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Brief article

A double-dissociation in infants' representations of object arrays

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Abstract

Previous studies show that infants can compute either the total continuous extent (e.g. Clearfield, M.W., & Mix, K.S. (1999). Number versus contour length in infants' discrimination of small visual sets. Psychological Science, 10(5), 408–411; Feigenson, L., & Carey, S. (2003). Tracking individuals via object-files: evidence from infants' manual search. Developmental Science, 6, 568–584) or the numerosity (Feigenson, L., & Carey, S. (2003). Tracking individuals via object-files: evidence from infants' manual search. Developmental Science, 6, 568–584) of small object arrays. The present experiments asked whether infants can compute *both* extent and number over a given array. Experiment 1 used a habituation procedure to show that 7-month-old infants can compute numerosity when the objects in the array contrast in color, pattern, and texture. Experiment 2 revealed that, with these heterogeneous arrays, infants no longer represent the array's total continuous extent. Since previous work shows that infants compute continuous extent but not numerosity when objects have identical rather than contrasting properties, these results form a double dissociation. Infants computed number but not extent over representations of contrasting objects, and computed extent but not number over representations of identical objects.

Keywords: Number; Continuous extent; Surface area; Contour length; Object features

Infants' quantitative competence appears to be subserved by two distinct representational systems. First, infants represent approximate large numerosities, enabling them to discriminate, for example, 8 vs. 16 items (Lipton & Spelke, 2003; Xu & Spelke, 2000). Importantly, this system for representing large numbers is ratio-dependent: 6-month old

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infants discriminate arrays with a 1:2 but not a 2:3 ratio, suggesting that the system is approximate and analog.

Infants also form precise quantity representations of small object arrays. That they do so via a second representational system is shown by their performance with varying numerosities (see also Feigenson, Dehaene, & Spelke, 2004; Xu, 2003). Consider the task by Feigenson, Carey, and Hauser (2002), in which infants chose between two quantities of crackers hidden in buckets. With choices of 1 vs. 2 and 2 vs. 3, infants picked the larger quantity. But with 3 vs. 4, 2 vs. 4, 3 vs. 6, and 1 vs. 4 (Feigenson & Carey, in press), infants chose at chance. This pattern contrasts with that exhibited by the large approximate system because numerical ratio did not determine success. Instead there was a sharp performance break: infants succeeded only when there were three or fewer objects per location. This pattern has also been obtained in manual search (Feigenson & Carey, 2003) and habituation tasks (Strauss & Curtis, 1981).

This 3-item limit on infants' performance is consistent with the limits of parallel attention and short-term memory in adults. Adults can track (Pylyshyn & Storm, 1988) and encode properties from (Halberda, Simons, & Wetherhold, submitted; Luck & Vogel, 1997) up to four items in parallel. This shared limit has suggested to many researchers that the same "object-file" representations of object-based attention and short-term memory (Kahneman, Treisman, & Gibbs, 1992) also underlie infants' abilities, suggesting developmental continuity in the mechanisms supporting the tracking of small numbers of individual objects (Carey & Xu, 2001; Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002; Scholl, 2001; Simon, 1997; Uller, Carey, Huntley-Fenner, & Klatt, 1999).

What kinds of quantity computations do infants perform over these object-file representations? Claims that infants compute the numerosity of small object arrays (e.g. Antell & Keating, 1983; Simon, Hespos & Rochat, 1995; Starkey & Cooper, 1980; Strauss & Curtis, 1981; Wynn, 1992, 1998) have been challenged by studies carefully controlling for continuous dimensions that often correlate with number. When number is pitted against area or contour length, infants preferentially respond to the continuous dimension (Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Hauser, 2002; Feigenson, Carey, & Spelke, 2002), and when area is controlled for, infants fail to respond to number altogether (Feigenson, Carey, & Hauser, 2002; Feigenson, Carey, & Spelke, 2002). That object-files underlie these computations of continuous extent is suggested by infants' failure to compute extent with arrays containing more than three objects (Feigenson, Carey, & Hauser, 2002). However, besides supporting computations of total continuous extent, object-files also support computations of discrete number. In a task demonstrating the 3-item limit of object-file representations, infants searched a box according to how many objects, and not how much total "object stuff," they had seen hidden (Feigenson & Carey, 2003).

