Developmental Science 10:4 (2007), pp 423–430 DOI: 10.1111/j.1467-7687.2007.00596.x

REPORT

Individuation of pairs of objects in infancy

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Abstract

Looking-time studies examined whether 11-month-old infants can individuate two pairs *of objects using only shape information. In order to test individuation, the object pairs were presented sequentially. Infants were familiarized either with the sequential pairs, disk-triangle/disk-triangle (XY/XY), whose shapes differed within but not across pairs, or with the sequential pairs, disk-disk/triangle-triangle (XX/YY), whose shapes differed across but not within pairs. The XY/XY presentation looked to adults like a single pair of objects presented repeatedly, whereas the XX/YY presentation looked like different pairs of objects. Following familiarization to these displays, infants were given a series of test trials in which the screen was removed, revealing two pairs of objects in one of two outcomes, XYXY or XXYY. On the first test trial, infants familiarized with the identical pairs (XY/XY) apparently expected a single pair to be revealed because they looked longer than infants familiarized with the distinct pairs (XX/YY). Infants who had seen the distinct pairs apparently expected a double pair outcome. A second experiment showed outcomes of a single XY pair. This outcome is unexpected for XX/YY-familiarized infants but expected for XY/XY-familiarized infants, the reverse of Experiment 1. This time looking times were longer for XX/YY infants. Eleven-month-olds appear to be able to represent not just individual objects but also pairs of objects. These results suggest that if they can group the objects into sets, infants may be able to track more objects than their numerosity limit or available working memory slots would normally allow. We suggest possible small exact numerosity representations that would allow tracking of such sets.*

Introduction

How do infants keep track of physical objects undergoing occlusion in a 3-D world? By 12 months of age (and younger under simplified conditions), infants can use property differences to individuate two physical objects (Tremoulet, Leslie & Hall, 2000; Wilcox & Baillargeon, 1998; Wilcox, 1999; Xu & Carey, 1996). Infants familiarized to a duck and a truck, individually and alternately drawn from and replaced behind a screen, look longer when the screen is removed to reveal only one of these objects than when it reveals both (Xu & Carey, 1996). If infants do not see both objects at the same time, the only way to distinguish them as individuals is on the basis of property differences. Tremoulet *et al*. (2000) showed that infants of 12 months will judge two objects to be distinct individuals if they differ in shape only (disk vs. triangle). There is, however, no data on whether infants can individuate *pairs* of objects by shape. Here we probe the limits of object individuation by testing whether infants can use shape to individuate pairs of objects.

Limits on individuation can inform us about the processing mechanisms infants use to track small sets of physical objects. Currently, there are three main views on this question. One is that infants *count* the objects and remember the cardinal value of the set (Wynn, 1992, 1998). The second view is that they merely individuate the objects in a set and store representations that individually refer to or *index* each of the individuals (Káldy & Leslie, 2003, 2005; Leslie, Xu, Tremoulet & Scholl, 1998; Scholl & Leslie, 1999; Simon, 1997; Uller, Carey, Huntley-Fenner & Klatt, 1999). We will use 'index' to refer to any representation that functions one-to-one as a pointer to an individual object and that tracks that object through changes of location (Leslie *et al*., 1998; Pylyshyn, 1989, 2000; see also Kahneman & Treisman, 1984). The third view is that infants evaluate and store a representation of a magnitude property of the set *other than* numerosity, such as total volume or perimeter (Clearfield & Mix, 1999, 2001; Feigenson, Carey & Spelke, 2002).

None of these accounts logically excludes the others; infants may use all three types of representation in a task driven manner. Indeed, arguably, successful counting requires keeping track of the objects being counted and that may depend upon indexing (Trick & Pylyshyn,

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1994). Likewise, in totaling magnitudes, such as volume or perimeter, individual objects that contribute to the summing operation have to be picked out from those that don't, and that too may depend upon indexing.

