 1992).

Object-file representations implicitly contain information about the number of objects in an array, in that there is a one-to-one correspondence between object-files and objects. Hence, infants can represent the discrete numerosity of small object arrays via object-file representations. Object-files can also be used to store information about object features such as size. Thus, infants can also represent an array's total continuous quantity (e.g. total surface area or total contour length; for discussions of infants' discrete vs. continuous quantity representations, see Clearfield and Mix (1999, 2001), Feigenson (in press), Feigenson and Carey (2003), Feigenson, Carey, and Hauser (2002), Feigenson, Carey, and Spelke (2002) and Feigenson, Dehaene, and Spelke (2004)). Crucially, because there are only 3–4 available visual indexes or memory tokens (object-files), this system only allows for the parallel representation of up to 3 or 4 objects (Pylyshyn & Storm, 1988),[2] which explains why infants appear to compute neither the numerosity nor the total continuous extent of arrays containing more than 3 items (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002).

The experiments that demonstrate the set-size limit of object-file representations have contrasted infants' performance in discriminating 1 vs. 2 and 2 vs. 3 (successes) with their performance in discriminating 2 vs. 4, 3 vs. 4, and 3 vs. 6 (failures). Thus, the events with which infants have failed have been longer and more complex than those in which infants succeeded. Feigenson, Carey, and Hauser (2002) included a control for the possibility that sheer complexity and presentation duration caused infants' failure. However, the hypothesis that the object-file system cannot represent arrays containing more than 3 objects makes the strong and counter-intuitive prediction that infants will also fail to differentiate arrays of 1 object from arrays of 4, despite the extremely discriminable ratio between these numerosities. The first aim of the present studies was to test this hypothesis using both the cracker choice and manual search paradigms described earlier. Crucially, the total number of objects in a 2 vs. 3 comparison, with which infants have demonstrated

[2] It remains an open question whether the failure of infants and adults to represent more than 3–4 items in parallel is caused by limits on the number of available attentional indexes, short-term memory tokens (object-files), or both. For ease of discussion, we will refer to a limit on the number of available object-files.

success in previous studies (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002) is the same as that in a 1 vs. 4 comparison, but only in the 1 vs. 4 comparison does one of the arrays exceed the limit on available object-file representations. Therefore, only with 1 vs. 4 do we predict failure. Notice, these experiments require that infants can form representations of at least two arrays, each of which is constrained by the set-size limit on parallel representation (see Feigenson and Halberda (2004), for convergent evidence that infants indeed have the capacity to represent multiple arrays, each containing fewer than 3 objects).

To date, details of infants' performance have shed light on the format of the representations underlying infants' ability to represent small object arrays, demonstrating that they do so via a limited number of object-files. However, little is known about how infants represent small arrays containing *more than* 3 items. How do infants represent scenes that exceed the limit on the number of available object-files, as when they are presented with arrays of 4 or 6 crackers? Data from the evidence just reviewed shows that infants fail to form representations of the precise number of individual objects in such arrays (i.e. they fail to represent them as "4", either exactly or approximately). Do infants form any representation of a 4-object array?

One possibility is that when more than 3 objects are presented, infants maintain the representation of 3, merely ignoring the extra object. This possibility is ruled out by infants' previous failures to discriminate 4 vs. 2 (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002).

A second possibility is that when more than 3 objects are presented, infants fail to represent the objects altogether, storing no short-term memory representation of the array. The data just reviewed make this possibility unlikely—if infants failed to store *any* representation of 4 objects, then when shown 2 vs. 4 crackers in the cracker choice paradigm they should have systematically preferred the container with 2. Instead, infants chose at chance. This evidence is not conclusive, however, for exceeding the child's short-term memory capacity may just confuse them, causing them to lose any representation in either bucket, and thus chose randomly. A stronger test of the claim that infants form *some* representation of sets of 4 would be a 0 vs. 4 comparison. If infants maintain a representation of as set of 4 objects as *something*, but cannot represent its precise numerosity, they should systematically choose the bucket with 4 objects over an empty bucket.

Alternatively, infants might be able to represent 4 quantitatively, but not numerically—for example as "a plurality" or as "some" (in the discrete plural sense of "some"). This would entail recognizing that the array contains multiple individuals, but having no commitment as to how many there are, except that there exist "more than 1". Previous data do not bear on this question, since infants' failures with 2 vs. 4 (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002) are predicted on this hypothesis; as both sets of 2 and sets of 4 are pluralities. If infants can in fact represent 4 as "a plurality", they should succeed with the 1 vs. 4 comparisons.

Finally, if infants form *some* representation of 4 (i.e. they succeed with 0 vs. 4) but do not represent 4 as a plurality (i.e. they fail with 1 vs. 4), we will ask whether infants' representation includes information about the type of object seen. For instance, infants might represent that a container contains "cracker", or even "cracker of a certain size", while still failing to represent the number of tokens of the object type (i.e. failing to represent "exactly 4", "approximately 4", or even "a plurality"). To test this possibility, we present infants with a 1 vs. 4 comparison in which each of the 4 crackers is much larger than the single cracker. If infants successfully store information about the type of object in the 4-object array (e.g. the size of an individual cracker), they should choose that container even without remembering how many object tokens it contains. But if infants represent only "cracker", they should remain at chance.

We begin our exploration of infants' representations of arrays exceeding the limits of the object-file system with a 1 vs. 4 comparison in the manual search paradigm.

