Cognitive Psychology **44,** 33–66 (2002)
doi:10.1006/cogp.2001.0760, available online at http://www.idealibrary.com on IDEAL®

Infants' Discrimination of Number vs. Continuous Extent

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Seven studies explored the empirical basis for claims that infants represent cardinal values of small sets of objects. Many studies investigating numerical ability did not properly control for continuous stimulus properties such as surface area, volume, contour length, or dimensions that correlate with these properties. Experiment 1 extended the standard habituation/dishabituation paradigm to a 1 vs 2 comparison with three-dimensional objects and confirmed that when number and total front surface area are confounded, infants discriminate the arrays. Experiment 2 revealed that infants dishabituated to a change in front surface area but not to a change in number when the two variables were pitted against each other. Experiments 3 through 5 revealed no sensitivity to number when front surface area was controlled, and Experiments 6 and 7 extended this pattern of findings to the Wynn (1992) transformation task. Infants' lack of a response to number, combined with their demonstrated sensitivity to one or more dimensions of continuous extent, supports the hypothesis that the representations subserving object-based attention, rather than those subserving enumeration, underlie performance in the above tasks.

A wealth of recent evidence seems to establish that even preverbal infants represent the cardinal values of small sets of individuals. Two empirical paradigms provide the bulk of this evidence: habituation studies (Antell & Keating, 1983; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Treiber & Wilcox, 1984; Van Loosbroek & Smitsman, 1990; Wynn, 1996) and transformation studies (Koechlin, Dehaene, &

This work was supported by NSF Grant SBR-9514695 to Susan Carey, by NIH grant R37-HD23103 to Elizabeth Spelke, and by an NSF predoctoral fellowship to the first author.
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0010-0285/02 $35.00

Mehler, 1998; Simon, Hespos, & Rochat, 1995; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Wynn, 1992, 1995).

In habituation studies, which rely on a preference for novelty, infants see repeated presentations of a fixed number of items and then are tested with a novel number. An increase in looking time to the novel number suggests that infants discriminated the numerosities. In most of the number habituation studies, the stimuli were sets of visually presented, two-dimensional individuals. For example, Starkey and Cooper (1980) showed 4- to 7-month-old infants repeated presentations of two dots. During this habituation phase, infants' looking time decreased as they grew bored with the repeated displays. After habituation, infants were tested with two dots vs three. Infants increased their looking to the novel numerosity, but not to the familiar one. The pattern was symmetrical for infants habituated to three dots and tested with two. A two dot vs three discrimination has also been shown in newborns (Antell & Keating, 1983). However, infants' success with larger numerosities appears limited, as Starkey and Cooper found that infants failed to dishabituate to the change between four and six.

Other applications of the habituation paradigm have found 6- to 12-month old infants to discriminate among photographs or drawings of sets of objects of different numerosities (two vs three and three vs four, but not four vs five; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981), and among numbers of moving shapes (two vs three, three vs four, and four vs five; Van Loosbroek & Smitsman, 1990).

The second source of empirical support for early numerical competence comes from violation-of-expectation transformation studies. In these experiments infants are shown simple arithmetic problems, and looking times to expected and unexpected outcomes are compared. Stimuli in these studies are small sets of real, three-dimensional objects. For example, in Wynn's (1992) landmark study, infants saw a toy mouse on a stage that was then hidden by a screen. A hand carrying a second mouse entered, passed behind the screen, and emerged empty. Infants' reasoning about this 1 + 1 event was probed by showing them the expected outcome of two mice vs the unexpected one mouse. Infants looked longer at the one-mouse display, suggesting that they expected that 1 + 1 = 2. Another group of infants saw a subtraction condition in which two mice appeared on stage and were hidden by the screen, and then a hand took one away. Infants again looked longer at the unexpected outcome (2–1 = 2). A 1 + 1 = 2 or 3 condition showed that infants expected exactly two, and not just ''more than one.'' Wynn's pattern of results has been replicated many times (e.g., Koechlin et al., 1998; Simon et al., 1995; Uller et al., 1999), and extended to 2 + 1 and 3–1 transformations (Wynn, 1995).

Confounding Stimulus Dimensions

Together, the habituation and transformation studies have been taken to indicate that infants represent the numerosity of small sets of objects and reason about their numerical properties. However, a serious confound prevents us from drawing such conclusions from the studies testing infants' enumeration of sets of objects: We do not know whether infants in these studies are responding to number or to some continuous variable correlated with number. In Starkey and Cooper's study, for example, infants looked longer at three dots after seeing repeated presentations of two dots. Support for numerical competence is predicated on the assumption that infants repeatedly encoded the numerosity ''2'' during habituation. The numerosity ''3'' would then prompt a novelty response based on the change in number. Since the size of each element was constant throughout the session, however, several continuous measures were confounded with number, including the total surface area and total perimeter of the elements and global properties of the array such as brightness and spatial frequency. Although these variables form a diverse set, all depend on continuous spatial dimensions, and so we refer to them as *continuous extent.* The novelty of the test outcome may have been based on a change in one or more dimensions of continuous extent rather than on the change in number. Since number and extent covary in the above studies, infants' looking patterns do not allow us to decide between these possibilities.

