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PAPER

Tracking individuals via object-files: evidence from infants' manual search

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Abstract

In two experiments, a manual search task explored 12- to 14-month-old infants' representations of small sets of objects. In this paradigm, patterns of searching revealed the number of objects infants represented as hidden in an opaque box. In Experiment 1, we obtained the set-size signature of object-file representations: infants succeeded at representing precisely 1, precisely 2, and precisely 3 objects in the box, but failed at representing 4 (or even that 4 is greater than 2). In Experiment 2, we showed that infants' expectations about the contents of the box were based on number of individual objects, and not on a continuous property such as total object volume. These findings support the hypothesis that infants maintained representations of individuals, that object-files were the underlying means of representing these individuals, and that object-file models can be compared via one-to-one correspondence to establish numerical equivalence.

Introduction

A variety of experimental methods have yielded data in support of the claim that infants represent number. In habituation studies, infants from a few days through 10 months old are sensitive to matches or mismatches in number: habituated to arrays of 2 dots, objects, jumps, moving shapes, or syllables, infants dishabituate to arrays of 3. Conversely, when habituated to 3 individuals, infants dishabituate to 2 (Antell & Keating, 1983; Bijeljac-Babic, Bertoncini & Mehler, 1993; Clearfield & Mix, 1999; Feigenson, Carey & Spelke, 2002b; Starkey & Cooper, 1980; Starkey, Spelke & Gelman, 1990; Strauss & Curtis, 1981; Van Loosbroek & Smitsman, 1990; Wynn, 1996; Wynn & Bloom, 1999). Infants also increase looking to the change between arrays of 1 object and arrays of 2 (Feigenson *et al.*, 2002b). Recently, Xu and Spelke (2000) extended this finding to a discrimination of 8 dots from 16.

Infants also represent the outcomes of simple addition and subtraction events. For example, in Wynn's paradigm, infants see $1 + 1$ events in which 1 object is placed on a stage, is hidden by a screen, then another object is placed behind the screen. In this case, infants look longer at outcomes of 1 object than 2, relative to looking in $2 - 1$ events (Feigenson *et al.*, 2002b; Koechlin, Dehaene & Mehler, 1997; Simon, Hespos & Rochat, 1995; Uller, Huntley-Fenner, Carey & Klatt, 1999; Wynn, 1992).

Although these tasks were originally designed to explore number, the representations underlying infants' performance have been a matter of debate. One interpretation of the results cited above is that infants' success depends on symbolic number representations. The proposal is that the cardinal value of the array is represented by a single symbol, a magnitude that is proportional to number. Because the magnitude exhibits scalar variability, the ability to discriminate two quantities behaves according to Weber's Law, with discriminability behaving as a function of the ratio between the quantities (Dehaene, 1997; Gallistel, 1990; Gallistel & Gelman, 1992; Whalen, Gallistel & Gelman, 1999).

In contrast to analog magnitude models of quantity, attention-based models propose that infants represent number only implicitly, via symbols such as object-files (see Kahneman, Treisman & Gibbs, 1992). This hypothesis has been offered by several researchers, including Feigenson, Carey and Hauser (2002a), Feigenson, Carey and Spelke (2002b), Carey and Xu (2001), Scholl and Leslie (1999), Uller *et al.* (1999), and Simon (1997). The

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proposal is that spatiotemporal evidence for a unique, bounded, cohesive object in the visual scene causes infants to assign a visual index, or 'pointer' to each item in the array (Pylyshyn, 2001). Having this index of attention on an object allows the opening of an object-file in short-term memory. This object-file is a mid-level representation, situated between earlier representations of unbounded features and later representations of object kinds. The object-file is connected to the real-world object via the index, which is 'sticky' and follows the individual target through space and time. Limits on the number of indexes available result in limits on the number of individuals that can be attended to in parallel, and therefore on the number of object-files that can be opened (shown with adults in subitizing tasks: Trick & Pylyshyn, 1994, and multiple-object tracking (MOT) tasks: Scholl & Pylyshyn, 1999). This limit is around 3 (Scholl, Pylyshyn & Feldman, 2001).[1] Therefore, evidence that infants represent the number of individuals in an array by using object-file representations would come from a similar 3-item limit on their performance. Evidence that infants instead represent number with a system of analog magnitudes would come from performance dependent on ratio differences, as according to Weber's Law.

Feigenson, Carey and Hauser (2002a) provide evidence in favor of the object-file model of infants' numerical abilities using a choice method. Ten- and 12-month-old infants received a choice between two quantities of crackers placed in opaque containers. Infants saw, for example, 1 cracker placed in a container on the left, and 2 crackers placed in a container on the right. The dependent measure was which container infants approached first. Feigenson *et al.* found that infants successfully chose the container with the greater number of crackers, but also found an absolute limit on infants' abilities. Infants succeeded with choices of 1 vs. 2 and 2 vs. 3, but failed with 2 vs. 4, 3 vs. 4 and 3 vs. 6. Feigenson *et al.* called this pattern, in which infants succeeded only when the number of crackers in either container did not exceed 3, the 'set-size signature of object-file representations'. This contrasts with the pattern expected under analog magnitude models of numerical performance (Meck & Church, 1983; Dehaene & Changeux, 1993; Church & Broadbent, 1990), in which the discriminability of two numerosities is determined by their ratio. Such models predict better performance with choices of 2 vs. 4 and 3 vs. 6 than with 2 vs. 3. This set-size signature, with infants' performance breaking down after 3 items, can also be seen in habituation studies, in which infants dishabituate to the change between 2 vs. 3 items but not to the change between 4 vs. 6 (e.g. Strauss & Curtis, 1981). The break between 3 and 4 items in infants' performance in the choice and habituation tasks is analogous to the break in adults' performance in subitizing and MOT tasks, with both arising from limits on the number of available attentional indexes.

Infants appear to rely on object-file representations in the choice and habituation tasks discussed above, but it is likely that they also have access to analog magnitude representations of number. Infants dishabituate to changes between numerosities outside the range of object-file representations, e.g. 8 vs. 16 dots (Xu & Spelke, 2000), when all non-numerical factors are carefully controlled for. And in the large number range, infants' discrimination abilities follow Weber's Law. Success is a function of numerical ratio: 6-month-old infants dishabituate to the change between 8 vs. 16 and 16 vs. 32 (a 1:2 ratio), but fail with 8 vs. 12 and 16 vs. 24 (a 2:3 ratio; Xu & Spelke, 2000; Xu, 2000). It is important to note that the representation that supports this dishabituation (analog magnitudes) is distinct from the one infants rely on in the choice task and the habituation tasks testing smaller numerosities (object-files). With the same stimuli and design as in the 8 vs. 16 study, infants failed to discriminate 1 from 2 (Xu, personal communication, July 2002). Thus, using the same methods, large numbers appear to elicit analog magnitude representations while small numbers do not. While we endorse the notion that infants can represent number via analog magnitudes, our focus here is on the nature of the object-file system of representation.

Although there is clear evidence for infants' use of object-file representations in the small number range, there is currently no evidence that infants can compute the numerical equivalence between two sets of object-files or between a set of object-files and a set of objects in the world. Indeed, that infants represent number at all in tasks using small numbers of visually presented items has recently been challenged. In both the habituation and addition/subtraction tasks, infants appear to be attending to the non-numerical dimension of continuous extent. Using the habituation paradigm, Clearfield and Mix (1999) and Feigenson *et al.* (2002b) found that infants dishabituated to a change in contour length or surface area rather than to a change in number when the two dimensions were pitted against each other, and failed to dishabituate to a change in object number when surface area was controlled for (Feigenson *et al.*, 2002b). And while the set-size signature has not been obtained with

[1] Subjects in MOT tasks perform at 85–90% accuracy when asked to track 4 moving items in a field of 8. This performance is consistent with tracking 3 items perfectly, and guessing at chance on the fourth. See Appendix A in Scholl, Pylyshyn and Feldman (2001) for details. We thank an anonymous reviewer for pointing out this precise consistency in performance between adults and infants.

Wynn's addition/subtraction task, Feigenson *et al.* (2002b) found that infants seeing simple arithmetic events responded more strongly to outcomes unexpected in total surface area than to outcomes unexpected in number.

The same reliance on continuous extent is found in Feigenson *et al.*'s choice task (2002a). Recall that in this task infants' performance showed the set-size signature of object-file representations. However, Feigenson *et al.* also found that infants' choices were determined by a continuous quantity, rather than by number of individuals. Given a choice between 1 large cracker vs. 2 small ones, where the surface area of the large cracker was twice the combined total of the 2 small crackers, infants chose 1 large over 2 small. This suggests that the dimension over which infants made their comparison was total surface area.

Feigenson *et al.* proposed that infants opened object-files for each cracker they saw, and that property information such as surface area was bound to the object-files. Infants then summed surface area across object-files for each container, and determined which container held more total 'cracker material'. This area comparison could not take place when the number of crackers exceeded 3, because infants had no way of representing the individuals being presented.