The evidence that infants count sets of occluded objects is currently weak because, in every case, there is an alternative explanation for the infants' performance. For example, in Wynn's (1992) classic studies, infants may have tracked individuals with indexes. Although indexes cannot represent cardinal values, they would allow the infant to represent each of the individuals behind the screen and thus *implicitly* their numerosity. Alternatively, the infant may have incremented a magnitude representation in response to the volume of each individual to yield a representation of the total of the set. Feigenson, Carey and Spelke (2002; Experiments 6 and 7 modeled on Wynn, 1992) found that 6-month-olds responded to a magnitude property such as total volume/perimeter but not to numerosity. Feigenson, Carey and Hauser (2002) similarly find no evidence at 10 and 12 months old for counting of occluded objects. In this study, infants chose a container that held more crackers than another. Crackers were placed one at a time into each container. In order to calculate which container held more, infants were therefore forced to add up sequential placements. In conditions where the crackers were the same size, Feigenson *et al.* found that infants chose correctly in comparisons involving 1 versus 2 and 2 versus 3 but not in comparisons involving 2 versus 4 and 3 versus 6. This set size limit is not consistent with a Weber fraction, and, given the absence of this signature, the authors concluded that infants were not counting. Instead, they proposed a limit on the number of indexes the infant can maintain, a limit of *three*.[1] Indexing limits have been identified in studies of multiple object tracking (MOT) in adults (Scholl & Pylyshyn, 1999; Trick & Pylyshyn, 1994) and analogous limits have been proposed for infants (Feigenson, in press; Leslie, 1999; Leslie & Káldy, 2001, in press; Leslie *et al.*, 1998; Scholl & Leslie, 1999).

The limit on object indexing arises, not from a Weber fraction, but because there is a cost for actively maintaining each index in attention or in working memory (WM). This means that the number of individuals that can be concurrently tracked is limited by available attention/WM resources, apparently ~ 3 in infants, ~ 4 in adults (Cowan, 2000). Here we ask what happens when infants are required to keep track of two sets of objects whose total numerosity exceeds their indexing limit of three but whose individual set size falls within that limit. If infants fail, it will suggest that the nature of that limit is *global*, applying to the total numerosity of objects that can be tracked. A global limit is predicted by indexing with limit three. If infants succeed, it will suggest that the nature of their limit applies *per set*, rather than to the total across sets, and some other explanation will be required.

Experiment 1

Simultaneous display of all objects in a set allows the infant to individuate the objects by spatiotemporal information, because objects occupy distinct locations at the same time (Xu & Carey, 1996). Feigenson, Carey and Hauser (2002) found that, though infants of 10 to 12 months succeeded with three objects, they were unable to individuate displays of four objects spatiotemporally. Feigenson and Halberda (2004), using manual search, found that 14.5-month-olds could succeed with four objects presented simultaneously but only if they were grouped spatially into pairs. Perhaps infants of that age require the support of a visual grouping Gestalt in order to individuate four objects. In this experiment, we ask whether infants can individuate two pairs of objects, where each pair is presented *sequentially*. This means that spatiotemporal information is not available for individuating the pairs. Spatiotemporal information is only available for individuating the objects within a pair. Infants are given two sequential pairs to track, for a total of four objects. One group of infants saw sequential pairs that differed in shape, thus making featural information available for individuation. The other group saw sequential pairs with identical shapes and thus had no basis, spatiotemporal or featural, on which to individuate the pairs.

The objects were either disks or triangles. One group of infants was familiarized with the sequential pairs XX followed by YY. These infants have the opportunity to register distinct pairs. If infants can individuate pairs, then this group should expect two pairs to be behind the screen (Expected Pairs condition). A second group of babies was familiarized with the same objects but presented as sequentially identical pairs, XY followed by XY. These infants should register only a single repeating pair and should look longer when the screen reveals two XY pairs (Unexpected Pairs condition). However, if infants are unable to individuate and track two pairs (or four objects), then group looking times will not differ. This design has the advantage that infants with different numerical expectations can be tested on numerically identical outcomes, avoiding different baseline preferences (Wynn, 1992; Xu & Carey, 1996) (see Figure 1).