In an attempt to avoid this confound, Strauss and Curtis (1981) and Starkey, Spelke, and Gelman (1990) tested infants' discrimination of numerosities with object arrays that were drawn or photographed from different distances such that the continuous extent of the displays varied from slide to slide. Infants still dishabituated to the change in the number of elements: for instance, from two to three. However, because infants saw all object sizes over the course of habituation, infants might have habituated to an average of any of the correlated dimensions of continuous extent. If object size was randomly determined on the test trials, then, on average, the extent of the three-object displays must be greater that of the two-object displays.[1] Therefore, infants saw a majority of novel-number test trials that were also novel in extent, leaving us with the ambiguous result described earlier: the covariation of number and continuous extent prohibits isolating the source of infants' response.

This problem can be avoided by using a design with precise controls for

[1] The implications of the confound can be seen in Table 1 of Strauss and Curtis (1981), which lists examples of typical stimuli. In one condition, habituation consisted of two-item arrays varying in size between trials (item size: 1, 4, 2, 6, 3, 1, 4, . . .; the precise dimensions of continuous extent manipulated were not specified). Given these stimuli, infants saw arrays with an average total extent of 6.4 over habituation. Infants were then tested with two-item arrays with each item of size 2, and three-item arrays with each item of size 6. Therefore, compared to the average seen over habituation (6.4), the novel number outcome was more novel in extent (18) than was the familiar number outcome (4). Because object identity repeated over habituation trials (dogs, butterflies, houses, dolls, cats, dogs) and because object identity was always novel in the test trials (parrots and flags), infants may have dishabituated to both test outcomes and more strongly to the outcome that was most novel in extent.

continuous variables. One such design involves pitting number against those variables. After habituation to a constant number and continuous extent, infants see one test display that is novel in number but familiar in extent, and another display that is novel in extent but familiar in number. Such a design was used by Clearfield and Mix (1999), who manipulated contour length (the sum of the perimeters of the elements) in this way. They found that 6- to 8-month old infants dishabituated to the novel contour length but not to the novel number. Note that the display that was novel in contour length was also more novel in total surface area than the display that was familiar in contour length. For example, Clearfield and Mix habituated infants to a two-square display with a contour length of 16 cm. Infants dishabituated to a two-square test display with a contour length of 24 cm, but not to a three-square display with a contour length of 16 cm. This result is also predicted by the change in total surface area, as the two-square test display (total surface area 18 cm^2) represents a bigger change than the three-square test display (5.31 cm^2) from the habituation display (8 cm^2). Clearfield & Mix's findings therefore do not establish the dimension of continuous extent to which infants responded. More importantly, Clearfield and Mix's results leave open the question of whether infants simply responded more strongly to the change in continuous extent than to the change in number or whether they failed to represent number altogether. That is, infants may have represented both number and continuous extent, but responded on the basis of the more salient representation.

The number/extent confound is not limited to habituation studies but is also a problem in transformation experiments because all have used stimuli of a constant size. In Wynn's original study and in subsequent replications, infants saw one object + one object, with outcomes of two or one. It is easy for adults to recognize that the one-object outcome is unexpected on the basis of number. Note, however, that the same outcome is also unexpected on the basis of several measures of continuous extent: front surface area, total surface area, volume, contour length, and other correlated variables. A single object represents a fixed extent; add a second object, and the extent doubles. The one-object outcome represents only half as much total extent as is expected. Infants' increased looking at one object after seeing 1 + 1 might thus be due to a violation of their expectations about *how many objects* to expect or to a violation of their expectations about *how much of a continuous quantity* to expect.

In sum, none of the extant habituation or transformation studies with small sets of single objects as stimuli provide unequivocal evidence that infants represent the number of individuals in the array because none has adequately controlled for correlated dimensions of continuous extent. The single study that did so (Clearfield & Mix, 1999) revealed sensitivity to total contour length, or to some correlated dimension of extent, and no sensitivity to number.

Two studies, however, do provide unequivocal evidence for sensitivity to number. In one, 6-month old infants dishabituated to the change between 8 dots and 16 dots, with total surface area, total envelope of the array, dot density, and brightness all controlled for (Xu & Spelke, 2000). This finding has recently been extended to the change between 16 dots and 32 (Xu, 2000). Importantly, infants' discrimination abilities appear to depend on the Weber fraction between the to-be-discriminated numerosities: Although infants discriminate 8 vs 16 and 16 vs 32, they fail to discriminate 8 vs 12 and 16 vs 24 (Xu & Spelke, 2000; Xu, 2000). This suggests that infants require at least a 1:2 ratio between large numerosities in order to discriminate them.

In a second unequivocal success, 5-month old infants dishabituated to a change in the number of collections of dots on a screen (Wynn & Bloom, 1999). In this study, infants were habituated to collections of dots moving across the screen as a single unit. One group of infants was habituated to two collections composed of three dots each (2×3), and the other group was habituated to four groups of three dots each (4×3). Infants were then tested with both two groups of four (2×4), and four groups of two (4×2). Infants habituated to (2×3) dishabituated to (4×2), and infants habituated to (4×3) dishabituated to (2×4). Thus, even with total amount of surface area and brightness held constant, infants looked longer at the test displays with the novel number of dot collections.