This formulation of the object-file model, in which object-files can be compared on the basis of their summed properties, contrasts with previous accounts which suppose that the individual object-file representations are compared directly via one-to-one correspondence (Carey & Xu, 2001; Scholl & Leslie, 1999; Uller *et al.*, 1999; Simon, 1997). As yet, there is no evidence in the infant literature to support the conclusion that infants can operate on object-files to determine numerical equivalence between two sets (for example, between a set of object-files stored in memory and a set of objects in the world). In order to show that object-file representations can represent the *number* of objects in an array, we must demonstrate a response based on number when continuous extent is controlled for.

One task using small numerosities that did show a numerical response with spatial extent controlled for is that of Wynn, Bloom and Chiang (2002), who found that 5-month old infants dishabituated to the change between 2 and 4 moving collections of items. While this task convincingly shows infants responding to number, it is not clear which representational system infants relied on. Because the authors did not test numerosities other than 2 vs. 4, we cannot know whether infants relied on object-files or on analog magnitudes. Indeed, because the 'objects' in this study were 2-D collections with shifting boundaries, infants may not have represented them using the same object-tracking mechanisms that they use in tasks involving actual objects. Therefore, it is still open whether infants can compare numbers of object-files directly.

The present experiments had two goals. First, we looked for convergent evidence for the set-size signature of object-file representations in a new procedure for exploring infants' number representations. Second, we sought the first evidence that infants can compute one-to-one correspondence over object-files. Such a finding would suggest that object-files subserve infants' performance in our task, and that infants can compute matches and mismatches in numbers of object-files, thus establishing numerical equivalence.

We used a modified version of the manual search procedure (Van de Walle, Carey & Prevor, 2001; Starkey, 1992). Infants watched an experimenter present an array of identical objects on top of a box. The experimenter then placed the objects sequentially inside and allowed infants to reach in and retrieve them. This allowed us to ask how many objects infants represented inside the box. This task was chosen in order to maximize the likelihood that infants would demonstrate a number-based response, even when continuous extent was controlled for. We anticipated that the activity of reaching for objects was most likely to elicit a response based on the *number* of individual objects because: (1) reaching is an action oriented toward obtaining individual objects, and (2) unlike the choice task, in which the goal was most likely to obtain the most total food, there is less reason to attend to the continuous properties of non-food objects (see General Discussion).

Trials were presented in pairs of 1 vs. 2, 2 vs. 3 and 2 vs. 4. For example, consider a 2 vs. 3 pair. On a third of the trials, 2 objects were hidden in the box and searching was measured after infants had retrieved 2 objects. Infants were not expected to search much on these trials, since they should expect the box to be empty. On another third of the trials, infants saw 3 objects hidden, and were allowed to retrieve 2. In this case infants were expected to search the box because there is a another object still expected inside. On the last third of the trials, infants were given the third object by the experimenter, and their subsequent searching was measured. Again, searching was expected to be minimal since infants had retrieved all of the objects they had seen hidden. So an 'x vs. y' pair ('1 vs. 2', '2 vs. 3', '2 vs. 4') compares searching after x objects have been hidden and x retrieved with searching after y objects have been hidden, and only x retrieved. In general, search time should be greater on trials when infants expect another object in the box than on trials when they have already retrieved all of the objects.

Experiment 1 explores the limit on the number of individuals infants can represent. We presented infants with the numerical comparisons 1 vs. 2, 2 vs. 3 and 2 vs. 4 to test the hypothesis that performance would reflect the set-size signature of object-file representations. If infants rely on object-files in the manual search task, then they should only succeed with comparisons in which the number of objects in the box does not exceed 3. Therefore, we predicted success with 1 vs. 2 and 2 vs. 3 comparisons, and failure with 2 vs. 4. Experiment 2 explores whether the representations guiding search reflect the number of individuals infants saw hidden, or reflect a continuous dimension such as total object volume. If infants see 2 small objects hidden, will retrieving 1 big object satisfy their expectations?

Experiment 1

Method

Participants

Thirty-two full-term 14.5-month-old infants participated (range: 14 months, 0 days to 15 months, 14 days; mean age = 14 months, 22 days). Approximately half of the infants were boys (20/32). Sixteen infants participated in the 1 vs. 2/2 vs. 3 condition, and 16 participated in the 1 vs. 2/2 vs. 4 condition. Fourteen additional infants were excluded due to fussiness (9), experiment error (2), parental interference (2) or prematurity (1).

Stimuli

Infants observed ping pong balls (diameter = 3.5 cm) being hidden in a black foam-core box. The box measured 25 cm wide × 31.5 cm deep × 12.5 cm high. Its front face had a 14 × 7.5 cm opening covered by blue spandex material with a horizontal slit across its width. The back face of the box had an identical opening covered by a black felt flap. Eight small washers were affixed to the top of the box so that balls could be placed on top without rolling off.

After retrieving balls, infants were encouraged to drop them into a plastic chute. The chute ('Ball Party', manufactured by TOMY) consisted of a spiral track with a funnel opening on top. Balls dropped in the funnel rolled down the track and landed in a ring at the bottom. The chute was included in the task in order to increase infants' motivation to retrieve the balls from the box.

Design

Infants were assigned to one of two conditions. Infants in the 1 vs. 2/2 vs. 3 condition received 1 vs. 2 and 2 vs. 3 comparisons. Infants in the 1 vs. 2/2 vs. 4 condition received 1 vs. 2 and 2 vs. 4 comparisons.

Infants received 2 blocks of 4 presentations each. One block was always composed of a 1 vs. 2 comparison. The other block was composed of either a 2 vs. 3 (1 vs. 2/2 vs. 3 condition) or a 2 vs. 4 comparison (1 vs. 2/2 vs. 4 condition). Which comparison block infants were tested with first was counterbalanced across participants. Within each comparison block, comparisons could be presented in two possible orders. Infants saw either the larger number of objects presented first (for 1 vs. 2 blocks: 2, 1, 1, 2; for 2 vs. 3 blocks: 3, 2, 2, 3; for 2 vs. 4 blocks: 4, 2, 2, 4), or the smaller number presented first. This factor, Trial Order, was counterbalanced across infants.

Therefore, the experiment involved five factors: Condition (whether infants were tested with 1 vs. 2/2 vs. 3 or with 1 vs. 2/2 vs. 4), Comparison (1 vs. 2, 2 vs. 3, or 2 vs. 4), Comparison Order (whether infants received the 1 vs. 2 comparison first or second), Trial Order (whether infants were tested with the larger number of balls first or second) and Trial Type (whether the box was expected to be empty, expected to contain more balls, or expected to be empty after the last object had been retrieved; these will be termed '1st expected empty trial', 'more remaining trial' and '2nd expected empty trial'). Because each comparison contained 2 pairs of each of the 3 trial types, infants received a total of 12 trials per comparison block.

Procedure

Infants sat in a high chair in front of a table, with parents sitting a few feet away. The experimenter knelt next to the chute, to infants' left. A video camera recorded a side-view of the session.

Familiarization. The experiment began with a familiarization trial. The experimenter first brought out the box and showed it to infants. She reached in through the spandex-covered opening and said, 'Look! Do you see my box? See how I can reach into the box?' Infants were encouraged to reach inside. Next, the experimenter brought out a single ball. This 'familiarization ball' was larger and differently colored from the balls used in the rest of the experiment. The experimenter showed infants as she inserted the ball through the opening of the box. Infants were encouraged to reach in and retrieve the ball. Once they had done so, the familiarization was considered complete.

1 vs. 2 test pairs. Trials were presented in 1 vs. 2, 2 vs. 3 or 2 vs. 4 pairs. For 1 vs. 2 pairs, infants' searching after seeing 1 ball hidden and retrieving 1 was compared with their searching after seeing 2 balls hidden and retrieving 1. For the 1-object presentation (see Figure 1), the experimenter placed the box on the table, out of infants' reach. She brought out 1 ball and placed it on top of the box (whether it was placed on the right or left side of the box was counterbalanced). The experimenter pointed to the ball and said, '(Baby's name), look at this.' Then, in order to equate amount of motion and speaking with those on the 2-object presentation, she pointed to the empty space on the other side of the box and said, '(Baby's name), look at this.' Finally, she picked up the ball and inserted it through the box's opening. If infants did not attend during any point in this sequence, the experimenter drew their attention and did not proceed until they were watching. The experimenter slid the box forward, and said, 'What's in my box?'

Infants were then allowed to retrieve the ball. After having done so, they were encouraged to drop it into the chute or give it to the experimenter. Infants were not allowed to keep the ball for more than 10 s before the experimenter took it away.

A 10 s measurement period followed, during which the box was left in place and search time was coded later from videotape. This trial was called '*1-object (expected empty)*' because infants had seen only 1 object hidden, had retrieved it, and now the box was expected to be empty. During the trial the experimenter looked down to avoid providing any cues as to whether or not there was anything left in the box. After 10 s, the experimenter removed the box and the trial ended. If infants were in the middle of searching after 10 s, the trial was allowed to continue until they removed their hand from the box.

The 2-object presentation was structured like the 1-object presentation, but contained two trial types rather than one: '2-objects (1 remaining)' and '2-objects (expected empty)' (see Figure 2). The experimenter again placed the box on the table. She brought out 2 balls simultaneously, and placed them on top of the box. The experimenter pointed to each and said, '(Baby's name), look at this.' Then she picked up both balls in one hand and inserted them through the box's opening. Unbeknown to infants, the experimenter surreptitiously removed one of the balls from the back of the box. Hence, infants saw 2 balls placed in the box, but there was actually only 1 ball inside to retrieve. The experimenter slid the box forward and said, 'What's in my box?'