Thus, infants can compute an array's numerosity or its total continuous extent via object-file representations. Furthermore, which of these two computations infants perform appears to be partly under exogenous control. When objects have similar properties (Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Spelke, 2002) or are from a domain in which continuous extent is especially salient, as with food (Feigenson, Carey, & Hauser, 2002), infants have responded to extent and not to number. But when a task requires reaching for individual objects, infants have responded to number and not to extent

(Feigenson & Carey, 2003). There is the suggestion of a double dissociation in this previous work, with the properties of the array or of the elicited behavior pushing infants to compute either number or extent, but not both. What factors determine which computation infants perform over a given object array?

Under certain conditions, whether infants compute an array's numerosity depends on the properties of the objects in the array. Imagine seeing a yellow duck emerge from the right side of a screen, disappear again, then seeing a yellow duck emerge from the left side of the screen. In this situation it is ambiguous how many objects the scene contains: two identical ducks, or just one? Twelve-month-old infants seeing such a sequence are neutral as to how many objects the scene contains (Bonatti, Frot, Zangl, & Mehler, 2002; Tremoulet, Leslie, & Hall, 2000; Xu & Carey, 1996). However, with two contrasting objects (e.g. a yellow duck and a red truck), 12-month-old (but not 10-month-old) infants expect the screen to reveal 2 objects (Bonatti et al., 2002; Xu & Carey, 1996; but see Wilcox and Baillargeon). That is, older infants use the property differences between the duck and the truck to individuate the objects and correctly compute the array's numerosity.

Like the above studies, the present experiments are concerned with object individuation. The above studies tested infants' use of properties to represent the correct number of individuals in spatiotemporally ambiguous arrays, in which properties were the only cue to the number of objects hidden. The role of properties in infants' individuation of spatiotemporally *un*ambiguous arrays has not yet been explored.

Previous studies have found that infants fail to represent the numerosity of static arrays containing 1, 2, or 3 fully visible identical individuals (Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Spelke, 2002), but do successfully represent the array's continuous extent. Experiment 1 asks whether, under the same conditions, infants will succeed at representing number if the individuals have contrasting rather than identical properties. Experiment 2 asks whether infants can also represent the total continuous extent of such heterogeneous arrays.

1. Experiment 1

Previous studies in which infants responded to continuous extent and not to number used identical objects. The present experiment was modeled on one such study, Experiment 4 in Feigenson, Carey, and Spelke (2002). All aspects of that study and Experiment 1 were identical (including the manner in which extent was controlled), with the single exception that here infants saw objects with contrasting properties. By highlighting the distinctiveness of each individual object, we hoped to draw infants' attention to the number of individuals in the array.

1.1. Participants

Sixteen infants participated (eight boys). Three additional infants were excluded for fussiness. Infants' ages ranged from 6 months, 13 days to 7 months, 11 days (mean = 6 months, 29 days).

1.2. Procedure and stimuli

Infants sat in a highchair in front of a puppet stage. The stage had a concealed opening in the rear wall, allowing the addition or removal of objects when a screen was raised. Infants' gaze was recorded on videotape.

Object arrays consisted of colored foam blocks with painted faces. Because it was not known which properties infants would find most salient in this task, we maximized the chance that infants would notice objects' property differences by using objects that contrasted in multiple basic-level features such as color, texture, and pattern orientation[1]. For example, 2-object habituation arrays contained one object with green "fur," and another that was smooth and blue with colored "antennae". Objects within an array were identical in size and shape (Fig. 1).

Property contrasts were not chosen to make the objects appear to be from different object kinds. Rather, Experiment 1 manipulated property information while holding kind constant. Although the objects used here and by Feigenson et al. had schematic faces (and objects in the present series also had "antennae" and "fur" that might further indicate animacy), this was considered unlikely to help infants individuate the arrays. Since Bonatti et al. (2002) found that 10-month-olds did not successfully individuate two human-like dolls in a spatiotemporally ambiguous presentation, animacy alone does not appear to enable infants to correctly individuate an array.