In addition to these two unequivocal successes, there are also two habituation experiments in which most, but not all, correlated dimensions of extent were controlled for. Both studies presented infants with nonobject stimuli. In one, four-day-old infants discriminated two-syllable utterances from three-syllable utterances (Bijeljac-Babic, Bertoncini, & Mehler, 1991). Although the length of the two-syllable utterances was extended and that of the three-syllable utterances was compressed in order to control for total utterance duration, three-syllable utterances were, on average, longer. Therefore, we cannot firmly conclude that infants responded to syllable number. In Wynn (1996), 6-month-old infants dishabituated to the change between two vs three jumps of a puppet. Total duration of the jump sequence and the tempo of the jumps were controlled for. However, the three-jump sequences contained more total upward motion than the two-jump sequences, leaving open the possibility that infants responded to this continuous dimension rather than to number.

Combining the unequivocal successes and the successes in which extent was at least partially controlled for, we see that infants appear able to discriminate different numbers of large sets of items and different numbers of sets where the individuals are not single objects (collections, syllables, and jumps). But, surely, objects are canonical individuals. Although representation of number, or any other feature of an array, is optional, we would expect that if number can be represented at all, it would sometimes be represented for small sets of real objects as well as for large sets, collections, sounds, and events.

The present series of studies seek evidence that infants represent the number of individuals in small sets of objects. There were several aims. First, we presented infants with small sets of real, three-dimensional objects in order to ask whether infants' numerical abilities extend beyond large sets and sets of nonobject stimuli. Second, infants' numerical responses were examined when one dimension of continuous extent, total front surface area, was systematically manipulated. In addition to pitting number and front surface area against each other, we tested infants' responses to a numerical change when the change in front surface area was neutralized.[2] Third, in addition to presenting infants with a two vs three discrimination, we presented a numerical comparison not previously explored using the habituation method: one vs two. One vs two was chosen in order to maximize the possibility that infants would respond to number because a 1:2 ratio is more discriminable than a 2:3 ratio. This comparison also allowed us to examine responses to the same numerosities as are used in the 1 + 1 transformation paradigm. To examine the possibility that a different pattern of results would be found in the transformation paradigm, the last two experiments explored infants' responses to number and extent in a 1 + 1 = 2 or 1 paradigm. Finally, we discuss the implications of infants' surprising pattern of performance in these experiments for claims about early numerical ability. To preview, we suggest that performance in many previous ''numerical'' tasks may have reflected sensitivity to one or more dimensions of continuous extent rather than sensitivity to number. While we agree that infants do represent number under certain conditions (such as with large numbers of elements and nonobject stimuli), infants may not easily encode number when presented with small sets of objects. Instead, they may represent object properties such as extent. We propose a model by which infants create representations of objects that can be compared on either number or extent.

EXPERIMENT 1

Experiment 1 was modeled after previous habituation studies (e.g., Starkey & Cooper, 1980). Here, we sought to confirm the standard finding that infants dishabituate to the change from one number of objects to another when number and continuous extent are confounded and to extend this finding to a one vs two discrimination with three-dimensional objects. Infants were habituated to either one or two objects. Objects were of two sizes, with the large objects having twice the front surface area as the small objects.

[2] Total front surface area is often confounded with other dimensions of continuous extent such as total volume, total contour length, total envelope, and total brightness of the display. Like Clearfield and Mix (1999), we do not attempt to isolate which dimension of continuous extent contributes to infants responses. Thus, although we manipulated total front surface area, we use the general term *continuous extent* to refer to the collection of continuous perceptible dimensions in these displays.