As in the 1-object presentation, infants were allowed to retrieve 1 ball, and then were encouraged to drop it into the chute. Alternatively, the experimenter took the ball away within 10 s of its retrieval. Next came a 10 s measurement period. This was called the '*2 objects (1 remaining)*' trial, because infants had seen 2 objects hidden in the box, had retrieved 1, and the box was now expected to contain another object. Because the experimenter had surreptitiously removed the second ball from the back of the box, there were no physical cues as to anything else remaining inside. For instance, infants could not have heard a ball rolling inside, nor have touched one while searching. No cues to the presence of more balls were present during a '2-objects (1 remaining)' trial that were not present during a '1-object (expected empty)' trial. We expected that if infants had represented 2 balls being hidden in the box and maintained this representation, they should search inside during the '2-objects (1 remaining)' trial.

After 10 s, the experimenter reached in and retrieved the second ball, saying 'Let me see if I can help you!' She gave infants the ball, giving them the opportunity to either drop it into the chute or to play with it for up to 10 s before she took it away. After infants relinquished the second ball, a final measurement period began. This trial was called '*2-objects (expected empty)*' because infants had seen 2 objects hidden, had retrieved both, and now the box was empty again. After 10 s, the trial ended and the experimenter removed the box.

Thus, for each paired presentation there were three trial types: '1-object (expected empty)', '2-objects (1 remaining)' and '2-objects (expected empty)'. The dependent measure was the cumulative duration of infants' searching during the 10 s measurement period. Comparing search time over these three trials provides a measure of whether infants represented the correct number of objects in the box at any given time. Representing exactly 1 ball during 1-object trials and exactly 2 balls during 2-object trials would result in little or no searching during '1-object (expected empty)', much searching during '2-objects (1 remaining)' and little or no searching again during '2-objects (expected empty)'. 'Two-objects (expected empty)' trials were included to ask whether infants might be representing 'many objects' in the box as opposed to 'exactly 2 objects' in the box. If this were the case, we would expect long search times in both the '2-object (1 remaining)' and the '2-objects (expected empty)' trials.

2 vs. 3 test pairs. For 2 vs. 3 pairs, infants' searching after seeing 2 balls hidden and retrieving 2 was compared with their searching after seeing 3 balls hidden and retrieving 2. These pairs were structured almost identically to the 1 vs. 2 pairs. As before, the number of motions and phrases spoken by the experimenter were equated between trial types. For example, on 2-object presentations the 2 balls were placed one at a time on top of the box, then were inserted one at a time into the box. When the experimenter pointed to them and said, 'Look at this', she also said the same thing while pointing

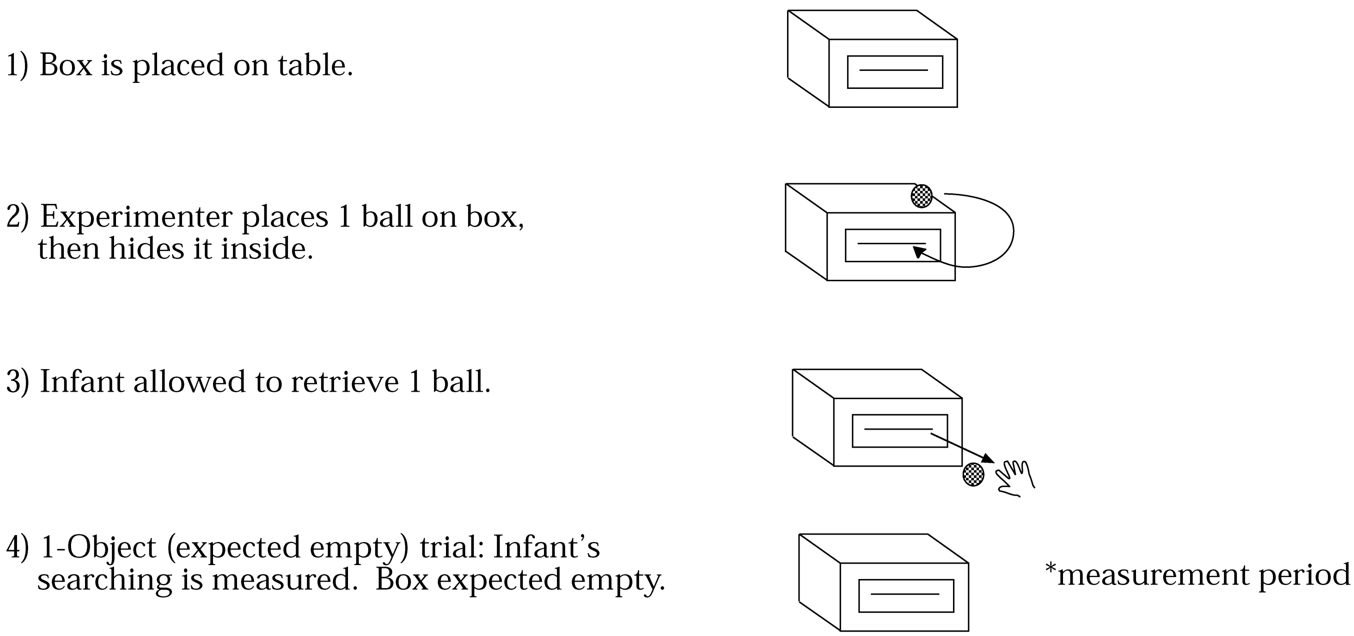

Figure 1 *1-Object (expected empty) trial in Experiment 1.*

to an empty location on top of the box. This sequence matched the number of pointings and utterances of the 3-object presentation, in which 2 balls were placed on top of the box together, and then a third ball was added. The 3 balls were also placed inside the box with 2 movements: the experimenter picked up and inserted two together, followed by the third.

Two vs. 3 presentation pairs contained three trial types, each lasting 10 s. In the '*2-objects (expected empty)*' trial, searching was measured after infants saw 2 balls hidden, and had retrieved both. In the '*3-objects (1 remaining)*' trial, searching was measured after infants saw 3 balls hidden, and had retrieved 2 (with the third ball having been surreptitiously removed). Finally, the '*3-objects (expected empty)*' trial measured searching after the experimenter handed infants the third ball that had been 'stuck' in the back of the box. As with the 1 vs. 2 presentation, success consisted of a pattern of little searching, followed by much searching, followed by little searching.

2 vs. 4 test pairs. For 2 vs. 4 pairs, infants' searching after seeing 2 balls hidden and retrieving 2 was compared with searching after seeing 4 balls hidden and retrieving 2. These pairs were structured identically to the previous pairs. As before, the number of motions and phrases spoken by the experimenter were equated between trial types. The three trial types were: '*2-objects (expected empty)*' (searching during the 10 s after infants saw 2 balls hidden and had retrieved them both), '*4-objects (2 remaining)*' (searching after infants saw 4 balls hidden and had retrieved 2, with the remaining balls having been surreptitiously removed) and '*4-objects (expected empty)*' (searching after infants saw 4 balls hidden, had retrieved 2, then were given the last 2 by the experimenter). Note that representing 'exactly 4' is not necessary for success here. Infants could also succeed by representing the 4-ball array as containing 3 balls, or simply 'more than 2 balls'. Failure, however, would show that 4 balls had not been represented (nor 3, nor 'more than 2').

Dependent measure. Search time was coded from videotape by two observers. Seconds spent searching were summed across all reaches infants made in a given trial.[2] Searching was defined as a period during which the knuckles of one or both of infants' hands passed through the slit in the spandex-covered opening in the front of the box. Grasping the spandex did not count as searching. Searching was measured only after infants had relinquished the ball(s) either to the experimenter, or by dropping them in the chute. Trials began when the experimenter removed the ball(s) from the chute, and lasted for 10 s thereafter. Occasionally infants reached into the box while still holding the first ball they had retrieved (i.e. before giving it to the experimenter or dropping it in the chute). When this happened, the 10 s measurement period started from the beginning of that reach. Search

[2] Although we report here the total seconds infants spent searching, measuring the number of times infants reached also yielded the same pattern of results.