2. Experiment 1

Experiment 1 used the manual search task (Feigenson & Carey, 2003; Van de Walle, Carey, & Prevor, 2000) to explore the limits of infants' quantification of small object arrays. To provide a stronger test than any to date of the set-size signature on object-file representations, we contrasted a 1 vs. 4 comparison with 1 vs. 2, 2 vs. 3, and 1 vs. 3 comparisons. We expected infants to succeed with the latter three comparisons. Previous evidence has shown that 12- to 14-month-old infants cannot represent "exactly 4" or "approximately 4", for they do not search further when they have seen 4 placed in the box but have retrieved only 2 of them (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002). However, if infants can represent 4 as a plurality, then after having seen 4 objects hidden in the box and retrieving only 1 of them, they should continue searching just as they do when they have retrieved only 1 after seeing 2 hidden, or when they have retrieved 2 after seeing 3 hidden. If infants can represent a set of 4 as "a plurality", they should fail to continue searching.

Besides the crucial 1 vs. 4 comparison, we also tested infants with 1 vs. 2 and 2 vs. 3 because existing data from this task come from older infants (14-month olds), and because these serve as key comparisons against infants' performance with 1 vs. 4. Additionally, the 1 vs. 3 comparison (in which infants see 3 objects hidden, retrieve just 1 of them, and any subsequent searching is measured) provides a test of whether infants successfully continue to search the box when more than 1 object is expected still inside, as long as the original array contains no more than 3 objects.

As in the experiments by Feigenson and Carey (2003), objects were always presented as part of an x vs. y comparison. For any x vs. y comparison, we contrasted infants' searching after they saw x balls hidden and had retrieved x of them with their searching after they saw y balls hidden and had retrieved only x of them. Take the example of 1 vs. 4. On 1-Object trials, infants saw the experimenter hide 1 ball in the box. Searching was measured after infants had retrieved it, and was expected to be minimal given that the box was now empty. We compared this to searching on 4-Object trials, in which infants saw 4 balls hidden and were allowed to retrieve just 1 of them. While the experimenter surreptitiously held the remaining 3 balls out of reach, we measured how long infants searched for the "missing" balls. If infants represent 4 as being greater than 1 (e.g. if they represent 4 as "exactly 4", as "3", as "approximately 4", or as "a plurality"), they should continue searching the box.

Subtracting the time spent searching after infants saw 1 ball hidden and had retrieved 1 from time spent searching after infants saw 4 balls hidden and retrieved had 1 creates a difference score. If infants represent 4 as more than 1, this difference score should be positive. Difference scores were also calculated for the other comparisons tested: 1 vs. 2, 2 vs. 3, and 1 vs. 3. The latter conditions involved numbers that were predicted to be within infants' range of object-file representations, and based on previous results with 12- and 14-month olds (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002), we expected infants to succeed with these comparisons.

2.1. Participants

Thirty-two 12.5-month-old infants participated (mean = 12 months, 14 days). Fifteen were boys. Six additional infants were excluded due to fussiness (3), sibling interference (1), or failure to reach into the box (2).

2.1.1. Stimuli

Infants watched the experimenter hide identical ping–pong balls in a foam-core box (31.5 × 25 × 12.5 cm). The box's face had a 14 × 7.5 cm opening covered by spandex cloth with a slit across its width. The box also had an opening in back, hidden with a black felt flap, which allowed the experimenter to surreptitiously withhold objects on certain trials.

2.1.2. Procedure

Infants sat in a high chair in front of a table, with the experimenter kneeling to the left. The parent or caregiver sat to infants' right, approximately 1 m away. A video camera recorded a side-view of the session.

Two groups of 16 infants were tested. One group received 1 vs. 2 and 1 vs. 4 comparisons, and the other group received 1 vs. 3 and 2 vs. 3 comparisons. Each comparison pair was presented twice per infant.

2.1.2.1. 1 vs. 2 Comparisons. Comparisons were composed of three trial types. In the case of 1 vs. 2, 1-Object (Box Empty) trials measured searching after infants saw 1 ball hidden and had retrieved it (Fig. 1). The experimenter introduced the box and set it on the table, then brought out 1 ball and set it atop the box on either the left or the right side. She pointed and said, "Look at this". Then, to equate motion and presentation length with 2-Objects trials, she pointed to the empty space on the other side of the box and said, "Look at this". Finally, she picked up the ball, inserted it through the box's opening, and said, "What's in my box?" Infants were allowed to retrieve the ball and play with it very briefly before the experimenter took it away. All infants successfully retrieved the ball. A silent 10 s measurement period followed in which the box was left in place and any searching was coded later from videotape. Infants were not expected to search much during this 1-Object (Box Empty) trial, since they had already retrieved the 1 object they had seen hidden. After 10 s, the experimenter removed the box and the trial ended.