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[1] In this context, the terms 'index' and 'object file' are essentially interchangeable (see Leslie *et al.*, 1998; Scholl & Leslie, 1999; and Pylyshyn, 2000, for discussion).

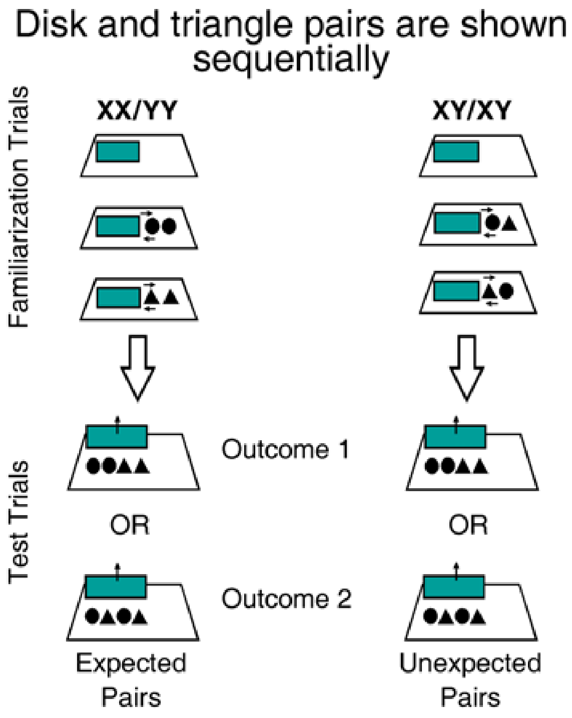

Figure 1 *Experiment 1. Two groups of infants were familiarized with either an XX/YY display in which sequentially displayed pairs of objects are identical within but differ across pairs or with an XY/XY display in which sequentially displayed pairs differ within but are identical across pairs. XX/YY familiarized infants should expect (and see) two pairs behind screen in the test phase, while XY/XY infants should expect only a single pair. Each group is then tested with one of two outcomes, XXYY or XYXY. If infants can individuate successive pairs of objects differing only in shape, then when the screen is removed Unexpected Pairs infants should look longer at outcomes than Expected Pairs infants.*

Method

Design

In a between-subjects design, we familiarized one group of infants (Expected Pairs condition) to a pair of disks (triangles) (XX) retrieved from, displayed, then returned behind a screen. Next a pair of triangles (disks) (YY) was displayed in the same way. A second group (Unexpected Pairs condition) was familiarized to the same set of objects but displayed as two successively identical disk-triangle pairs (XY and YX). Thus the first group is familiarized with objects that are identical within-pairs but different across-pairs, whereas the second is familiarized with objects that are different within-pairs but identical across-pairs. Following familiarization, both groups were tested on events that began the same as familiarization but the screen was removed at the end of the trial. For each familiarization group, half the infants saw an XXYY configuration (Outcome 1) and half saw the objects in an XYXY configuration (Outcome 2). This design yields four groups with familiarizations and outcomes crossed (Figure 1).

Subjects

Data from 72 healthy full-term infants were analyzed. A further 26 babies were rejected, 10 for fussing, nine through experimenter errors, five for being distracted or inattentive, and two for sleepiness. The remaining infants (38 females) were aged between 47 and 51 weeks (mean age 48.75 weeks, SD = 1.29 weeks). Infants were randomly assigned to one of four conditions, with 18 in each group.