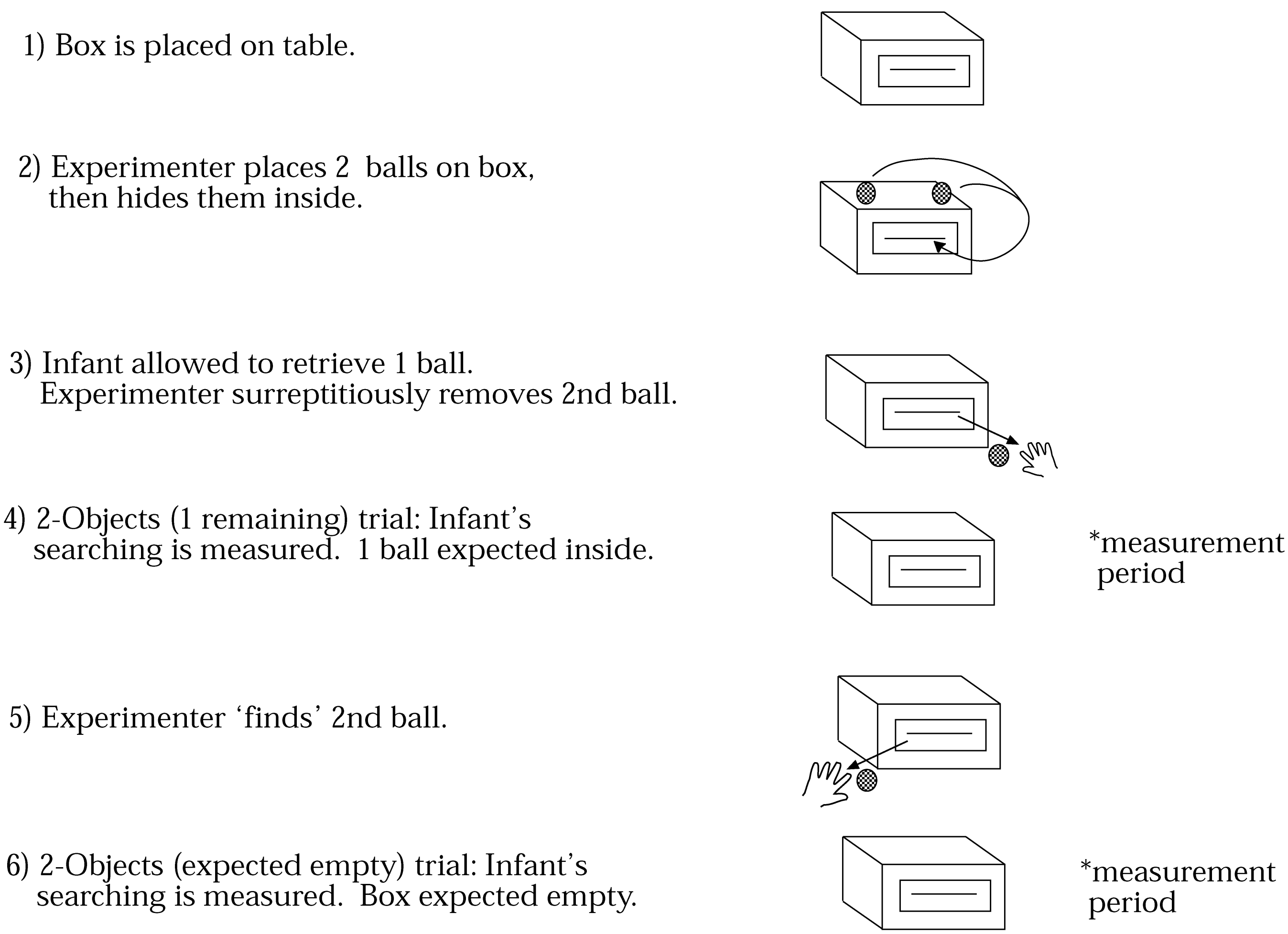

Figure 2 *2-Objects (1 remaining) trial and 2-Objects (expected empty) trial in Experiment 1.*

time was coded using a button-box connected to event-recording software. Inter-observer agreement was 96%.

Results

We examined infants' searching with an analysis of variance (ANOVA) involving three within-subjects factors and four between-subjects factors. Within-subjects factors were: Comparison (smaller numerical comparison (i.e. 1 vs. 2) or larger numerical comparison (i.e. either 2 vs. 3 or 2 vs. 4)), Trial Pair (whether it was the first or second presentation of any given comparison) and Trial Type (1st 'expected empty' trial, 'more remaining' trial, 2nd 'expected empty' trial). Between-subjects factors were: Condition (1 vs. 2/2 vs. 3 or 1 vs. 2/2 vs. 4), Comparison Order (whether 1 vs. 2 was presented first or second), Trial Order (whether the larger number of balls was presented first or second) and Sex. There were no significant effects of Trial Pair, Comparison Order, Trial Order or Sex (with the exception of two five-way interactions that were uninterpretable). The ANOVA revealed a main effect of Trial Type, $F(2, 32) = 11.67$, $p < .01$, which resulted from longer search times on 'more remaining' trials than on 'expected empty' trials (see Figures 3 and 4). This main effect was mediated by a Trial Type × Comparison interaction, $F(2, 32) = 8.07$, $p < .01$, due to the fact that infants succeeded most robustly on 1 vs. 2 comparisons. Lastly, there was a marginally significant three-way interaction between Trial Type, Comparison and Condition, $F(2, 32) = 2.20$, $p = .12$. This interaction motivated closer inspection of infants' performance in each comparison of each condition.

For the 1 vs. 2/2 vs. 3 condition, a 2 (Comparison: 1 vs. 2 or 2 vs. 3) × 3 (Trial Type: 1st 'expected empty' trial, 'more remaining' trial, 2nd 'expected empty' trial) × 2 (Comparison Order) × 2 (Trial Order) × 2 (Test Pair) ANOVA was conducted. This analysis revealed a main effect of Trial Type, $F(2, 24) = 16.75$, $p < .01$, due to infants searching longer on 'more remaining' trials than on 'expected empty' trials in both the 1 vs. 2 and the 2

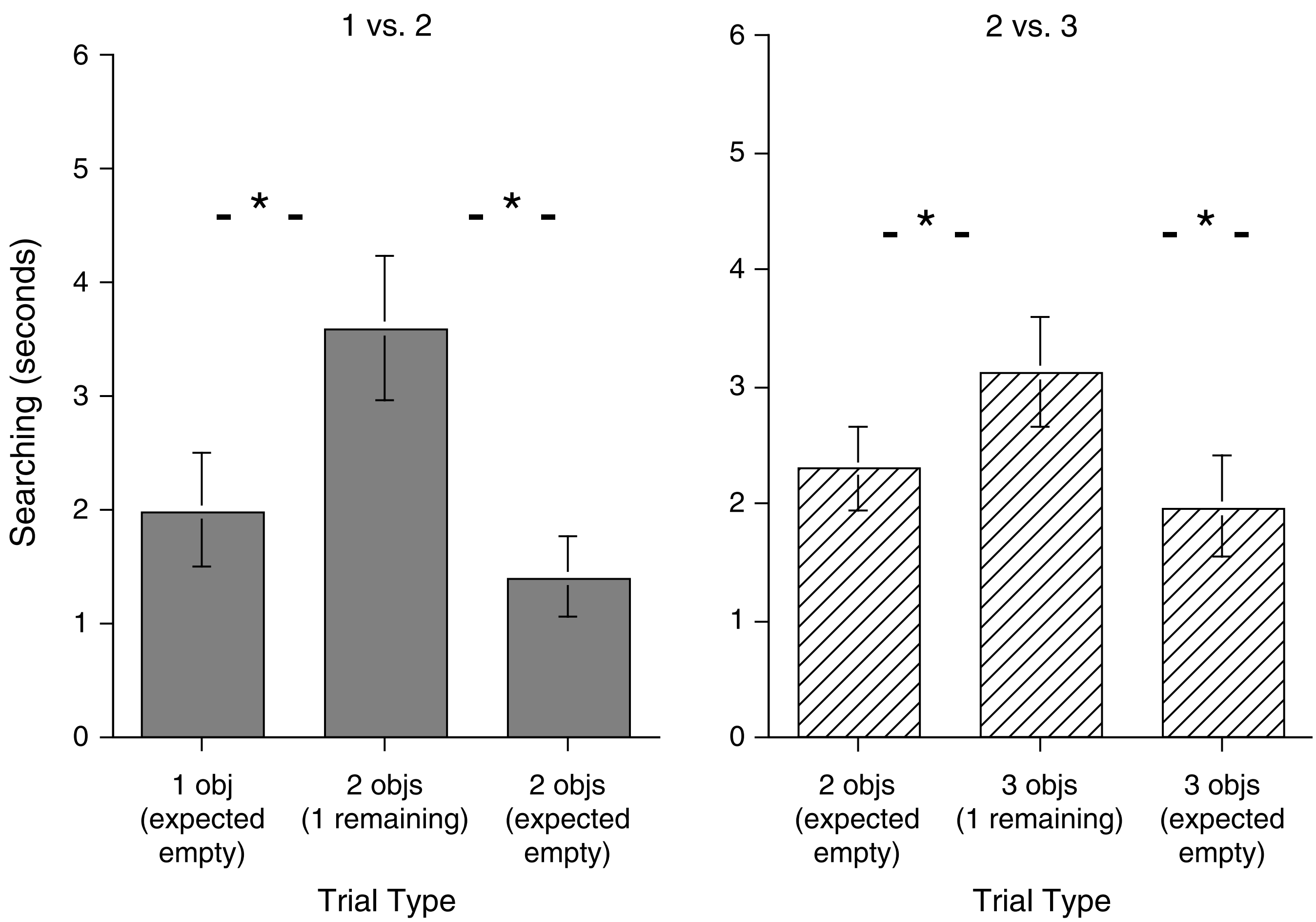

Figure 3 *Search times by trial type for 1 vs. 2 and 2 vs. 3 conditions of Experiment 1.*

vs. 3 comparisons (Figure 3). No other main effects or interactions were observed. Importantly, there was no Trial Type × Comparison interaction, $F(2, 24) = 0.88$, $p = .43$. Regardless of whether the presentation was 1 vs. 2 or 2 vs. 3, infants searched longer on 'more remaining' trials than 'expected empty' trials.