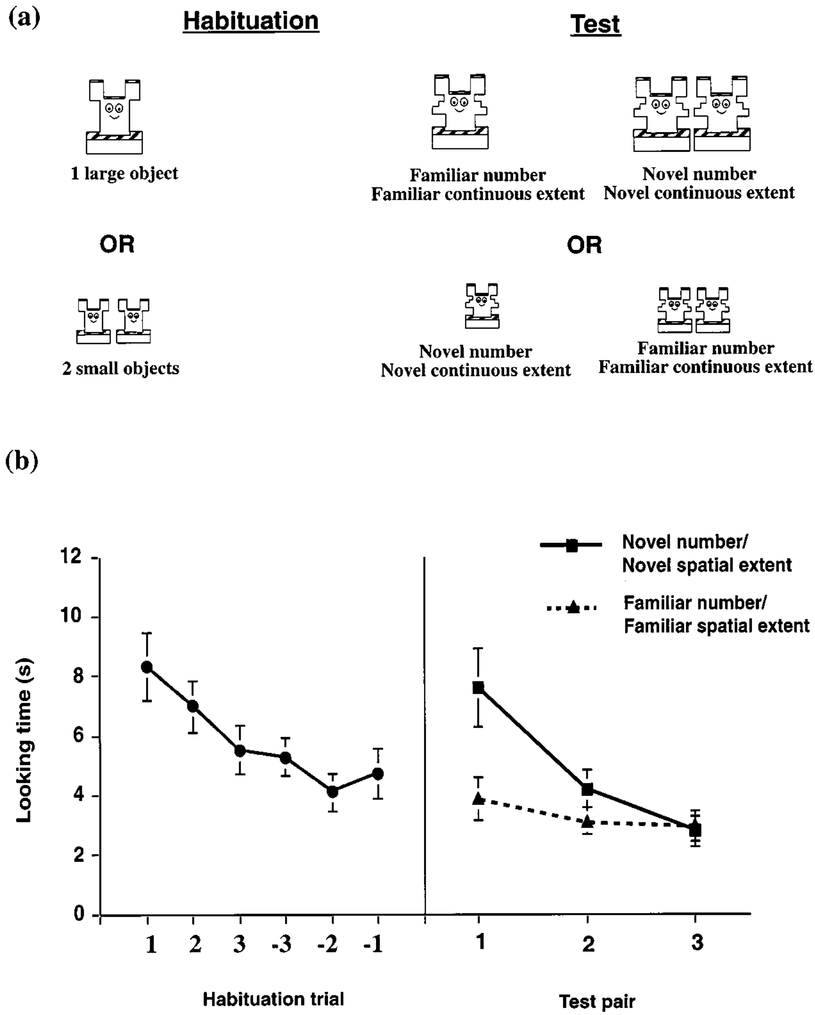

FIG. 1. (a) Displays and (b) looking times for Experiment 1, in which number and continuous extent were confounded.

Infants habituated to one large object were tested on half of the test trials with one large object of a novel color (see Fig. 1a). This display was familiar in number (since infants were habituated to one object), and also familiar in continuous extent (since infants were habituated to a large object of the same size). On the other half of the test trials, infants saw two large objects of a novel color. This display was novel in number (twice as many as in habituation) and also novel in total extent (twice as much as in habituation). The other group of infants was habituated to two small objects and tested with one small object (novel number and novel extent) vs two small objects (familiar number and familiar extent). The expectation was that infants in both habituation conditions would look longer at the display that was novel in number and in extent.

Method

Participants. Twenty infants participated (8 boys and 12 girls). Two additional infants were excluded from the analysis: 1 due to fussiness, and 1 who ceased to look during the session. Infants ranged in age from 6 months;16 days to 7 months;15 days (M = 6 months;23 days). All participants were healthy infants from Ithaca, New York, or the New York City area.

Apparatus. Infants sat in a highchair approximately 90 cm in front of a puppet stage made of foam-core. The stage was 40 cm high, 114 cm wide, and 32 cm deep. There was a 56 × 12 cm opening in the rear wall of the stage, concealed with black fabric. This opening allowed the experimenter to surreptitiously add or remove objects when a screen was raised. The screen was a 53 × 26 cm piece of foam-core affixed to an aluminum rod at the stage base, which the experimenter could rotate outside of infants' view to reveal or occlude the center of the stage.

The stage was lit by a 20-watt fluorescent tube mounted on top of the display. The tube was hidden from view with a piece of black cardboard attached to the top of the light fixture and extending down in front of it. This allowed light to shine onto the stage, but prevented infants from seeing the tube itself. The room was lit by a dim halogen lamp not visible to infants.

A video camera behind the stage provided a direct view of infants' faces. The camera lens extended through a hole in the rear wall of the stage. The image was recorded by the camera and appeared on a TV monitor in a separate room for coding purposes.

The stimuli were animallike, irregularly shaped objects made of Legos. There were two sizes and three colors. The large objects were approximately 11.5 cm high, 9.5 cm wide, and 6.5 cm deep.[3] The small objects were approximately 8 cm high, 6.5 cm wide, and 5 cm deep. The front surface area of the large objects was, on average, 80.5 cm^2 (object size varied slightly between the three colors). The front surface area of the small objects was, on average, 38.9 cm^2. Each color (green, orange, or purple) corresponded with a slightly different shape of object, and all objects had simple faces painted on them to attract infants' attention.

Procedure. Parents faced infants during the experiment. Classical music at low volume masked the noise of adding objects to and removing objects from the stage. Infants were randomly assigned to habituation condition, with half of the infants habituated to one large object, and half habituated to two small objects. During the habituation phase the experimenter presented two colors of objects in alternation (e.g., one large purple, one large green, one large purple, etc.). Objects were alternated in order to increase the likelihood that infants would attend to the numerosity of the array rather than to the features of a single object. For test trials, the experimenter always presented objects of a novel color not seen during habituation, but which were of the same size as the habituation objects (e.g., one large orange and two large orange). This was done so as to maintain infants' interest in the displays. Color was novel on both types of test trials. Habituation condition (one or two objects), test color (green, orange, and purple), and test order (one or two objects on the first test trial) were counterbalanced across infants.

The habituation phase began when the experimenter said, ''Screen up,'' and raised the screen. She placed one or two objects on stage out of the infant's view, said, ''Screen down,'' and lowered the screen. A trial began when the infant looked at the display for at least 0.5 s and ended when the infant looked away for 2 continuous s. When the trial ended, the experi-

[3] These measures are approximate because the objects were taller and wider in some parts than in others (see Fig. 1a).

menter said, ''Screen up,'' and raised the screen again. She removed the object(s) and replaced them with a different object or pair of objects. Objects were placed on a 3×4 grid on the stage floor. Which cell the object occupied was determined pseudorandomly, with the restriction that no object could be placed directly in front of another object. Therefore, the distance between objects and their depth on the stage floor varied from trial to trial throughout habituation and test. The average interobject distance across the length of the stage was approximately 18 cm (range: 6–30 cm), and the average interobject distance across the depth of the stage was approximately 10 cm (range: 0–20 cm).