Materials

The display objects were a pair of identical wooden disks, 10.5 cm in diameter and 0.9 cm thick, and a pair of identical wooden triangles, 11.5 cm high with base 10.5 cm by 0.9 cm thick. All objects were painted bright red with an average luminosity of $4.56^{\text{cd-m2}}$. A white cardboard screen 21 cm × 48 cm (wide) hid the objects, presented on the blue textured floor of a three-sided white posterboard stage, 55 cm (tall) by 90 cm (wide) by 45 cm (deep).

Procedure

Objects were moved by inserting a white-gloved hand through a slit running the length of the back wall of the stage. The slit was concealed by two strips of overlapping elastic cloth.

Familiarization trials began with the removal of the first pair from behind the screen and presenting it on stage. Each object was moved individually and audibly tapped twice on stage before setting it down. Objects were stationary and visible as pairs for 2 seconds during each presentation before being individually replaced behind the screen in order of their appearance. Each of the two sequentially alternating pairs was presented twice in this fashion in each familiarization trial. There were three such familiarization trials. Across familiarization trials, all presentation factors were counterbalanced: an XX/YY trial would be followed by a YY/XX trial and an XY/YX trial by a YX/XY trial, and vice versa. The first-moved object of each pair was counterbalanced across presentations within trials. Experiment-initial presentation order was counterbalanced across subjects.

To ensure that the mechanics of presentation was the same across conditions, we used two identical disk-triangle pairs and alternated the pairs across presentations within each trial. In the Unexpected Pairs condition, the successive XY pairs appeared to adult observers to be a single pair repeatedly presented. Infants should likewise expect only a single pair to be behind the screen.

Immediately following the familiarization trials, three test trials were given. Test trials began the same way as familiarization trials, but then the screen was removed to reveal the outcomes shown in Figure 1. The alternation scheme of familiarization was continued through the test phase and thus sidedness within pairs and presentation order of pairs were both counterbalanced across subjects too. Specifically, the alternates shown on the first test trial were counterbalanced across infants.

Trials began with the lowering of a felt curtain to reveal the screen centered on the illuminated stage. Subjects sat on parent's/caregiver's lap at a distance of approximately 1.5 m from the middle of the stage. The room was dimly lit and subjects, parents and stage were screened off by drapes. Presentations were paced by a 1 Hz metronome. A concealed video camera fed a head-and-shoulders view of the infant to a trained observer blind to condition. When the screen was removed, the experimenter signaled the observer to begin timing infant looking. The observer held down a button as long as the infant was looking at the stage and a computer recorded looking times. When the infant looked away, the observer released the button. When look-away duration equaled 2 seconds, the computer extinguished the stage lights and recorded the looking time for that trial. The curtain was then raised.

Videotapes of all infants were later rescored by an independent trained blind observer. Inter-observer agreement averaged 92.6%.

Results

To investigate baseline looking times, we scored from videotapes a randomly chosen 12 s for each of the displays, XX/YY and XY/XY, and timed total amount of looking during each familiarization trial. Mean trial looking times per display were similar (XX/YY = 39.3 s, SD = 3.1; XY/XY = 38.1 s, SD = 2.6; $t_{22} = 0.97$, $p = .35$, two-tailed).

Test trial looking times were right skewed and converted to log form for analysis. Preliminary analysis of log looking times across all three test trials revealed an uninterpretable three-way interaction between Pairs (Expected/Unexpected) × Outcomes (XXYY/XYXY) × Sex ($F_{1,\,64} = 3.86$, $p = .054$, $\eta^2 = .057$). Separate analyses by Sex showed that on test trials two and three there were significant Pairs × Outcomes interactions for males but not for females (who showed only a significant effect of Pairs). This interaction for males was not present on the first trial ($F_{1,\,30} = 2.52$, $p = .12$). Therefore, data from the first test trial only are reported here.