Two-Objects (More Remaining) trials measured searching after infants saw 2 balls hidden and had retrieved only 1 of them (Fig. 2). The experimenter brought out 2 balls

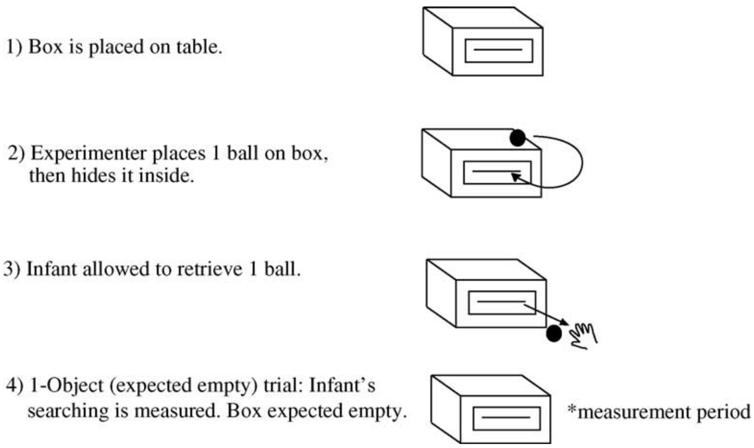

Fig. 1. 1-Object (Expected Empty) trial in Experiment 1.

simultaneously and set them atop the box. She pointed to each and said, "Look at this", then picked up both balls in one hand and inserted them through the box's opening. After the balls were inserted, the experimenter used her other hand to surreptitiously hold one of them at the back of the box, out of infants' reach. Hence, infants saw 2 balls hidden, but

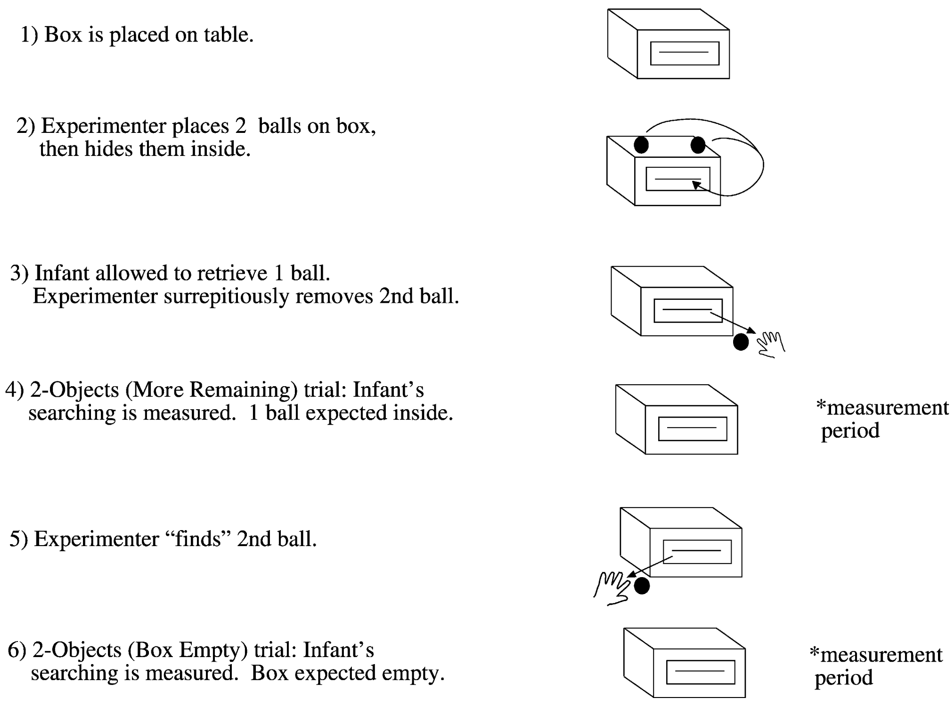

Fig. 2. 2-Objects (More Remaining) trial and 2-Objects (Box Empty) trial in Experiment 1.

could only retrieve 1 of them. As in the 1-Object (Box Empty) trial, infants were allowed to retrieve 1 ball and handle it briefly before the experimenter took it away. A silent 10 s measurement period followed. If infants successfully represented 2 objects in the box, they should search more on this More Remaining trial than on the Box Empty trial.

After the 10 s measurement period ended, the experimenter reached into the box and retrieved the 2nd ball. She gave it to infants and allowed them to handle it for a few seconds before it was taken away and the last 10 s measurement period began. This trial was called 2-Objects (Box Empty) because infants had seen 2 balls hidden, had retrieved both, and now the box was empty again (Fig. 2). If infants correctly represented 2 objects in the box, searching should return to its baseline Box Empty rate.

Each of these three trial types was presented twice. Whether the 1-Object (Box Empty) or the 2-Objects (More Remaining) trial was presented first was counterbalanced such that the presentation order was 1, 2, 2, 1 for half the infants, and 2, 1, 1, 2 for the other half. Two-Objects (Box Empty) trials always immediately followed 2-Objects (More Remaining) trials.

2.1.2.2. 1 vs. 4 Comparisons. These trials were structured identically to those comprising the 1 vs. 2 comparisons. The 1-Object (Box Empty) trial measured searching after infants saw 1 ball hidden and had retrieved it. The 4-Objects (More Remaining) trial measured searching after infants saw 4 balls hidden and had retrieved only 1 of them (the remaining 3 being withheld by the experimenter). Finally, the 4-Objects (Box Empty) trial measured searching after infants were given the remaining 3 balls that had been withheld by the experimenter. If infants represent 4 as more than 1 (even just as "a plurality"), they should search longer on More Remaining trials than on Box Empty trials.

As with the 1 vs. 2 comparisons, 1 vs. 4 comparison trials were equated for amount of motion and number of experimenter vocalizations. Therefore, the experimenter presented all 4 balls at one time, with one hand, and pointed to them only once.

The presentation order was 1, 4, 4, 1 for half the infants, and 4, 1, 1, 4 for the other half. Half of the infants were presented with the 1 vs. 4 block first and half were presented with the 1 vs. 2 block first.