Planned comparison *t*-tests confirm the source of this main effect of Trial Type. There was no difference in searching between the 1st 'expected empty' trial and the 2nd 'expected empty' trial, $t(1, 15) = 1.18$, $p = .256$, so these two trial types were collapsed. Infants searched significantly longer on 'more remaining' trials than on the average of the two 'expected empty' trials, $t(1, 15) = -4.58$, $p < .05$. Collapsed across 1 vs. 2 and 2 vs. 3 trials, infants searched an average of 3.4 s on 'more remaining' trials and 1.7 s on 'expected empty' trials. Inspection of Figure 3 suggests that in spite of the lack of an interaction, the effect was weaker in the 2 vs. 3 comparison than in the 1 vs. 2 comparison. However, planned *t*-tests revealed that success was robust on the 2 vs. 3 comparisons alone. Infants searched longer on the '3-objects (1 remaining)' trials (mean = 3.2 s) than on the average of the '2-objects (expected empty)' or '3-objects (expected empty)' trials (mean = 2.0 s), $t(1, 15) = -3.12$, $p < .01$.

A separate ANOVA was conducted for the 1 vs. 2/2 vs. 4 condition, with the same factors as in the above analysis. This revealed a main effect of Trial Type, $F(2, 24) = 4.28$, $p < .05$, mediated by a Trial Type × Comparison interaction, $F(2, 24) = 9.92$, $p < .01$. This interaction arises because which comparison infants were presented with determined whether or not they searched longer on some trial types than others.

We isolated the source of this interaction with planned comparison *t*-tests, which revealed a difference in search times between 'more remaining' vs. 'expected empty' trials for 1 vs. 2 comparisons, but not for 2 vs. 4 comparisons. For 1 vs. 2 comparisons, there was no difference between the 1st 'expected empty' and the 2nd 'expected empty' trials, $t(1, 15) = -1.58$, $p = .135$, which were then collapsed. Infants searched significantly longer on 'more

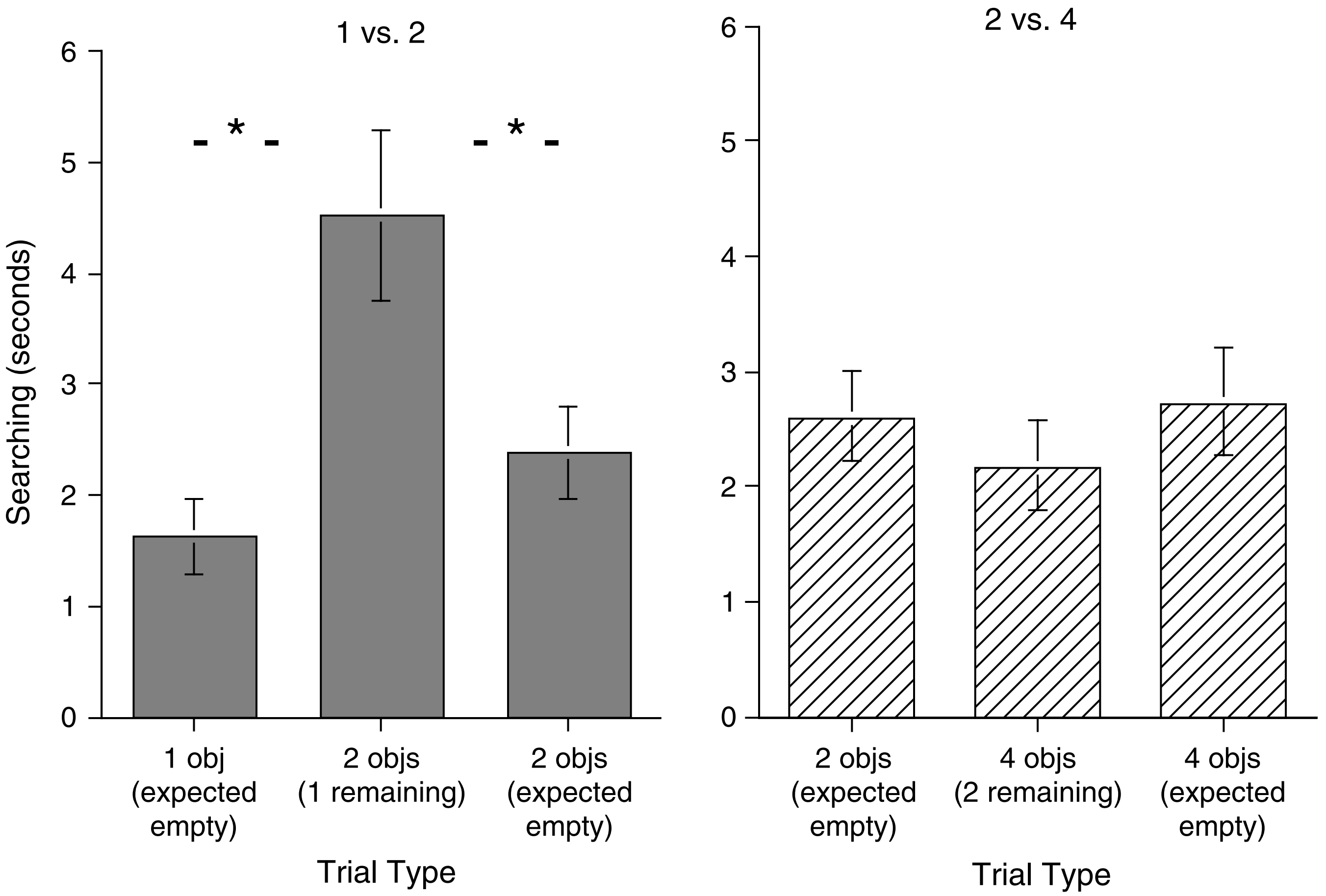

Figure 4 *Search times by trial type for 1 vs. 2 and 2 vs. 4 conditions of Experiment 1.*

remaining' trials (mean = 4.5 s) than on the average of the 'expected empty' trials (mean = 2.0 s), $t(1, 15) = -3.60$, $p < .05$. This pattern contrasts with the 2 vs. 4 comparison, in which there was no difference between trial types. Paired t-tests found no difference between the two types of 'expected empty' trials, $t(1, 15) = -0.56$, $p = .582$, nor between the 'more remaining' trials (mean = 2.2 s) and the average of the 'expected empty' trials (mean = 2.6 s), $t(1, 15) = 0.89$, $p = .387$.

Finally, because the important result in this study is infants' failure with 2 vs. 4 in the face of success with 2 vs. 3, we compared these two conditions directly. We conducted a 2 (Comparison: 2 vs. 3 or 2 vs. 4) × 3 (Trial Type) × 2 (Comparison Order) × 2 (Trial Order) × 2 (Test Pair) ANOVA to ask whether there was a significant difference between performance in the 2 vs. 3 condition and the 2 vs. 4 condition. A Comparison × Trial Type interaction revealed that there was, $F(2, 48) = 4.23$, $p < .05$. The only other finding was a three-way interaction between Trial Type, Comparison Order and Test Pair. This results from the fact that when they received the small number comparison first, infants in both the 2 vs. 3 and 2 vs. 4 comparisons reached longer on the 'expected full' trials during the second test pair than the first. This interaction did not contribute to the difference in infants' performance in the 2 vs. 3 comparison relative to the 2 vs. 4 comparison.

A concise way of depicting these results is to view infants' searching as a series of difference scores. These difference scores are created by subtracting searching on trials when the box is 'expected empty' from those when there are 'more remaining' inside.[3] Positive difference scores would indicate that infants searched longer on

[3] Recall that for each comparison, there were two types of 'expected empty' trials. For example, infants tested with a 1 vs. 2 comparison received a '1-object (expected empty)' trial and a '2-objects (expected empty)' trial. However, a 4 (Type of Empty Trial) × 2 (Condition) ANOVA revealed that there was no difference in searching times between any of these 'expected empty' trials in any comparison, $F(3, 90) = 1.56$, $p = .205$. Because searching was always the same on 'expected empty' trials, it can be taken as a baseline measure of searching in the box, regardless of whether anything was expected inside.