Experiment 1 controlled for the number of different properties and the continuous extent of the arrays. For infants habituated to 2, the number of properties in both novel and familiar test arrays was equated to that from habituation. For infants habituated to 1, a different strategy was required[2], in which the numerically *familiar* test array contained a novel number of properties, while the numerically novel array contained the same number of properties relative to habituation. This design worked against our hypothesized results by making it more difficult to achieve a positive response to number.

As in Experiment 4 of Feigenson, Carey, and Spelke (2002), there were three sizes of habituation objects, only one size of which was used per habituation trial. The average total front surface area of habituation arrays across these sizes was 92.3 cm^2 (habituation to 1) and 184.6 cm^2 (habituation to 2). Infants were tested with objects with a front surface area of 63.8 cm^2 (habituation to 1) or 127.1 cm^2 each (habituation to 2). The change in total front surface area from the habituation average to both the numerically novel and familiar arrays was approximately 30%. Fig. 3 reports these area measurements, along with measurements of contour length, another continuous dimension to which infants are sensitive (Clearfield and Mix, 1999, 2001).

Trials began when infants looked at the display for at least 0.5 s, and ended when infants looked away for two continuous seconds. Trials were presented in multiples

[1] Wilcox (1999) documents the ages at which infants individuate a spatiotemporally ambiguous scene using various object properties. Since it is not clear that infants seeing a spatiotemporally *un*ambiguous scene will weight properties in the same way, we used several property contrasts rather than focusing on any single contrast.

[2] For infants habituated to one it was impossible to equate the number of properties in both test arrays with that of the habituation arrays without also introducing a difference in the number of properties on each individual object.