Habituation continued until (a) looking time on 3 consecutive trials was less than half of looking time on the first 3 trials or (b) infants completed 12 trials without meeting criterion (a). The 6 test trials followed the same procedure as habituation trials. Test displays were either novel in number and in continuous extent (novel/novel) or familiar in both (familiar/familiar). Coding was performed on-line in another room by an observer blind to what the infant was seeing. Looking time was later recoded by a separate pair of observers, and average interobserver reliability was .93 across all trials (habituation and test) for a random half of the participants.

Results

Infants dishabituated to the display that was novel in number and in continuous extent (novel/novel) and not to the display that was familiar in number and extent (familiar/familiar, see Fig. 1b). Paired *t* tests showed that infants' dishabituation from the average of the last three habituation trials to the first novel/novel display was significant, $t(1, 19) = -2.08$, $p < .03$, one-tailed, whereas there was no dishabituation to the first familiar/familiar display, $t(1, 19) = 1.1$, $p < .14$, one-tailed.

A $2 \times 2 \times 2 \times 3 \times 3$ repeated-measures ANOVA examined the effects of Habituation Condition (habituation to one large or two small objects), Test Type (one or two objects), Test Order (1,2,1,2,1,2 or 2,1,2,1,2,1), Test Color (green, orange, or purple) and Test Pair (first, second, or third) on infants' looking times during the test trials. No effects of Test Color were found, so this variable was excluded from all subsequent analyses. A second $2 \times 2 \times 2 \times 3$ ANOVA examined the remaining variables. There was a significant interaction between Habituation Condition and Test Type, with infants looking longer at the novel/novel display, $F(1, 16) = 17.23$, $p < .01$. Infants who were habituated to one large object looked longer at two large objects during test trials, and infants habituated to two small objects looked longer at one small object during test trials. There was a main effect of Test Pair, with infants looking longest on the first pair, $F(2, 32) = 7.87$, $p < .01$. A Habituation Condition × Test Type × Test Pair interaction showed that infants looked longer at the novel/novel display on the first pair of test trials than on the next two pairs, $F(2, 32) = 7.5$, $p < .05$. Finally, there was a main effect of Test Order. Infants shown the 2,1,2,1,2,1 sequence looked longer overall than infants shown the 1,2,1,2,1,2 sequence, $F(1, 16) = 8.0$, $p < .05$. No other main effects or interactions were significant.

Discussion

Experiment 1 extended the standard habituation results to a one vs two comparison with three-dimensional objects. These findings are consistent with the possibility that infants represent object number and respond to numerical changes. However, as we have seen, they are also consistent with the alternative that infants are responding to changes in one or more dimensions of continuous extent. In Experiment 1, the test displays that were novel in number were also novel in a variety of dimensions of extent, including total front surface area, total surface area, contour length, and volume. Therefore, neither this experiment nor others like it allow us to decide between the hypothesis that infants responded to number versus the hypothesis that they responded to continuous extent.

To address this issue, number and extent were pitted against each other. Experiment 2 explored whether infants respond to number and/or extent when the properties are no longer confounded, and compared the relative strengths of the responses.

EXPERIMENT 2

Experiment 2 used the habituation procedure to compare separate responses to number and to the total front surface area of the array. We presented displays novel in *either* number *or* surface area to determine whether infants would respond to each dimension alone. Infants who were habituated to one large object saw one small object on half of the test trials (see Fig. 2a). This display was familiar in number, since infants had been habituated to one. However, the display was novel in continuous extent because the small object had only half of the front surface area of the large object seen during habituation. On the other half of the test trials, infants who were habituated to one large object saw two small test objects. In this case, the display was novel in number. However, because the combined surface area of the two small objects equaled that of the one large object, continuous extent was familiar. A separate group of infants was habituated to two small objects. They were tested with one large object (novel number and familiar extent) vs two large objects (familiar number and novel extent).

If infants habituate to a specific number of objects, then looking to the novel number should increase during the test trials. If infants habituate to a specific total extent, then looking to the novel extent should increase. This procedure is a conceptual replication of Clearfield and Mix (1999), using three-dimensional objects instead of two-dimensional images, using a one vs two comparison rather than a two vs three comparison, and manipulating total front surface area rather than contour length.