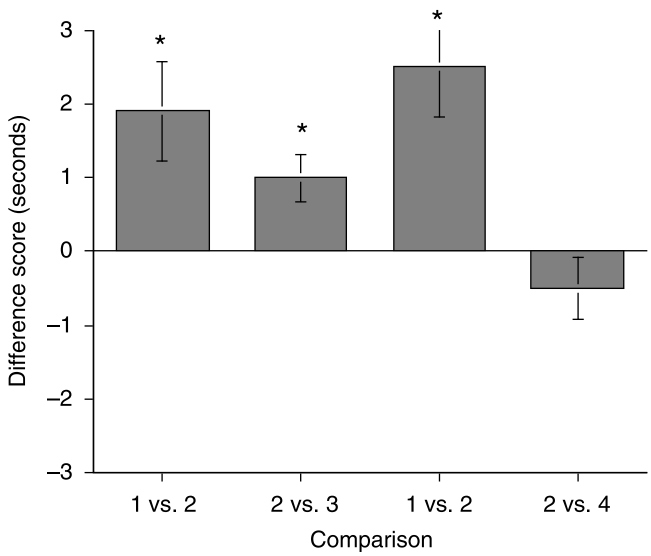

Figure 5 *Difference scores ('more remaining based on number' searching – 'expected empty based on number' searching) for the 4 conditions in Experiment 1. Difference scores are significant for both 1 vs. 2 comparisons and for the 2 vs. 3 comparison, but not for 2 vs. 4.*

'more remaining' than 'expected empty' trials. Difference scores for each comparison are displayed in Figure 5. These scores are different from chance for all comparisons except 2 vs. 4 (1 vs. 2 in first condition: $t(1, 15) = -2.85$, $p < .05$; 2 vs. 3: $t(1, 15) = -3.12$, $p < .05$; 1 vs. 2 in second condition: $t(1, 15) = -3.60$, $p < .05$; 2 vs. 4: $t(1, 15) = 1.18$, $p = .257$), demonstrating that infants succeeded at discriminating 1 vs. 2 and 2 vs. 3, but not 2 vs. 4.

Discussion

Experiment 1 demonstrates the set-size signature of object-files, providing a conceptual replication of Feigenson *et al.* (2002a). Fourteen-month-old infants represented the exact numerosity of arrays of 1, 2 and 3 objects. After seeing 2 balls hidden and retrieving 1, infants searched for the second ball. And after seeing 3 balls hidden and retrieving 2, infants searched for the third ball. In both cases, infants decreased their search times after having retrieved all of the balls that had been hidden showing that they represented exactly 1, 2 or 3.

We found a limit on infants' enumeration abilities in this task. While infants succeeded with comparisons of 1 vs. 2 and 2 vs. 3, they failed with 2 vs. 4. That is, after seeing 4 balls hidden and retrieving 2, infants did not continue to search for any further balls. Indeed, their search times were the same as when they had seen 2 hidden and had retrieved 2. Infants' failure with 2 vs. 4 (which is the same ratio as the 1 vs. 2 comparison on which they succeeded) indicates that infants were not relying on the analog magnitude system of representation.[4]

That infants failed to represent 4 individuals is striking. As noted earlier, representing 'exactly 4' is not necessary for success in the present task. Infants' failure with 2 vs. 4 indicates not only that they failed to represent the 4-ball array as containing 'exactly 4', but that they also failed to represent 4 as '3', or simply 'more than 2'. Any of these latter representations would have led to success. This raises the following question: if infants are opening an object-file for each individual they see, and infants have a limit of 3 object-files, why don't they simply represent 3 of the 4 balls, and thereby succeed at the 2 vs. 4 comparison? Equally, in the choice task of Feigenson *et al.* (2002a) in which infants fail to choose 4 crackers over 2, why don't infants represent 3 out of 4 and thereby succeed at this comparison? We suggest that the problem occurs in the act of assigning indexes to the individual objects in attention. Once an index is stably assigned to an individual, that individual can be stored in short-term memory (e.g. an object-file representation can be created). A possible account of the difficulty with 4 objects is that, when confronted with 4 objects, attention attempts to index them but cannot because of the 3 index limit. Infants' attention therefore circulates the array, with attention 'jumping' between individuals but failing to be consistently assigned to individual objects. Because of this instability in the encoding process, infants might never set up a short-term memory representation of the 4 individuals, nor of a subset of them. This could lead to their failure to discriminate 2 from 4 in this task.

Experiment 1 corroborates that object-files are likely to be the representations underlying infants' performance in this task, consistent with arguments that they may also underlie performance in the Wynn addition/subtraction tasks (Simon, 1997; Uller *et al.*, 1999) and in the choice task (Feigenson *et al.*, 2002a). However, it leaves open the question of whether infants can establish numerical equivalence between two sets of object-files, or between a set of object-files and a set of objects in the

[4] We take infants' failure with 2 vs. 4 to reflect an absolute limit on the number of individuals infants can represent in this task; infants failed because they could not represent 4. An alternative account is that the failure reflects a difference in the size of the comparison being made. The numerosities in 2 vs. 4 differ by 2, whereas the numerosities in 1 vs. 2 and 2 vs. 3 differ by only 1. We consider this account unlikely to explain infants' performance. In data not reported here using the same procedure (Feigenson & Carey, in preparation), infants succeeded with a 1 vs. 3 comparison. In this case the numerosities also differ by 2, but the number of balls presented at any one time is always 3 or fewer. We take this as support for the claim that there is an absolute limit on infants' abilities to represent individuals.

world. The set-size signature observed by Feigenson *et al.* (2002a) showed that infants formed object-file representations when comparing two sets of crackers in memory. In that task, however, infants' choices were determined by overall amount of cracker (total cracker area). Similarly, when Feigenson *et al.* (2002b) controlled for total front surface area in habituation and addition/subtraction tasks, they failed to find evidence of number-preserving computations such as one-to-one correspondence. An open question, then, is whether infants can compute numerical equivalence between sets of object-files.

Experiment 2 addresses this question by asking whether infants in the manual search task track individual objects or track the total continuous extent of objects. Does searching depend on infants' expectations about more individuals remaining in the box, or more continuous extent remaining in the box? We addressed this by manipulating the size of the objects infants retrieved.

In Experiment 2, we gave infants a 1 + 1 task in which 2 small objects were placed in the box. Infants were allowed to retrieve 1 object, after which any subsequent searching was measured. Given the results of Experiment 1, we expected infants to search for a second object. The crucial manipulation was that on half of the trials, infants retrieved an object of the expected size (i.e. it was one of the small objects they had seen hidden). On the other half of trials, the object was twice as big as expected. If infants' decisions to search the box are based on the number of individuals they saw hidden, they should search regardless of the size of the first object they retrieve. Under this hypothesis, infants would match their searching to the number of individuals expected in the box. If instead infants' searching is based on a continuous dimension such as total object volume, then the 'double-size' object should meet their expectations of the total object volume in the box, and no more searching should occur. In this case, infants would match their searching to the total object volume expected in the box.

Experiment 2

Experiment 2 combined the manual search method used in Experiment 1 with the addition method used by Wynn (1992). Instead of presenting infants with an array of simultaneously visible objects, infants saw a 1 + 1 event in which one object was brought out and then hidden in the box, then a second object was brought out and hidden. We asked how many objects infants represented in the box by allowing them to retrieve 1, then measuring subsequent searching. On half of the trials, infants saw 1 small object + 1 small object, and retrieved 1 small object. In this case, infants were expected to search into the box whether they were tracking number of individuals or total object volume. One small object is only half as many individuals as expected, and is also only half the total volume as expected. On the other half of trials, infants saw 1 small object + 1 small object, and retrieved 1 big object. One big object does not meet expectations about how many individuals are in the box ($1 + 1 \neq 1$), but does meet expectations about the total object volume in the box (small volume + small volume = big volume). In this way, we asked whether infants were searching for a specific number of objects, or for a specific total volume.

Method

Participants

Sixteen full-term 12.5-month-old infants participated (range: 12 months, 4 days to 12 months, 27 days; mean age = 12 months, 13 days). Infants in Experiment 2 were younger than those in Experiment 1 because the experiments in which infants have shown sensitivity to the continuous extent of object arrays have tested infants between 7 months (Clearfield & Mix, 1999; Feigenson *et al.*, 2002b) and 10 to 12 months (Feigenson *et al.*, 2002a). Half of the infants tested were boys (8/16). One additional infant was excluded due to fussiness.

Stimuli

Infants retrieved objects from the same box as in Experiment 1. Small toy objects were substituted for the ping pong balls. There were four object types: a car, a horse, a bottle and a wooden ring. Each object type came in two sizes. The small objects were all less than half the volume of the big objects, but were otherwise identical in shape, color, texture and markings. The difference in volume between the small and large objects was expected to be noticeable to infants based on the results of Feigenson *et al.* (2002a) and Feigenson *et al.* (2002b). In these studies, infants responded to differences in object sizes that were smaller than the differences used here. The large objects were between 2 and 7 cm high and 8 and 11.5 cm long. The small objects were between 2 and 4.5 cm high and 5 and 7.5 cm long.

Design

Infants were tested with four presentation events in which 1 small + 1 small objects were hidden. There were two events in which infants saw 1 small + 1 small, retrieved 1 *small* object, and subsequent searching was measured. In the other two events, infants saw 1 small + 1 small and retrieved 1 *big* object, and subsequent searching was measured. The volume of the big object was more than the combined volume of the two small objects. Which event type was presented first was counterbalanced across infants, with event types presented in an a, b, b, a order.

As in Experiment 1, we compared infants' searching when the box was expected to contain another object vs. when it was expected to be empty. However, in Experiment 2, whether or not the box is expected to contain more depends on whether infants track number of individuals or total object volume. For example, infants who retrieve 1 big object after seeing 1 small + 1 small hidden would expect the box to contain more based on number of individuals, but expect it to be empty based on total object volume. As such, the box could be expected either full or empty based on either number or total volume.

Figure 6 shows the four resulting trial types. One trial type ('1 + 1, retrieve 1 small') measured searching after infants saw 1 small + 1 small, and retrieved 1 small object. Here, infants should expect the box to contain more based on either number or volume (number expected to contain more, volume expected to contain more). After 10 s the experimenter handed infants the second small object from inside the box, and another reaching period followed ('1 + 1, retrieve 2 small'). Here, the box should be expected empty on the basis of both number and volume.