Figure 2 shows raw looking times by condition on the first test trial. Analysis of log looking times in a univariate ANOVA with factors Pairs (2) × Outcomes (2) × Sex (2) showed only a significant main effect of Pairs ($F_{1,\,64} = 13.1$, $p = .001$, $\eta^2 = .17$), all other effects $p > .16$, $\eta^2 < .03$. Planned comparisons for Pairs showed longer log looking in the Unexpected Pairs groups for both Outcome 1 ($t_{34} = 1.91$, $p = .033$, one-tailed) and Outcome 2 ($t_{34} = 3.13$, $p = .002$, one-tailed).

Discussion

Eleven-month-old infants appeared to individuate two pairs of objects presented sequentially when the pairs differed by shape. However, the configural complexity of

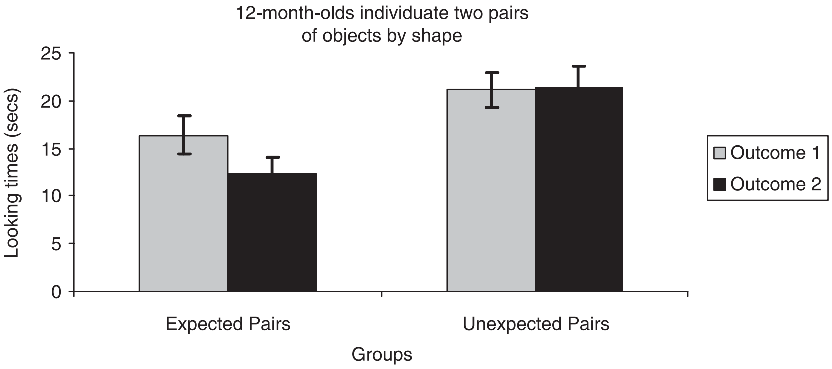

Figure 2 *Experiment 1. Infants in the Unexpected Pairs groups looked longer than the Expected Pairs groups. Shown are raw first test trial looking times with error bars showing SE of the mean.*

an outcome with four objects may be a taxing display for infants. In the next experiment we simplify the task by using a single pair outcome.

Experiment 2

All details were identical to Experiment 1, except that four familiarization trials were given and outcome events showed a single XY pair.

Method

Design

Following familiarization both XX/YY and XY/XY groups were tested on a single pair outcome XY. Expectations should now reverse relative to Experiment 1, with XY being the expected outcome for the XY/XY group and unexpected for the XX/YY group (see Figure 3).

Subjects

Data from 24 healthy full-term infants were analyzed. A further five babies were rejected, three for fussing, one through equipment failure, and one for being distracted. The remaining infants (10 females) were aged between 43 and 57 weeks (mean age 49.9 weeks, SD = 4.32 weeks). Infants were randomly assigned to one of two conditions, with 12 in each group.

Materials and procedure

These were the same as in Experiment 1.

Results

To investigate baseline looking times, we scored familiarization looking times for all subjects from videotape. One subject's video was lost due to technical malfunction. Mean looking times per display were again similar (XX/YY = 37.2 s, SD = 3.4; XY/XY = 35.0 s, SD = 2.8; $t_{21} = 1.65$, $p = .113$, two-tailed).

Test trial looking times were again right skewed and were converted to log form for analysis. Repeated measures ANOVA with factors Trials (3) (repeated) × Pairs (2) × Sex (2) showed no significant effects of Trials or of Sex. Pairs was again significant ($F_{1,23} = 8.3$, $p = .009$, $\eta^2 = .29$). Planned comparisons on first trial looking times showed longer looking in the unexpected pairs condition (13.4 s, $SE_M = 1.8$) than in expected pairs (7.4 s, $SE_M = 0.9$) ($t_{22} = 2.61$, $p = .008$, one-tailed).