Method

Participants. Twenty infants participated (9 boys and 11 girls). Three additional infants were excluded from the analysis: 1 whose parent influenced looking during the session, 1 whose sibling caused a distraction during the study, and 1 due to a coding error. Infants ranged

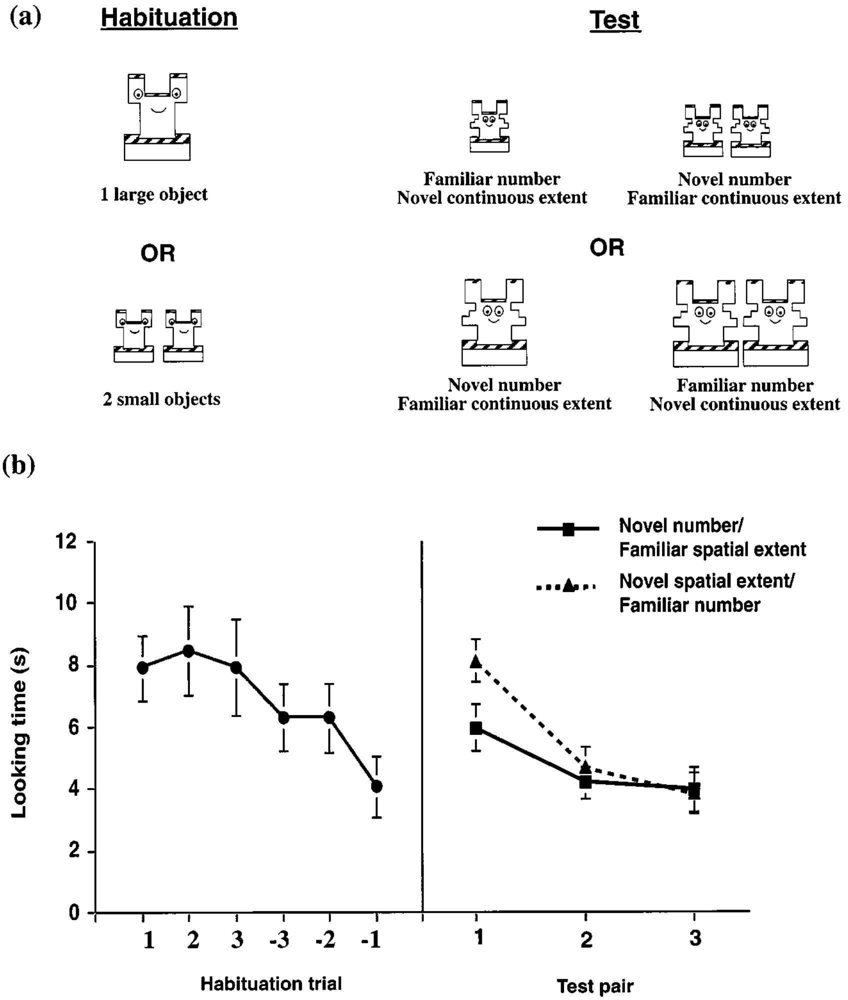

FIG. 2. (a) Displays and (b) looking times for Experiment 2, in which number was pitted against continuous extent.

in age from 6 months; 12 days to 7 months; 10 days ($M = 6$ months, 28 days). All participants were healthy infants from Ithaca, New York.

Apparatus and procedure. Infants sat in front of the same puppet stage and saw the same stimulus objects as in Experiment 1. Continuous extent was manipulated as a function of the area of the front surface of the objects, with the large objects having twice the front surface area of the small objects. Front surface area was chosen as the targeted measure of extent because objects were presented directly in front of infants, and therefore the front faces of the objects were most visible. Methods of presentation and criterion for habituation were the same as in Experiment 1. Average interobserver reliability was .95 across all trials for a random half of the participants.

Results

Paired *t* tests investigated whether infants dishabituated to either test display. Infants dishabituated only to the display that was novel in continuous extent (see Fig. 2b). Looking time to the average of the last three habituation trials was marginally different from looking to the first test display that was novel in extent, $t(1, 19) = -1.7$, $p < .054$, one-tailed, but was not different from the first test display that was novel in number, $t(1, 19) = -43$, $p < .34$, one-tailed.

A 2 × 2 × 2 × 3 repeated-measures ANOVA examined the effects of Habituation Condition (habituation to one large or two small objects), Test Type (one or two objects), Test Order (1,2,1,2,1,2 or 2,1,2,1,2,1), and Test Pair (first, second, or third) on infants' looking times during the test trials. Infants looked longer at the display that was familiar in number and novel in extent, seen as a Habituation Condition × Test Type interaction, $F(1, 16) = 4.81$, $p < .05$. Infants who were habituated to one object looked longer at one object during the test trials, and infants who were habituated to two objects looked longer at two objects. The ANOVA also yielded a main effect of Test Pair, with infants looking longer at the first test pair than on subsequent pairs, $F(2, 32) = 14.45$, $p < .001$. There was an interaction between Test Pair and Habituation Condition, $F(2, 32) = 3.44$, $p < .05$. This interaction resulted from infants who were habituated to two objects looking longer on the first test pair than infants who were habituated to one.

Finally, we compared the looking patterns obtained in Experiment 1 with those obtained in Experiment 2. A 2 × 2 × 2 × 3 ANOVA examined the effects of Experiment (Experiment 1 vs 2), Habituation Condition (habituation to one vs two), Test Type (novel number vs familiar number), and Test Pair on infants' looking times during the test trials. Infants in Experiment 1 looked longer at displays with a novel number, while infants in Experiment 2 looked less long at displays with a novel number. This was revealed in an Experiment × Test Type interaction, $F(1, 32) = 17.56$, $p < .001$. Only when number and continuous extent were confounded did infants look longer at displays that were numerically novel. The only other findings from this analysis were a main effect of Test Pair, $F(2, 64) = 20.94$, $p < .001$, with infants looking longest on the first test pair, and a three-way interaction between Experiment, Test Type, and Test Pair, $F(2, 64) = 6.72$, $p < .01$. No other main effects or interactions were significant.