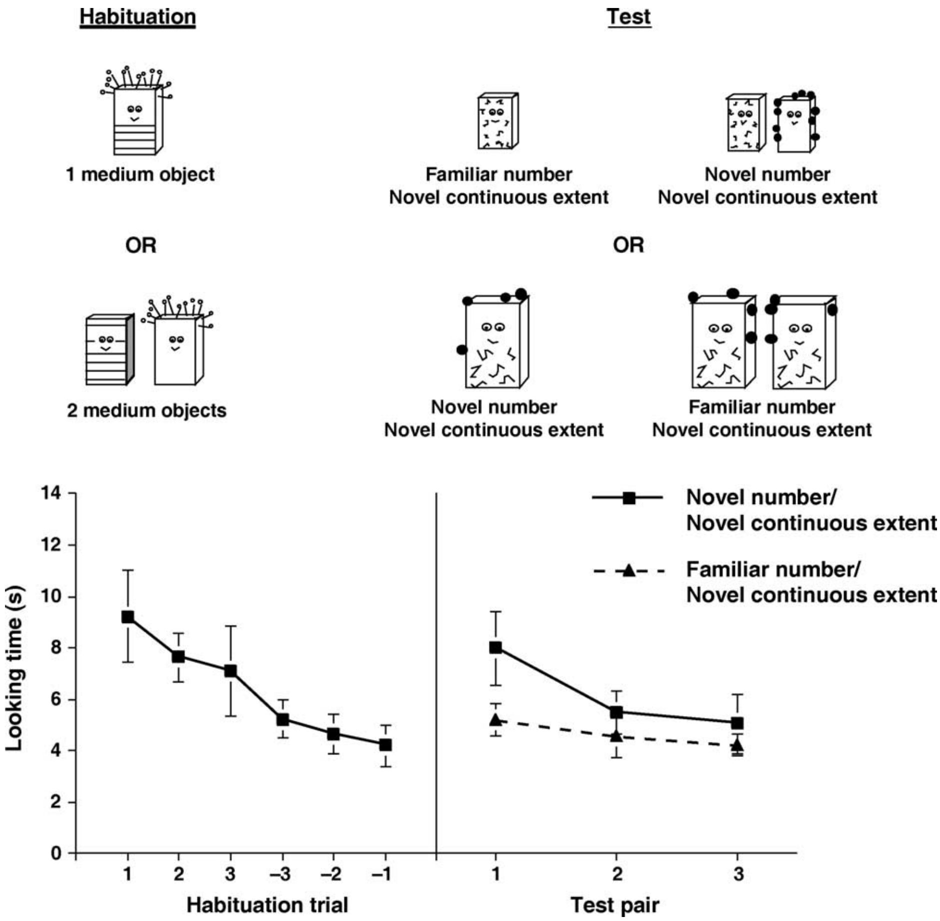

Fig. 1. Stimuli and looking times for Experiment 1.

of three to ensure that infants had equal exposure to the three sizes of habituation objects. Thus, infants saw 6, 9, 12, or 15 habituation trials. After habituation infants received three numerically novel and three numerically familiar test trials in alternation, with order counter-balanced across infants. Coding was performed on-line by an observer blind to what infants were seeing. Looking time was later re-coded by two other observers, and inter-observer reliability averaged 93%.

1.3. Results and discussion

Infants preferred the numerically novel test arrays (Fig. 1). A 3 (Test Pair)×2 (Test Type: novel or familiar number)×2 (Habituation Condition: 1 or 2)×2 (Test Order: novel or familiar number test array presented first) ANOVA revealed a main effect of Test Type, $F(1,12)=8.04$, $P<.05$. Additionally, there was an uninterpretable 4-way interaction between Test Pair, Test Type, Habituation Condition, and Test Order,

$F(2, 24) = 4.17$, $P < .05$. Paired t-tests confirmed that infants dishabituated to the first numerically novel test array, $t(15) = -2.3$, $P < .05$, but not to the one that was familiar, $t(15) = -.75$, $P = .46$.

To directly probe the effect of array heterogeneity we compared Experiment 1 with Feigenson et al.'s Experiment 4. A 2 (Experiment)×3 (Test Pair)×2 (Test Type)×2 (Habituation Condition)×2 (Test Order) ANOVA revealed a significant Experiment x Test Type interaction, $F(1, 24) = 5.18$, $P < .05$. Infants in Experiment 1 looked longer at numerically novel test arrays, whereas infants in Feigenson et al.'s Experiment 4 did not. Since the only difference between the experiments was whether objects had contrasting or identical properties, it appears that the heterogeneity of the array determined whether infants responded to number.

These results are the first demonstration of infants successfully responding to the numerosity of small arrays of static objects with continuous extent controlled. Presenting infants with contrasting rather than identical objects reversed infants' looking preferences. With identical objects, infants responded to total extent (Clearfield & Mix, 1999, 2001; Experiment 2 in Feigenson, Carey, & Spelke, 2002), but not to number (Experiments 3–5 in Feigenson, Carey, & Spelke, 2002). With heterogeneous objects, infants responded to number (Experiment 1 in the present series). This raises the question whether infants also represent the continuous extent of heterogeneous arrays, or whether they are limited to performing just one computation over a given set of object representations.

2. Experiment 2

Experiment 2 asked whether infants represent the total continuous extent of the heterogeneous object arrays from Experiment 1. Test arrays were always novel in number, but one of them was also novel in extent while the other was familiar in extent.

2.1. Participants

Sixteen infants participated (nine boys). Four additional infants were excluded for fussiness (2), sibling interference (1), and error (1). Infants' ages ranged from 6 months, 11 days to 7 months, 21 days (mean = 6 months, 28 days).