2.1.2.3. 2 vs. 3 and 1 vs. 3 Comparisons. These comparisons were presented according to the procedure just described. Two vs. 3 comparisons compared searching on three trial types: when infants saw 2 balls hidden and had retrieved both of them (2-Objects (Box Empty)), when infants saw 3 balls hidden and had retrieved only 2 of them (3-Objects (More Remaining)), and when infants saw 3 balls hidden and had retrieved all 3 of them (3-Objects (Box Empty)).

One vs. 3 comparisons compared searching when infants saw 1 ball hidden and had retrieved it (1-Object (Box Empty)), when infants saw 3 balls hidden and had retrieved only 1 of them (3-Objects (More Remaining)), and when infants saw 3 balls hidden and had retrieved all 3 of them (3-Objects (Box Empty)). Again, all presentation factors such as duration, motion, and experimenter vocalizations were equated between trial types.

Order of presentation between blocks and within blocks was counterbalanced as described above.

2.1.3. Results

The dependent measure was the duration of infants' searching during the 10-s measurement period when the box was expected to be empty (e.g. 1 object hidden, 1 object retrieved) vs. searching when the box should be expected to contain more objects (e.g. 2 objects hidden, only 1 object retrieved). Infants were scored as searching whenever either or both hands were in the box, with their knuckles past the spandex slit. Simply grabbing the spandex did not count towards search time, nor did leaving the hand inside but turning attention elsewhere (e.g. towards the parent). If infants were still searching as the 10-s measurement period ended, they were allowed to continue searching until they removed their hand from the box, and the total searching time was recorded. Searching times were coded from videotape by two observers, one of whom was blind to the condition in which infants were tested. Observers used event-recording software to indicate the duration of infants' searches on each trial. Agreement between the two observers on total searching time over all measurement periods averaged 93% across all experiment sessions.

We analyzed infants' performance in terms of difference scores. For each numerical comparison tested, these difference scores were created by subtracting searching on the average of the two types of Box Empty trials from searching on More Remaining trials. Positive difference scores reflected success at representing the correct number of hidden objects. Before we computed these difference scores, we checked that the two types of Box Empty scores being collapsed did not differ from each other. For each comparison condition, a paired t-test examined whether searching on the first Box Empty trial differed from searching on the second (e.g. 1-Object (Box Empty) vs. 2-Objects (Box Empty)). In none of the comparisons did the two types of Box Empty trials differ (1 vs. 2: $t(15)=0.06$, $P=0.95$; 2 vs. 3: $t(15)=-0.07$, $P=0.95$; 1 vs. 3: $t(15)=1.21$, $P=0.24$; 1 vs. 4: $t(15)=-0.16$, $P=0.88$).

Averaged Box Empty searching was subtracted from More Remaining searching to yield a difference score for each comparison condition (Fig. 3). A one-way ANOVA revealed a marginally significant difference between the difference scores in the 4 numerical comparisons we tested (1 vs. 2, 2 vs. 3, 1 vs. 3, and 1 vs. 4), $F(3,63)=2.64$, $P=0.057$.

We examined the source of this effect with a series of paired t-tests. We found that the average difference score on the 1 vs. 4 comparison (0.41 s) differed from those on the three other comparisons (1 vs. 2: 2.51 s; 2 vs. 3: 1.47 s; 1 vs. 3: 2.53 s). This difference between 1 vs. 4 and the other comparisons proved significant (1 vs. 4 compared to 1 vs. 2: $t(15)=2.17$, $P<0.05$; 1 vs. 4 compared to 2 vs. 3: $t(15)=-2.15$, $P<0.05$; 1 vs. 4 compared to 1 vs. 3: $t(15)=2.55$, $P<0.05$). In contrast, none of the difference scores in the other three conditions differed from each other (1 vs. 2 compared to 2 vs. 3: $t(15)=1.02$, $P=0.33$; 1 vs. 2 compared to 1 vs. 3: $t(15)=-0.02$, $P=0.98$; 2 vs. 3 compared to 1 vs. 3: $t(15)=1.20$, $P=0.25$).

Finally, we asked whether difference scores were greater than chance for each comparison condition. This allowed us to ask whether infants successfully differentiated the two numerosities being compared. For 1 vs. 2, 2 vs. 3, and 1 vs. 3, difference scores were significantly greater than chance (1 vs. 2: $t(15)=-3.36$, $P<0.01$; 2 vs. 3: $t(15)=-3.31$, $P<0.01$; 1 vs. 3: $t(15)=-3.80$, $P<0.01$. For 1 vs. 4, the difference score

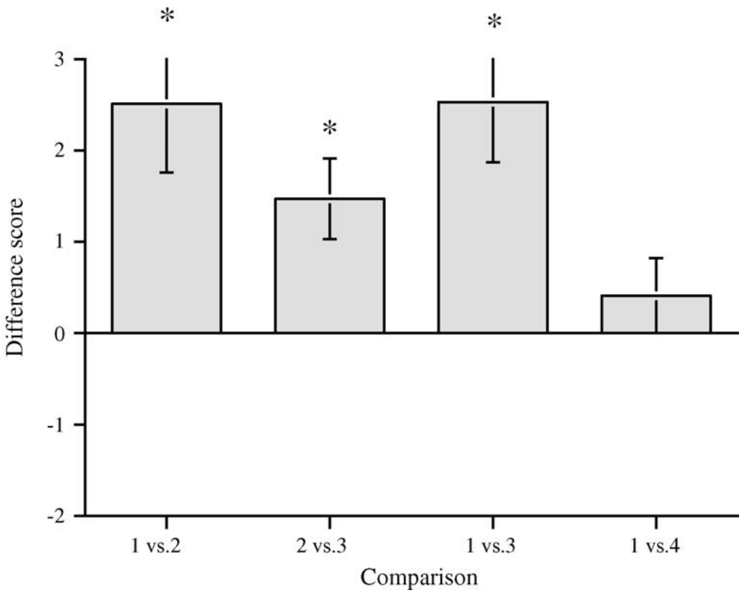

Fig. 3. Difference scores (More Remaining searching minus Box Empty searching) by numerical comparison in Experiment 1. Infants searched more on More Remaining than Box Empty trials for 1 vs. 2, 2 vs. 3, and 1 vs. 3 comparisons. On 1 vs. 4 comparisons, difference scores did not differ from chance.