'One + 1, retrieve 1 big' trials measured searching after infants saw 1 small + 1 small, and retrieved 1 big object. Here, infants should expect the box to contain more on the basis of number, but be empty on the basis of volume (number expected to contain more, volume expected empty). After 10 s the experimenter handed infants another, small, object from inside the box, there was another reaching period, '1 + 1, retrieve 1 big + 1 small'. In these trials, expectations of both number and volume had been met (number expected empty, volume expected empty). Each object (car, horse, bottle, ring) appeared equally often in '1 + 1, retrieve 1 small' and '1 + 1, retrieve 1 big' trials.

Infants also received a pair of familiarization trials included to introduce them to the game of retrieving toys from the box. There was a 1-object familiarization trial and a 2-object familiarization trial, with order counterbalanced across participants.

Procedure

Familiarization. The room was set up as in Experiment 1. Because there were fewer total trials in Experiment 2, and because the infants were slightly younger, Experiment 2 involved a more elaborate familiarization. First, the experimenter showed infants the box and encouraged them to reach inside. Next, the experimenter brought out a familiarization object and placed it on top of the box. The single familiarization object was always a small Barney toy. The experimenter pointed to Barney and said, 'See this? Look at this!' Then she inserted Barney through the box's opening. Infants were encouraged to reach in and retrieve the toy. After infants had done so, the second familiarization trial began. The experimenter brought out 2 objects simultaneously and placed them on the box. The 2 objects were always 2 triangular yellow blocks. The experimenter pointed to each and said, 'See this? Look at this!' Then she placed them one at a time in the box. Infants were encouraged to reach in and retrieve the objects. In the familiarization phase only, infants were allowed to retrieve both objects (in the test phase, the second object was always secretly removed). This was done so as to demonstrate the possibility of there being multiple objects in the box.

Test. Infants saw four addition events each. Addition events were identical, except for which object type was used. First, the experimenter brought out the box and placed it on the table, shaking it to show that it was empty. Then she brought out a small object and placed it on top of the box. She pointed to it and said, 'See this? Look at this!' After approximately 5 s, she picked up the object and inserted it through the opening in the front of the box. Next she brought out a second, identical object, and repeated the above sequence. The experimenter said, 'What's in my box?' and slid the box forward. Meanwhile, she surreptitiously removed one of the objects from the opening in the back of the box.

Infants were allowed to reach in and retrieve 1 object. For two of the addition events, they retrieved 1 *small* object (1 + 1, retrieve 1 small). After 10 s during which infants were allowed to handle the object, the experimenter took it away. Then came a measurement period during which the experimenter looked down to avoid providing any cues as to whether the child should search or not, and search time was coded later from videotape. This measurement period lasted for 10 s. Whether infants were tracking number or volume, they should expect the box to contain more objects. After the measurement period ended, the experimenter reached into the box, pretended to 'find' the second small object, and handed it to infants. Infants were allowed to handle the second object for 10 s before it was taken away. Then came a second 10 s measurement period during which searching was measured. Here, because infants had seen 1 small + 1 small and had retrieved 2 small objects, the box should be empty whether infants were tracking number or volume.

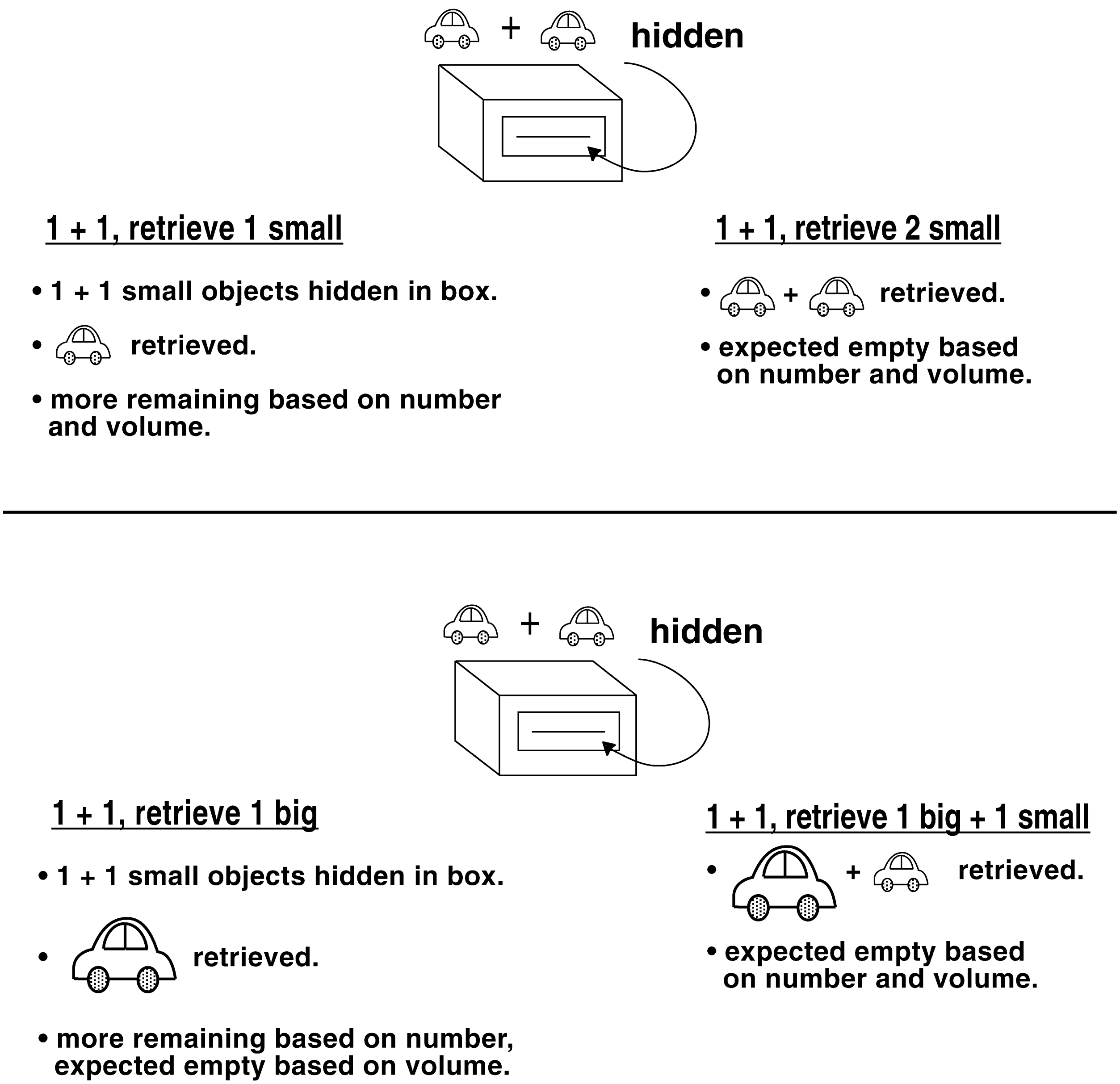

Figure 6 *Trial types in Experiment 2.*

On the other two addition events, infants saw 1 small + 1 small and retrieved 1 *big* object (1 + 1, retrieve 1 big). As above, after 10 s the object was taken away and a 10 s measurement period ensued. Here, because infants had seen 1 small + 1 small and had retrieved 1 big object, if they were tracking number they should expect the box to contain more, but if they were tracking volume they should expect it to be empty. After the measurement period ended, the experimenter 'found' the second small object in the box and handed it to infants. After 10 s of handling, the object was taken away and a final 10 s measurement period followed. Now infants had seen 1 small + 1 small and had retrieved 1 big + 1 small, so the box should be empty whether numerical or volume computations underlay infants' expectations.

Results

Figure 7 shows mean reaching times for each trial type in Experiment 2. An ANOVA with two within-subjects factors and three between-subjects factors was conducted. The within-subjects factors were: Trial Type ('1