2.2. Procedure and stimuli

Infants saw the habituation objects from Experiment 1, and new test objects (Fig. 2). For infants habituated to 2 (average total front surface area = 184 cm^2), test arrays always contained 1 object and were therefore numerically novel (presenting numerically novel test arrays paralleled Experiment 1, Feigenson, Carey, & Hauser, 2002, and Feigenson, Carey, & Spelke, 2002, in which test arrays were always novel in continuous extent). The 1 test object either had a front surface area of 91 cm^2 (approximately half that of habituation), or a front surface area of 184 cm^2 (equal to that of habituation). For infants habituated to 1 (average total front surface area = 92 cm^2), test arrays always contained 2 objects and were therefore numerically novel. The 2 test objects either had a front surface

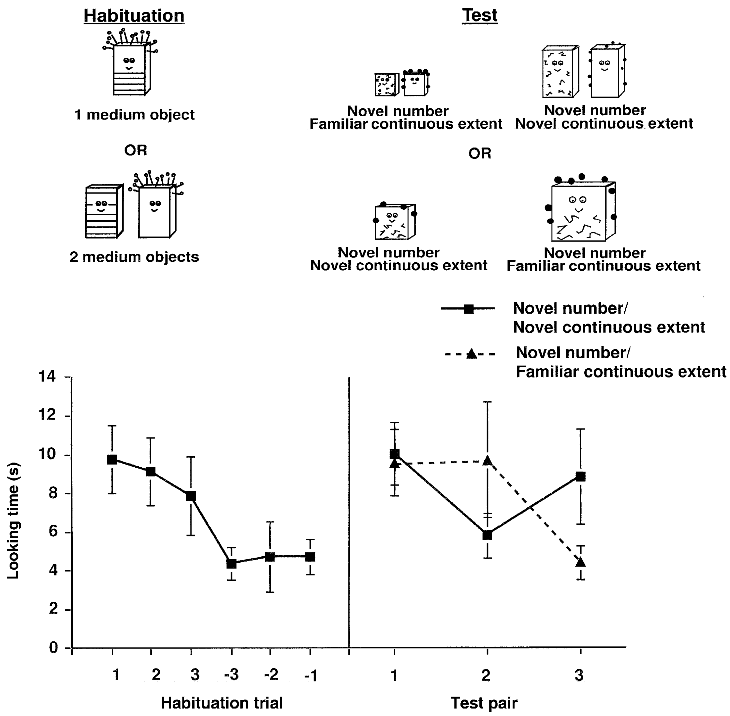

Fig. 2. Stimuli and looking times for Experiment 2.

area of 46 cm^2 each (equal to that of habituation), or 92 cm^2 each (double that of habituation).

The number of properties in the habituation and test arrays was equated. Infants were either habituated to 1 object with two sets of properties, or 2 objects with one set of properties each. All test arrays contained two sets of properties. All other aspects of the procedure were identical to those in Experiment 1.

2.3. Results

Infants did not differentiate the two types of test arrays, one of which was novel in continuous extent (Fig. 2). A 3 (Test Pair) × 2 (Test Type) × 2 (Habituation Condition) × 2 (Test Order) ANOVA confirmed that there was no effect of Test Type, $F(1, 12) = .06$, $P = .81$. Infants looked an average of 8.2 s at the arrays that were novel in extent, and 7.8 s at those that were familiar in extent. No other main effects or interactions were found. Paired t-tests revealed that infants did, however, dishabituate to the numerical novelty of both types of test arrays, $t(15) = -3.07$, $P < .01$ and $t(1, 15) = -3.11$, $P < .01$. This replicates the results of Experiment 1, showing that the heterogeneity of the array drove infants to represent the array's numerosity. Thus, infants appeared to notice the change in number, but not the change in total extent.