Discussion

In Experiment 2, infants looked longer at the display that was novel in total front surface area than at the display that was novel in number. This suggests that infants represent one or more total continuous variable during habituation, and respond to changes in that variable during the test trials. Infants' longer looking at the displays that were novel in continuous extent could not have resulted from noticing a change in the size of the individual objects. Both displays involved objects of a different size compared to those seen during habituation; therefore noticing a change in object size would have resulted in equal looking times between the two test displays. Instead, infants looked longer at those displays that were novel in the amount of total front surface area contained in the array. Experiment 2 extends the findings by Clearfield and Mix (1999) to a one vs two comparison with real objects. Furthermore, we replicated their finding of no evidence for a response to the cardinal values of small set of objects. Although infants could have dishabituated to both test displays, they increased their looking only to the display that was novel in continuous extent.

Is it possible that infants' stronger response to continuous extent masked a weaker response to number? Perhaps pitting number against extent allowed infants to respond only on the basis of the more salient of the two dimensions. Although infants' failure to dishabituate to the numerically novel display casts doubt on this possibility, the next three experiments tested it directly. Experiments 3–5 controlled for changes in continuous extent while manipulating number. By equating the change in extent between test outcomes, we asked whether infants respond to a change in numerosity when that change does not covary with a change in continuous variables.

EXPERIMENT 3

Experiment 3 sought unambiguous evidence that infants respond to number. In order to avoid the possibility that an extent-based response would overwhelm a numerical response, the total front surface area of the test displays was equated so that both displays were equally novel in front surface area. Infants were habituated to either one or two objects of a new, intermediate size. The front surface area of the medium-sized objects (58.7 cm^2) was midway between that of the small (38.9 cm^2) and the large (80.5 cm^2) objects used in Experiments 1 and 2, so that the surface area of the medium object was approximately the arithmetic mean of the small and the large objects (see Figure 3a).

Half of the infants were habituated to one medium-sized object and tested with one small vs two small objects. Note that in both the one-object and the two-object test displays, continuous extent is novel. In the one-object display, the total front surface area of the one small object seen during test is *less than* that of the one medium-sized object seen in habituation. In the two-object display, the total front surface area of the two small test objects is *more than* that of the one medium-sized habituation object. The difference in front surface area between each test display and habituation is equal. Therefore, if infants only dishabituate to a change in total front surface area, there should be no difference in looking to these two displays, since both

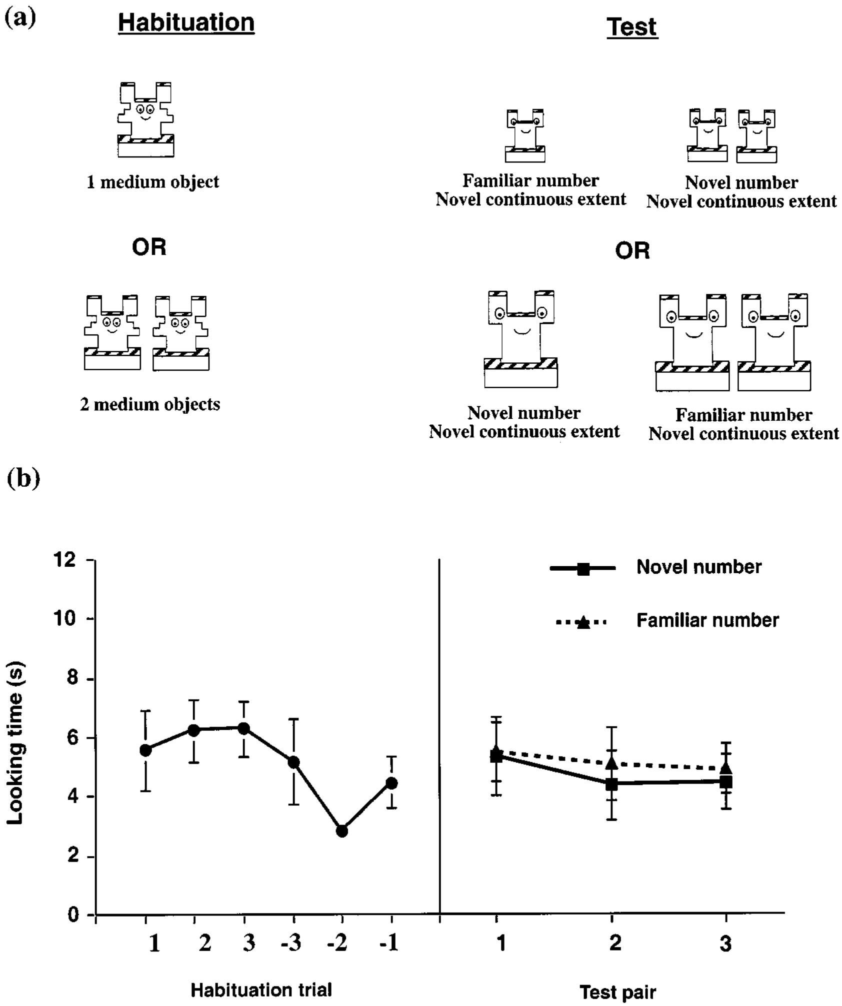

FIG. 3. (a) Displays and (b) looking times for Experiment 3, in which continuous extent was controlled for.

represent a novel extent. However, only the two-object display is novel in number.