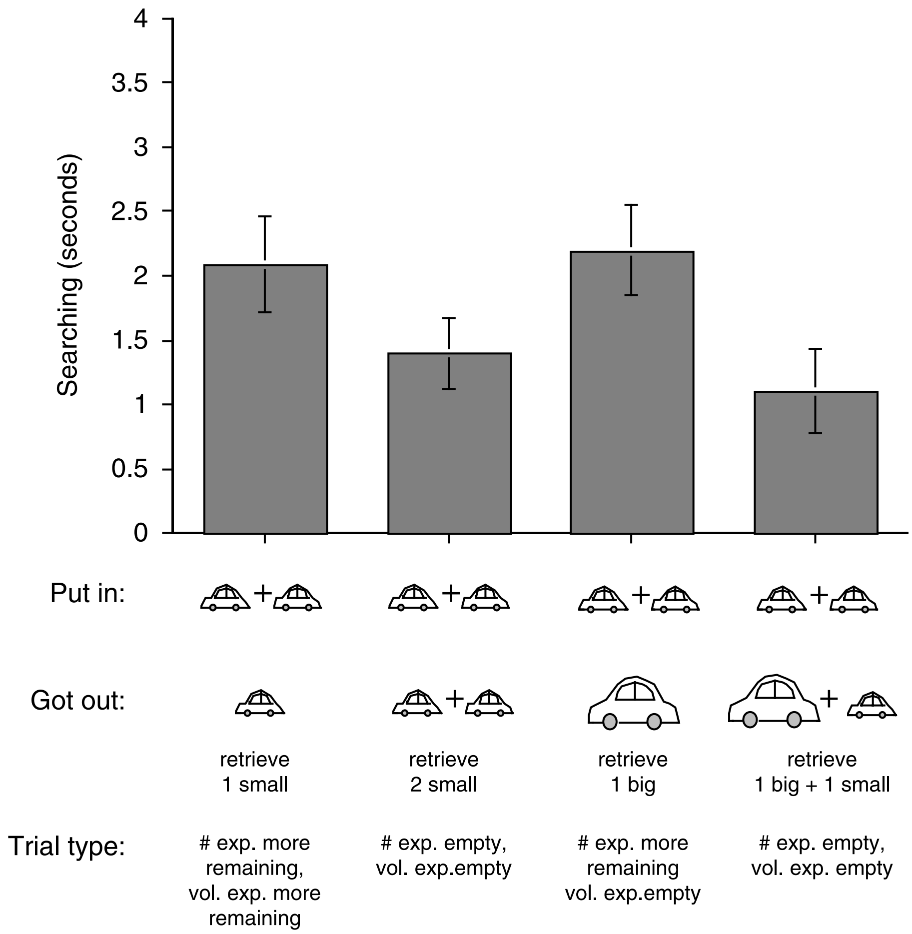

Figure 7 *Search times by trial type in Experiment 2.*

+ 1, retrieve 1 small', '1 + 1, retrieve 2 small', '1 + 1, retrieve 1 big' and '1 + 1, retrieve 1 big + 1 small') and Trial Pair (first pair, second pair). Between-subjects factors were: Familiarization Order (1 object familiarization first or second), Event Order (whether the '1 + 1, retrieve 1 small' event came first or second) and Sex. The ANOVA revealed only a main effect of Trial Type, $F(3, 24) = 2.87$, $p < .05$. The main effect was due to infants searching longer on trials in which the box was expected to contain more objects on the basis of number than on the trials in which it was expected empty on the basis of number.

We further investigated this main effect with planned *t*-tests under the hypothesis that infants would search longer on trials in which the box was expected to contain more based on number. This was confirmed. There was no difference in the two trials in which the box was expected to contain more based on number ('1 + 1, retrieve 1 small' and '1 + 1, retrieve 1 big'), $t(1, 15) = 0.27$, $p = .788$, which were therefore collapsed. There was also no difference in the two trials in which the box was expected to be empty on the basis of number ('1 + 1, retrieve 2 small' and '1 + 1, retrieve 1 big + 1 small'), $t(1, 15) = -0.69$, $p = .502$, which were also collapsed. We found a significant difference in searching between the collapsed 'more remaining based on number' and 'expected empty based on number' trials, $t(1, 15) = -4.43$, $p < .01$. Infants searched an average of 4.3 s on 'more remaining based on number' trials and 2.5 s on 'expected empty based on number' trials.

Discussion

The results of Experiment 2 suggest that in this task, searching was determined by representations of object number, and not by representations of a continuous dimension such as total object volume. After seeing 1 small + 1 small objects hidden, infants expected the box to contain 2 objects, regardless of the size of the first object they retrieved. Infants were not searching in the box for a specific amount of 'object material'. This is the first demonstration of infants' attention to number in a task which has been shown to rely on object-file representations.

These data also address the issue of whether infants used size as a cue for individuation. In Experiment 2, infants could have expected a third object in the box after seeing 1 small + 1 small, and retrieving 1 big + 1 small. That is, they could have recognized that the big object they retrieved was a different one from either of the 2 small objects they had seen hidden. Infants did not appear to do so, given that they decreased searching on the '1 + 1, retrieve 1 big + 1 small' trial. Indeed, they did not search any more on this trial than on the '1 + 1, retrieve 2 small' trial, in which they retrieved both of the objects they had originally seen hidden.

This result is not surprising, given evidence by Xu, Carey and Quint (under review). They also found that 12-month-old infants failed to use object-size for individuation. Seeing a large cup emerge from and then disappear behind the right side of a screen, followed by a small cup emerging from and then disappearing behind the left side of the screen, infants appeared to expect only 1 object to be present when the screen was lifted. Infants failed to use the difference in object size to infer the presence of 2 objects, despite the fact that they noticed the difference in the cups' sizes. That infants noticed the size difference can be seen from the fact that they required more trials to reach habituation when cups of 2 sizes emerged from opposite sides of the screen during habituation than when cups of the same size did so. Since the difference in object size in Experiment 2 was larger than the difference in Xu, Carey and Quint (under review), it is likely that infants in the present study noticed the size difference but were unable to use size difference to individuate.

General discussion

These experiments accomplish two goals. First, Experiment 1 provides convergent evidence for the set-size signature of object-file representations on infants' performance. The fact that infants represented 1, 2 and 3 objects, and failed to represent bigger numbers even with highly discriminable ratios, implicates object-file representations as underlying infants' performance in this task. A representational limit of 3 is predicted by models of object-based attention by Kahneman *et al.* (1992) and Pylyshyn (2001). No such limit is predicted by analog magnitude models (Meck & Church, 1983; Dehaene & Changeux, 1993; Church & Broadbent, 1990). We therefore propose that the representations deployed in these tasks are the same representations in the theory of object-files proposed by Kahneman *et al.* (1992) or by Pylyshyn's indexing theory (Pylyshyn, 2001). (See Carey & Xu (2001) and Leslie & Scholl (1999) for an extended argument aligning the two literatures.)

Further, Experiment 2 provides the first evidence that infants can compute numerical equivalence using object-file representations. Recall that infants in Feigenson *et al.*'s choice task (2002a) appeared to sum the total surface area of an array of crackers, suggesting that object-files can be compared via the properties bound to them. However, to date, there has been no evidence that infants can compare numbers of object-files on the basis of one-to-one correspondence (i.e. establish numerical equivalence between them).

Experiment 2 suggests that 12- month-old infants can. We manipulated the continuous dimension of volume to disentangle infants' expectations of object number vs. total object volume. We found that infants based their searching on the number of objects they saw hidden, and not on the total object volume they saw hidden. Infants continued to search for a second object even when the expected total volume had already been retrieved. After retrieving the expected number of objects, infants searched less.

In this task, then, infants appeared to ignore the dimension of object size in favor of object number. We propose that infants opened an object-file for each object they saw hidden. They then reached into the box and pulled out an object. Infants aligned the representation of this single object with the two object-files they had stored in memory, detected a mismatch and began searching the box. When the number of objects retrieved matched the number of stored object-files, infants stopped searching, irrespective of matches or mismatches in property information such as volume.

Together, the present experiments and those by Feigenson *et al.* (2002a) show that infants have object-file representations, and that these representations can support at least two types of computations. Infants performed different computations in the two tasks. The fact that infants in the present experiments based their behavior on number of individual objects, while infants in Feigenson *et al.* based their behavior on total surface area, is predicted for at least two reasons.

First, the tasks require different behaviors. In Experiments 1 and 2, we measured infants' search times. Searching relies on reaching, where each reach was presumably launched *for an object*, with the discrete presence or absence of an object (rather than continuous quantity of object) determining the decision to reach. Second, it is likely that the nature of the stimuli presented determined the relevant dimension. In a foraging situation like that used by Feigenson *et al.* (2002a), infants should want to maximize the total amount of food obtained, not the number of pieces of food obtained. This contrasts with the manual search task, in which object size was not expected to be especially salient.

While the present experiments and those reported by Feigenson *et al.* (2002a) show that infants can perform different computations over object-file representations depending on the task, it is possible that infants always have access to information about *both* object number and object properties, and perform whichever computation is best suited to the task at hand. For example, Feigenson *et al.* (2002a) found that infants chose which container to crawl to on the basis of total cracker area. However, infants might also have maintained representations of the individual objects whose surface area entered into the computation. Infants could have compared the total cracker area in each container, chosen the one with more, and also represented how many individuals were in one or both containers.

Future studies will investigate whether infants retain representations of individuals in tasks in which total surface area is the most relevant dimension. For example, measuring the number of times infants reach into containers in which crackers have been hidden can tell us how many individual crackers infants represented. We may also ask whether infants represent continuous properties in tasks such as those in Experiments 1 and 2, in which number of individual objects is most relevant. For example, measuring the shape of infants' grasp as they reach into the box for a hidden object can inform us as to their expectations about object size. Such studies will help to address not only which comparisons made over object-file representations are most relevant to guiding behavior (i.e. object number in the manual search task, total continuous extent in the choice task), but also what information is retained in the object-file representations.

Taken together, the present series and Feigenson *et al.* (2002a) show that object-files can underlie infants' representations of object arrays. At least two types of computations can be performed over these representations. Physical properties such as surface area can be summed and compared in memory, and the number of individual objects in an array can be compared with the number of individuals in memory. Further work is needed to address issues such as what other computations infants can make over object-files, what information might be bound to object-files and to what extent individual object-files are preserved in memory.

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