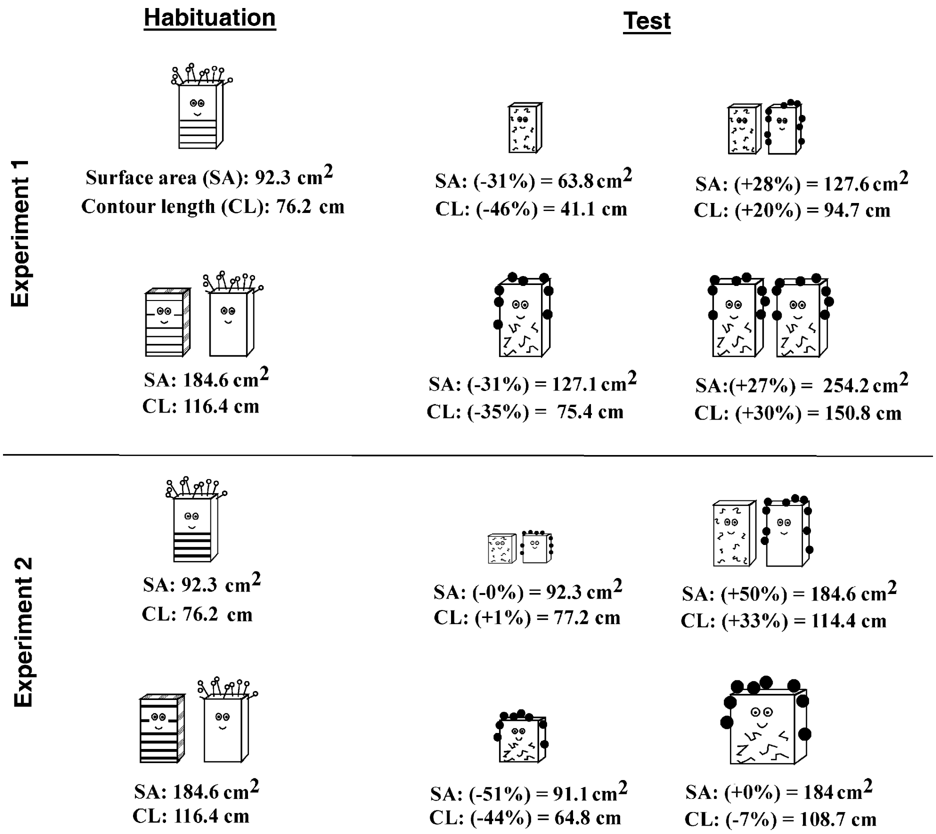

Fig. 3. Total front surface area (SA) and total contour length (CL) of the arrays. Surface area was calculated without including the objects' added features, which were sparse and thus added little area. Contour length did include the added features, since the features significantly increased the objects' perimeters. The percent change between habituation and test arrays is reported in parentheses. Percent change was calculated as a ratio between the smaller array and the larger array, such that an array half the size of the habituation array was considered equally novel as an array twice the size of the habituation array.

3. General discussion

Previous studies (Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Hauser, 2002; Feigenson, Carey, & Spelke, 2002) found that infants represent the total continuous extent but not the numerosity of small object arrays. Experiments 1 and 2 revealed that giving objects contrasting sets of properties reverses this pattern: infants successfully responded to the number of objects in the array, but not to its continuous extent.

Infants in Experiment 1 responded to numerosity with front surface area controlled for. Infants in Experiment 2 did not respond to front surface area with number controlled for. This suggests that across the two experiments, number, not area, drove infants' responses. Nor were infants' responses controlled by other measures of extent. While infants have been shown to respond to contour length (the total perimeter of all objects in the array,

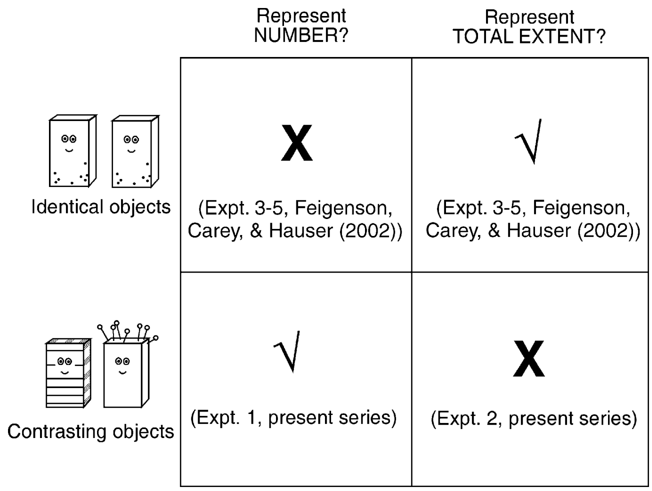

Fig. 4. Double dissociation between array heterogeneity and the computation infants perform over the objects in the array.