did not differ from chance, $t(15) = -0.99$, $P = 0.41$. Thus, infants differentiated all of the numerical comparisons presented except for 1 vs. 4.

2.1.4. Discussion

These data replicate previous findings that infants track small numbers of objects and represent them over occlusion. When shown 1, 2, or 3 objects placed in a box, infants demonstrate by their search patterns that they expect to find exactly that number of objects inside. These data also extend the finding that 14-month-old infants discriminate 1 vs. 2 and 2 vs. 3 objects in this search task (Feigenson & Carey, 2003) to 12-month-old infants. In addition, that infants continue searching after seeing 3 objects hidden and retrieving just 1 of them demonstrates that infants can succeed with comparisons in which multiple objects are expected still in the box, as well as with those in which only 1 more object is expected.

The most surprising result from Experiment 1 was that despite their success with all of the other numerical comparisons tested, 12-month-old infants did not discriminate 1 vs. 4. Rather, after seeing 4 objects hidden and retrieving just 1 of them, infants returned to their baseline level of searching. They searched as little after seeing 4 objects hidden and retrieving 1 as they did after seeing just 1 object hidden and retrieving 1. This result extends the evidence for the set-size signature of object-file representations, showing that infants in the manual search paradigm fail to discriminate 1 vs. 4, just as they fail to discriminate 2 vs. 4 (Feigenson & Carey, 2003). The 1 vs. 4 comparison matched the 1 vs. 3 and the 1 vs. 2 comparisons in presentation duration and presentation complexity. Still, infants failed with 1 vs. 4 and succeeded with 1 vs. 2, 1 vs. 3, and 2 vs. 3. Apparently, infants' capacity to represent small arrays of individual objects falls apart with arrays greater than 3, even when the ratio between the numerosities is highly discriminable. Indeed, the 1:4 ratio tested here is well within the range of 12-month-old infants' abilities to compare both large (Lipton & Spelke, 2003; Xu & Spelke, 2000) and small (Antell & Keating, 1983; Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002; Starkey & Cooper, 1980; Strauss & Curtis, 1981) numerosities.

Infants' failure to discriminate 1 vs. 4 objects is striking. This failure confirms that infants did not represent "exactly 4" or "approximately 4" in Experiment 1. Nor did infants represent 4 as "3", opening 3 object-files and ignoring the presence of any further objects. In addition, these new data rule out the possibility that infants represent 4 as "a plurality". If this had been the case, then seeing 4 objects hidden and retrieving only 1 of them would have led to continued searching.

However, infants' failures with 1 vs. 4 in Experiment 1 and with 2 vs. 4 in the studies by Feigenson and Carey (2003) leave open the question of whether infants stored *any* kind of representation of a 4-object array in this paradigm. While the fact that infants reached into the box at all on 4-Object trials might at first seem evidence that they did store a representation of the 4-object array and were directing their reaches toward these objects, these initial reaches may in fact be misleading. In this paradigm, infants exhibited a certain level of baseline searching (searching even when the box was expected to be empty). It was for this reason that we analyzed the results in terms of difference scores. Therefore, while infants always reached into the box and retrieved 1 object on 4-Object trials, it is not clear whether these reaches were directed towards something expected inside, or instead simply reflected baseline searching. In Experiment 2, we turn to the cracker choice paradigm for convergent evidence that infants fail to discriminate 1 vs. 4 objects, and to address whether infants stored any kind of representation of a 4-object array.

3. Experiment 2

In Experiment 1, infants who observed the hiding of 4 balls did not continue to search after retrieving only 1 of them. This result rules out three of the possible ways infants could have represented 4: as "exactly 4", as "3", or as "a plurality". However, infants' failure with 1 vs. 4 in the manual search task raises the question of whether infants represented the 4 balls at all. Given that they did not represent 4 as more than 1 (via any of the 3 possibilities suggested above), we are left with at least two remaining alternatives. Infants could have failed to represent the 4 objects entirely, representing nothing at all in the box. Or, infants could have represented the 4 objects as simply "some", with no commitment as to how many objects were present. Previous evidence from Feigenson, Carey, and Hauser (2002) suggests that infants did form some representation of a 4-object array, since infants chose randomly between 2 vs. 4 rather than systematically choosing 2. However, it is unadvisable to make base an argument for a representational capacity from random responding. Experiments 2 and 3 probe for positive evidence that infants indeed represent 4 as *something*, by including a 4 vs. 0 comparison condition, and probe further whether this representation preserves any of the properties of the object, such as its type or size.