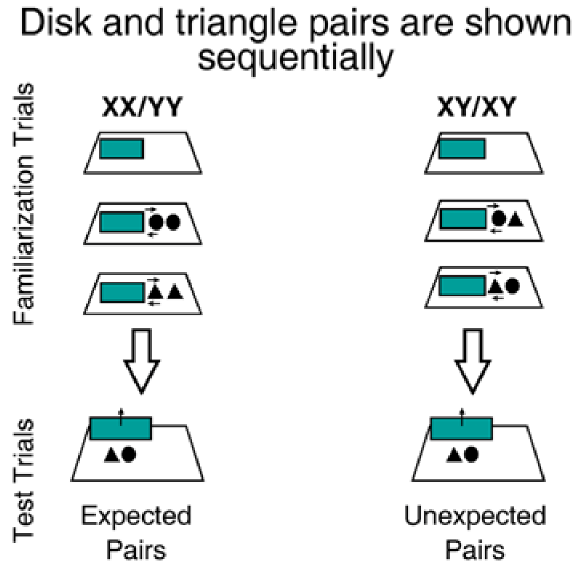

Figure 3 *Experiment 2. Two groups of infants were again familiarized with either an XX/YY display of pairs of objects identical within but different across sequential pairs or with an XY/XY display in which sequentially displayed pairs differ within but not across pairs. This time XX/YY familiarized infants should find the test outcome unexpected because it shows a single pair, while XY/XY infants should expect the single pair.*

General discussion

Experiment 2 with a simplified outcome display confirmed the results of Experiment 1. Base line looking during familiarization cannot explain our findings. Familiarization looking times to each display were again similar. Looking times during the first test trial were overall lower in this experiment compared to Experiment 1 because outcomes revealed two-object displays (this experiment) instead of four-object displays (Experiment 1). (This is not surprising given that infants typically look longer at more complex displays.) Crucially, test trial looking preference was again drawn to the unexpected pairs outcome, with the effect reversing across the two experiments relative to the familiarization display.

Taken together these results suggest that infants around 11 months can use shape to individuate two sequential pairs of objects. Feigenson and Halberda (2004) report data showing that older infants around 14.5 months can individuate two pairs of objects in a manual search task. In that study, which used four identical objects presented simultaneously, it was critical that the pairs were separated spatially. When infants were presented with the same four objects arranged in a row, they failed to search manually for exactly four objects after they were hidden. Presumably, infants required the spatial grouping because they could not break up the continuous row into two pairs voluntarily. The present results are consistent with these findings but extend them in two ways. First, the ability to represent two pairs of objects is present some $5\frac{1}{2}$ months earlier, and second, infants can form pairs sequentially based on featural (shape) differences. What implications does this have for the representations infants use to track sets of occluded objects? We offer five possibilities below.

1. Four object indexes

In the expected pairs condition, infants may have indexed each object in each pair. However, this would require that infants can maintain four active indexes concurrently, exceeding a limit of three active indexes typically found in numerosity studies (Feigenson, Carey & Hauser, 2002; see Feigenson, in press, for review). Ross-Sheehy, Oakes and Luck (2003) in a test of short-term memory (STM) obtained evidence consistent with an STM limit of both three and four items at this age. Either the infant indexing/numerosity limit is in fact four, or infants can track more objects than they can index.

2. One index per pair

Infants index a pair of objects using a single index per pair. This requires a total of two indexes for two pairs, and stays within an indexing limit of three. A single index might plausibly track a multiple entity, such as a flock of birds when it exhibits common motion. However, the price of using a single index to track a multiple entity is that the index now carries no information, even implicitly, about how many individuals comprise the entity. There is indeed evidence *both* that infants are able to track two multiple entities defined by common motion *and* that they have no idea how many individuals are in each collection (Chiang & Wynn, 2000; Wynn, Bloom & Chiang, 2002). However, the objects in the pairs used here were moved independently not with common motion. Also, according to this account, infants in the expected pairs condition would have two indexes active – the same as infants in the unexpected pairs condition. It cannot therefore account for the findings.