Clearfield & Mix, 1999, 2001), contour length cannot account for the present results. This is seen in Fig. 3, which reports the front surface area and contour length of the arrays, along with the percent change between habituation and test arrays. Test arrays were constructed such that, if responding to surface area, infants should fail to discriminate the Experiment 1 test arrays and should prefer the novel extent arrays in Experiment 2. If responding to contour length, infants should also fail to discriminate the Experiment 1 test arrays (or, if anything, should prefer the familiar number arrays), and should prefer the novel extent arrays in Experiment 2. Thus, neither a response to area nor to contour length accounts for the present results, in which infants preferred the novel number arrays in Experiment 1 and failed to discriminate the arrays that differed in extent in Experiment 2.

Combined with the findings of Feigenson, Carey, and Hauser (2002) and Feigenson, Carey, and Spelke (2002), these results form a double dissociation in infants' representations of small object arrays (Fig. 4). Infants responded to changes in the numerosity but not the total extent of heterogeneous arrays. Infants responded to changes in the extent but not the numerosity of homogeneous arrays. Within a single paradigm, infants performed one computation, but not both, and which computation was performed appeared exogenously driven by the distribution of properties across individuals.

How does the heterogeneity of an object array determine which computation infants perform? Findings with adult participants suggest that heterogeneity might affect either the initial creation of object representations or their storage in memory[3]. Support for the

[3] Heterogeneity might exert its effect earlier, during the initial encoding of the scene, perhaps by making the array easier to parse or by causing objects to be more effectively indexed. However, infants' success in the 1 object habituation condition of Experiment 1 mitigates against this possibility. To successfully dishabituate to the 2 object test array, infants had to form a representation of the single habituation object in the absence of heterogeneity information, since no such information exists in a 1 object scene.

former explanation comes from Kanwisher's work on repetition blindness. Normal subjects shown brief simultaneous presentations of stimuli with contrasting features (e.g. a yellow **S** and a blue **O**) had no difficulty reporting the color or identity of both items. However, subjects were less accurate with identical stimuli (e.g. two blue **O**'s) (Kanwisher, Driver & Machado, 1995). More dramatically, patients with unilateral parietal damage only reported the presence of 1 of the two stimuli when they were identical, and required contrasting features to report perceiving both (Baylis, Driver, & Rafal, 1993). Kanwisher (1991) suggests that although subjects *see* both stimuli, they fail to create a new token representation for objects of an already-represented type. Such an error could also account for infants' failure to recognize the numerosity of identical objects. Infants might fail to create two separate tokens when the objects are identical, but succeed when contrasting properties mark the objects as different types.

Alternatively, heterogeneity might affect the maintenance of object-file representations already in memory. Such an account is related to classic effects in forgetting, whereby dissimilar items are better remembered than similar items. For example, subjects were asked to recall a list of four letters. Recall was worse when an interference list contained letters that were phonemically similar to the recall list (Wickelgren, 1965), suggesting that similar items cause more short-term memory interference. On this account, infants create separate tokens (object-files) for two identical objects, but the similarity of these objects interferes with infants' recall. Because the object-files have identical features bound to them, they may be less likely to be maintained as distinct individuals. Infants may extract information about the overall properties of the array from the object-file representations (e.g. total amount of "green stuff") but then may discard or "forget" the information that the array contained two distinct objects. Future work will address these possible influences of heterogeneity on infants' numerical computations.

In summary, previous studies show that infants represent objects via mechanisms of object-based attention. Infants can compute over these representations: when objects have similar properties infants compute continuous extent. When objects have contrasting properties infants compute number. The present work suggests a double dissociation in these computations, with infants representing different dimensions of an object array depending on the array's properties. Thus, beyond questions of whether infants "have" or "do not have" a given ability, we can ask how various factors influence the representations infants form and the computations they carry out over these representations.

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