We addressed these questions using the cracker choice task. In addition, we sought to conclusively rule out the interpretation that infants' previously observed failure to choose 4 over 2 was due to the overall complexity of the presentation, or to the fact that the total number of objects presented was greater than in any of the conditions in which infants succeeded. Therefore, Experiment 2 sought to replicate infants' failure to distinguish between 1 vs. 4 objects. Importantly, the present 1 vs. 4 comparison using the cracker choice task equated the total number of objects presented with the 2 vs. 3 comparison with which infants have been shown to succeed. If infants fail with 1 vs. 4 in this choice task, as they did in the search task of Experiment 1, it confirms that infants' previous failures with 2 vs. 4 were not due to overall complexity or differences in the total number of objects seen. We anticipated that the strong prediction made by the 3-item limit of object-file representations would be confirmed, and that infants would fail to choose 4 crackers over 1. Finally, to establish conclusively whether infants form some representation of a 4-object array, we included a 4 vs. 0 comparison. If infants represent the 4-object array as "cracker" or "some cracker-stuff", they should choose 4 crackers over 0.

3.1. Method

3.1.1. Participants

Participants were 32 full-term infants between 10- and 12-months old (mean age = 11 months, 19 days). These were the same ages tested by Feigenson, Carey, and Hauser (2002), who found no difference between 10- and 12-month olds. Nineteen of the infants were boys. Ten additional infants were not included in the analysis due to failure to make a choice (9 infants) or parental interference (1 infant). Sixteen infants were offered the 1 vs. 4 choice and 16 were offered the 0 vs. 4 choice.

3.1.2. Stimuli

Infants observed 6.5×3 cm graham crackers removed from a small plastic container and placed into two opaque buckets. The buckets (13 cm in diameter, 14.5 cm high) were too tall for infants to see inside of.

3.1.3. Design and procedure

Infants sat on a playroom floor approximately 100 cm from the experimenter. A warm-up trial introduced the task. Infants watched the experimenter place a toy in the small container, and were encouraged to crawl and retrieve it. If they did not, the experimenter provided verbal encouragement.

Parents were instructed not to provide any feedback during the critical trial. The experimenter introduced the two buckets simultaneously and showed that they were empty. She placed them approximately 70 cm from infants and 70 cm from each other, far enough apart so that infants could not reach both at once, nor could they see the contents of either bucket without approaching them.

For the 1 vs. 4 choice, the experimenter retrieved a cracker from the small container and held it above one of the buckets. She showed it to infants, said, "Look at this", then placed it in the bucket. She then repeated this sequence with the other bucket, placing a total of 4 crackers inside it. For the 4-cracker array, the experimenter verbally called infants' attention by saying “Look at this” before each cracker placement. Side (1 cracker on the left or right) and order of presentation (1 cracker placed first or second) were counterbalanced across infants, with each infant receiving only one trial. The experimenter did not place crackers into the buckets unless she saw infants watching her do so. Notice that for this comparison, number of crackers is confounded with duration and amount of attention drawn to each bucket. A failure in this condition would therefore be all the more striking, given that infants could use either numerosity or duration/amount of attention in order to differentiate the buckets.

For the 0 vs. 4 comparison, the array of 0 crackers was presented as 4 sequential empty hand-waves above one of the buckets. The experimenter said “Look at this”, held her empty, open hand above the bucket, then moved it downwards to simulate the motion of a cracker presentation. This was done so as to equate the duration and amount of attention drawn to each bucket with the presentation of the 4 crackers. A success in this condition would mean that infants are tracking actual cracker placement(s), since duration and amount of attention was equated between the two choices.

After the presentation the experimenter looked down to avoid cueing infants. If infants did not approach within 10 s, the experimenter provided verbal encouragement without looking up. If infants did not approach after an additional 10 s, the experiment was terminated. Infants were considered to have chosen when they either: (1) reached into one of the containers, or (2) approached a container and sat in front of it for at least 8 s without reaching in. Choices were video-taped and re-coded by two observers. Agreement was 100%.

3.2. Results

Infants’ choices are shown in Fig. 4, along with infants’ reprinted performance in the 1 vs. 2 and 2 vs. 3 comparisons of Feigenson, Carey, and Hauser (2002). In the 1 vs. 4 comparison, infants chose at chance. There were no effects of side or presentation order, nor any difference between boys and girls. Note that infants’ failure here does not take the form of choosing 1 cracker over 4; instead, infants chose randomly. This result contrasts with infants’ previous success at choosing the greater quantity with comparisons of 1 vs. 2 and 2 vs. 3 (Feigenson, Carey, & Hauser, 2002)

However, infants succeeded with the 0 vs. 4 comparison. Thirteen/16 infants chose the bucket with 4 crackers over that with 0, $P<0.05$, two-tailed sign test.

3.3. Discussion

Experiment 2 replicates the striking failure of infants to discriminate 1 vs. 4 objects in Experiment 1. This finding bolsters the claim that it is the number of objects in an array, and not the complexity of the presentation, that determines whether infants will successfully represent the contents of that array. Given a choice between two hidden quantities, infants successfully chose between 2 vs. 3 crackers (Feigenson, Carey, & Hauser, 2002) and failed to choose between 1 vs. 4 crackers (Experiment 2 in the present series), despite the fact that the presentation events in these two conditions are matched