3. Total volume

Infants escape the indexing limit by forming a summary representation of the (expected) *total* volume/area of four objects (XX/YY groups) or two objects (XY/XY groups). Given that the differential response we found was based on shape difference, it seems unlikely that infants simply represented ‘total amount of stuff’.

4. The concept PAIR

Infants have the concept PAIR and can use this concept to simplify object tracking. This concept might reduce working memory demands by chunking individuals into couples and allow property information for two individuals to be bound to a single index. The representation, DISK PAIR, would track an identity distinct from both TRIANGLE PAIR and from DISK, TRIANGLE. The representations DISK PAIR, TRIANGLE PAIR would track a total of four objects using only two indexes and simultaneously represent the numerosity of each set.

5. Summary integer representation

Infants avoid the indexing limit by counting the individuals in each pair and using the resulting magnitude representation to summarize the set and represent its numerosity explicitly: TWO DISKS, TWO TRIANGLES.

We cannot tell yet which of the above accounts is correct, though the first three seem unlikely at this time, leading us to tentatively favor the last two possibilities.

Chunking past the limit

The results of the current study converge with those of Feigenson and Halberda (2004). By ‘binding into sets’ infants appear to escape the object file/indexing limit. But how is this done? The way in which object files represent numerosity is indirect and implicit. For each object in a set there is one corresponding object file that actively indexes it. Because object files are temporary representations that actively index the location of moving objects, it makes no sense to store object files in long-term storage (Kahneman & Treisman, 1984). Furthermore, if object files/indexes were stored in long-term memory, there would be no limit to the number that could be stored. Yet there is a wealth of evidence from infants that attests to strict limits. Feigenson (in press) suggests that the working memory limit itself underlies the object file limit (but see Leslie & Káldy, in press, for some cautionary considerations). There is emerging evidence that infant object working memory has about two slots available by 9 months (Káldy & Leslie, 2003, 2005) and about three by 12 months (Ross-Sheehy *et al.*, 2003). This suggests that each working memory slot can hold only about a single object file (Leslie & Káldy, in press). So, there is no obvious way in which object files/indexes themselves could be chunked in memory simply by ‘packing’ them in.

If infants can track four objects as two pairs of objects, how do they track that fourth object when their three object files are already used up? They would need to free up one of the three to track the fourth object; but then they lose track of the entity that *that* object file was indexing. They would end up still tracking only three objects. One possibility is that they employ a concept for sets, like SET-OF. When the infant sees a pair of disks followed by a pair of triangles, she might encode this as, SET-OF DISKS, SET-OF TRIANGLES, binding this property information to each of two indexes, respectively. She will then detect the discrepancy if the screen reveals only a single disk and a single triangle. However, this sort of representation is equivalent to a singular–plural distinction and Kouider, Halberda, Wood and Carey (2006) have recently found that infants do not distinguish, for example, sets of 1 vs. 4 things until 22 months. It seems unlikely then that much younger infants will employ the SET-OF concept.

If infants can (a) chunk objects in working memory into sets, (b) keep track of the discrete numerosity of the objects in each of the sets, *and* (c) respect working memory/object indexing limits, then there are only a limited number of possibilities for how they manage this feat. We can think of only the two possibilities mentioned earlier: the specific set concept, PAIR, and the integer concept, TWO. Either of these representations will encode small numerosities, do so exactly without a Weber fraction, and will chunk object sets so that two objects per WM slot can be represented and tracked. At this time, the literature on discrete number representation in infants has considered only two possibilities, accumulator magnitudes and object files. Perhaps it is time to consider other possibilities.

Acknowledgements

We are grateful to Monica Glanville and Nitin Mathur for help collecting part of the data reported here. We are also grateful to Rochel Gelman, Randy Gallistel, Zenon Pylyshyn, Denis Mareschal and two anonymous reviewers for helpful comments on earlier drafts. The research reported here was supported by National Science Foundation grant BCS-0079917.

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Received: 23 June 2003
Accepted: 2 June 2006