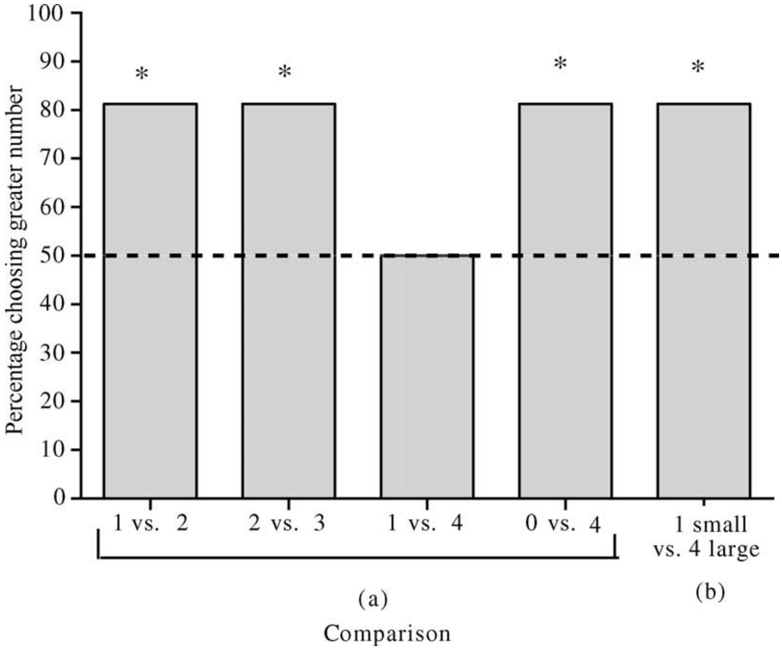

Fig. 4. Percent of infants choosing the greater number of crackers in Experiment 2 (1 vs. 2 and 2 vs. 3 comparisons reprinted from Feigenson, Carey, and Hauser (2002)). (b) Percent of infants choosing the greater number of crackers in Experiment 3.

with respect to total duration, complexity, and total number of objects. Infants failed only when one of the arrays exceeded the 3-item limit on parallel representation.

The pattern observed in Experiment 2 was not due to aspects of the cracker presentation such as total amount of motion or attention drawn to the buckets. Infants succeeded at choosing between 0 and 4 crackers when 0 and 4 were presented with equal durations and amounts of presentation motion. Infants failed at choosing between 1 and 4 crackers, despite the fact that for this comparison duration and presentation were not controlled for. The placement of 4 objects into the bucket took 4 times as long and drew 4 times as much attention to the bucket than did the placement of 1. This means that with the 1 vs. 4 comparison, infants could have used non-numerical cues to succeed but did not.

Infants' performance in Experiment 2 also confirms that infants do not represent 4 objects as "exactly 4", "approximately 4", "3", or even as "a plurality". That infants chose randomly between 1 and 4 also suggests that they did not fail to represent 4 altogether, as this would have led them to systematically prefer the bucket with 1 cracker. Indeed, infants' success with 0 vs. 4 shows that they did recognize that the 4-cracker bucket contained more "cracker-stuff" than the 0-cracker bucket. This pattern therefore leads us to favor the interpretation that infants represent 4 as "cracker", or "some cracker-stuff" but with no commitment as to how many individuals or how much continuous cracker-stuff "cracker" entails.

Our last experiment asked whether infants' representation of "some" includes any information about the *type* of individual hidden. To address this question, we presented infants with a choice between 1 small cracker and 4 larger crackers, where each large cracker was twice the size of the small cracker. If the 4-cracker array is represented merely as "cracker" or "some cracker-stuff", with no specification of the size of individual crackers, infants should still be at chance. Alternatively, infants may represent the type of individual they saw go into the box, specifying the size and shape and perhaps other properties of the object. If so, then even without representing anything about the discrete numerosity of the array (even plurality) infants may succeed at this comparison, because each individual cracker in the 4-cracker array is larger than the singleton in the 1-cracker array.

4. Experiment 3

4.1. Method

4.1.1. Participants

Participants were 16 full-term infants between 10- and 12-months old (mean age = 11 months, 14 days). Eight of the infants were boys. Three additional infants were not included in the analysis due to failure to make a choice.

4.1.2. Stimuli

Infants chose between a single 6.5×3 cm graham cracker and four 6.5×6.5 cm graham crackers. The buckets were the same as those used in Experiment 2.

4.1.3. Design and procedure

The procedure was identical to that in the 0 vs. 4 condition Experiment 2, in that duration, motion, and experimenter vocalizations were matched between the two choices. For the 1-cracker presentation, the experimenter said, "Look at this", and placed the single cracker in one of the buckets. She then added three empty "cracker placements" just as she had in Experiment 2, saying "Look at this" each time. The 4 crackers were presented sequentially, with identical verbalizations by the experimenter. Therefore, both the 1-cracker placement and the 4-cracker placement involved 4 motions and vocalizations, and lasted for the same duration. Side and order of cracker placement were counterbalanced across infants.

4.2. Results and discussion

As seen in Fig. 4(b), infants preferred the larger quantity. Thirteen out of 16 infants chose the bucket with 4 large crackers over the bucket with 1 small one ($P < 0.05$, two-tailed sign test).

Apparently, although 10- to 12-month-old infants do not represent the numerosity of arrays containing more than 3 objects, they do: (1) represent the array as containing *something* (as shown by their success with 0 vs. 4 crackers, and (2) represent some of the properties of the type of object in the array (as shown by their success with 1 small vs. 4 large crackers).

5. General discussion

The two methods employed here yielded a consistent set of findings: infants represented the numerosities 1, 2, and 3, but failed to represent 4. Together with the results of Feigenson and Carey (2003) and Feigenson, Carey, and Hauser (2002), these data provide strong evidence that object-files are the format of the representations supporting success in the manual search and cracker choice tasks. Infants can index up to 3 individuals in a given array, and can store object-file representations of these individuals in short-term memory. Furthermore, infants can perform at least two different computations over these representations. First, they can sum total surface area or volume over the object-files. This computation subserved success in the cracker choice experiment, as Feigenson, Carey, and Hauser (2002) demonstrated. Second, infants can determine numerical equivalence (for instance, via one-to-one correspondence) between the object-file representations stored in memory and a currently perceived array, as Feigenson and Carey (2003) showed with the manual search task. Performing either computation depends on the presence of object-file representations in memory. When there are too many objects to be represented via object-files, as was the case with the 4-object arrays in the present Experiments 1 and 2, infants fail to compute either total extent or number.

While Feigenson and Carey (2003) and Feigenson, Carey, and Hauser (2002) have already observed the set-size signature of object-file representations in the manual search and cracker choice paradigms, the present findings of infants' failure to discriminate 1 vs. 4 objects are an even more striking and counter-intuitive demonstration of the limit on object-files. This failure is robust, occurring when infants see objects presented simultaneously (in the manual search paradigm) and sequentially (in the cracker choice paradigm). In neither case did infants represent the 4-object array in a manner that allowed it to be distinguished from a single object.

The results of Experiments 1–3, together with those from previous studies, shed some light on the format of the representations infants store when faced with too many objects to represent via object-files. Infants did not represent 4 as "exactly 4", as "approximately 4", as "3", or as "a plurality". However, infants also did not fail to represent the 4-object array altogether. Infants' choices with the 1 vs. 4 and 0 vs. 4 comparisons in Experiment 2 suggest that they represented 4 as "some", without a commitment to the number of individuals involved. And their success in choosing between 1 small vs. 4 large crackers in Experiment 3 suggests that infants stored information about the type of individual in the array (e.g. its size, its identity as "cracker-stuff"), even though they did not know how many tokens of this type were present.

To understand these surprising results, it may help to introspect on the phenomenology of a task tapping adults' object-based attentional representations. In Pylyshyn's multiple object tracking (MOT) paradigm, participants see an array of identical items (dots) on a computer screen. A certain number of these flash briefly to indicate their status as targets. Then the entire array of identical targets and distractors is set in motion and the participants' task is to track the targets for several seconds. Normal adults can easily track 3 or 4 items in parallel (Pylyshyn & Storm, 1988). However, when asked to track 5 or 6, participants sometimes report losing track of all the targets they had been trying to follow.[3] Yet, even when this happens participants still recall some properties of the items they had been tracking prior to the disruption (e.g. that they were small white disks; that there were 5 of them).

Why did infants not represent a 4-object array as containing just 3, ignoring the fourth object in order to maintain some numerical representation of the array? We suggest that in the present experiments, infants tried to attend to all of the objects in an array, assigning one attentional index to each object presented. When the number of objects exceeded infants' capacity (when it exceeded 3), infants lost *all* of the assigned indexes or object-files, just as adults sometimes may do when trying to track 5 or 6 items in the MOT task. Infants most probably lack the strategic capability to ignore the fourth object and simply maintain 3 open object-files. Nor do infants have the linguistic resources to store a representation of the array verbally, for instance as "3 objects". Thus, unlike adults, infants exhibit a true breakdown in representing the numerosity of arrays greater than 3.

This breakdown has interesting implications for the development of quantificational concepts such as "singular" and "plural". Surprisingly, the evidence from Experiments 1 and 2 suggests that 12-month-old infants do not rely on a distinction between singular and plural numerosities when differentiating small object arrays, since doing so would have led them to successfully discriminate 1 vs. 4. This raises the question of whether infants in fact represent "singular" and "plural" at all. Clearly, children must do so by the time they have learned to linguistically mark this distinction. To date, the youngest age at which children have been found to discriminate singular vs. plural arrays in a linguistic comprehension task is at 24 months (Kouider, Halberda, Wood, & Carey, in press; see also Ferenz and Prasada (2002) and Mervis and Johnson (1991) for evidence from linguistic production tasks). In the study by Kouider et al., infants sat between two computer screens. One screen depicted an array of 8 identical unfamiliar objects and the other depicted a single unfamiliar object of a different type. Infants heard phrases containing either plural syntax and morphology (There are some gups) or singular syntax and morphology (There is a gup). Thus, the singular/plural distinction was redundantly marked on the verb (is/are), the quantifier (some/a), and the noun morphology (gup/gups). Twenty-four-month-old children looked longer at the screen that matched the linguistic input. That is, they looked longer at the screen with a single object when they heard "There is a gup", and at the screen with multiple objects when they heard "There are some gups". Twenty-month-old children, in contrast, did not shift their gaze in systematic response to the spoken phrase (Kouider et al., in press). Thus, young 2-year olds make use of some of the linguistic markers of the singular/plural distinction, which entails that they must represent the difference between 1 object, on the one hand, and arrays of multiple objects, on the other, even when the latter exceed the limits of parallel representation.

[3] Of course, whether these introspective reports are accurate, and whether subjects who are blocked from using other strategies in fact systematically lose track of all of the targets in such a situation, remains an open empirical question.

The results by Kouider et al., suggest that English-speaking children learn linguistic markers for singular and plural arrays between 20 and 24 months of age. The present experiments show that 12-month-old infants do not recruit a singular/plural contrast to discriminate arrays of 1 vs. 4 objects. In combination, these findings raise the question of whether pre-verbal infants have the concepts “singular” and “plural”, or whether they gain access to these through learning the linguistic markers for this distinction. This remains a question ripe for future research, answers to which will help elucidate the development of early quantificational abilities.

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