The other group of infants was habituated to two medium-sized objects and tested with one large vs two large objects. Again, both test displays are novel in total front surface area: 1 large object has less total front surface area than the two medium-sized objects seen during habituation, while two large objects have more total front surface area. Therefore, responding to a change in total front surface area alone would produce no difference in looking to these displays, whereas responding to a change in number would be revealed in longer looking at the arrays that were novel in number.

Method

Participants. Sixteen infants participated (8 boys and 8 girls). One additional infant was excluded from the analysis for being more than 21 days premature. Infants ranged in age from 6 months;21 days to 7 months;14 days (M = 7 months;2 days). All participants included in the analysis were healthy infants from the New York City area.

Apparatus and procedure. Infants sat in front of the same puppet stage and saw the same objects as in Experiments 1 and 2 in addition to new objects of an intermediate size. These medium-sized objects were approximately 11 cm high, 8 cm wide, and 6.5 cm deep. The average front surface area of the medium-sized objects was 56.0 cm^2. Methods of presentation and coding were the same as in Experiments 1 and 2, and average interobserver reliability was .94 across all trials for a random half of the participants.

Results

Infants did not dishabituate to the novel number (see Figure 3b). There was no increase in looking to either the display that was novel in number and extent, $t(1, 15) = -.675$, $p < .26$, one-tailed, or to the display that was familiar in number and equally novel in extent, $t(1, 15) = -.722$, $p < .24$, one-tailed.

A $2 \times 2 \times 2 \times 3$ repeated-measures ANOVA examined the effects of Habituation Condition (habituation to one medium or two medium objects), Test Type (one or two objects), Test Order (1,2,1,2,1,2 or 2,1,2,1,2,1), and Test Pair on infants' looking times during the test trials. No significant influences on looking were found. Most importantly there was no preference to look at the test displays that were novel in number, as seen by the absence of a significant Habituation Condition × Test Type interaction, $F(1, 12) = 3.39$, $p = .09$. Furthermore, the observed trend resulted from infants looking longer at the *familiar* number of objects. No other main effects or interactions were significant.

Discussion

Experiment 3 yielded no evidence for a response to the cardinal values of sets. When continuous extent was equated between test trials, looking time to the outcomes in which number was novel was not different from those in which it was familiar. Also, infants did not dishabituate to either type of trial, both of which were novel in extent.

One might ask why we failed to find dishabituation in Experiment 3, since both test arrays were novel in continuous extent, and since Experiment 2 demonstrated that infants can dishabituate to changes in extent. The continuous extent encoded during habituation in Experiment 3 was intermediate between that encoded in habituation in Experiments 1 and 2. Therefore, the change in extent between habituation and test trials in Experiment 3 was not as great as it was in Experiments 1 and 2. In both Experiments 1 and 2, the average change in front surface area was about 60 cm^2. This is approximately double the change in Experiment 3, in which the average change in front surface area was about 30 cm^2. This smaller change was likely insufficient to cause dishabituation.

Infants did not respond to number in Experiment 3, but the method used here differed in one important way from other experiments that have reported a positive response to number (e.g., Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Van Loosbroek & Smitsman, 1990). In Experiment 3, both the number of objects and the total extent were constant on every habituation trial. This contrasts with other procedures in which infants saw a constant number but varying extent during habituation. This procedural difference may have been important, as keeping only number constant during habituation might serve to cue infants that number is a relevant variable.

Earlier studies using this method of varied habituation (Strauss & Curtis, 1981, Starkey et al., 1990, Van Loosbroek & Smitsman, 1990) did not fully control for continuous extent. Simply varying stimulus size over habituation does not suffice because infants may have habituated to the average extent of all the habituation stimuli. Because the test displays that were novel in number were also, on average, novel in extent, and at least sometimes outside of the range of the extents of the habituation items, infants' performance cannot be definitively attributed to a numerical response. Experiment 4 tested the hypothesis that varying continuous extent during habituation and controlling for extent across test trials would result in a clear numerical response.

EXPERIMENT 4

Experiment 4 controlled for continuous extent in the test phase in the same manner as in Experiment 3, but varied continuous extent throughout habituation. Infants were habituated to objects of three sizes (large, medium, and small) and tested with displays that were equally different in total front surface area from the average seen during habituation. Because the front surface area of the test objects was within the range seen over habituation, the novelty of the continuous extents of the test arrays was minimal. This was done to increase the likelihood that infants would show an unambiguous response to number.

An additional issue addressed in Experiment 4 was the method for equating this change. In Experiment 3, the total front surface area of test displays was equated in arithmetic distance. That is, the one- and two-object displays differed by approximately the same number of square centimeters from the habituation average. For infants habituated to one object, for instance, both the one- and two-object displays were smaller by about 20 cm^2. However, evidence from the animal literature suggests that the geometric mean, rather than the arithmetic mean, is perceived as the midpoint between two quantities (Meck & Church, 1983). The ratio of the difference between two numbers or quantities,

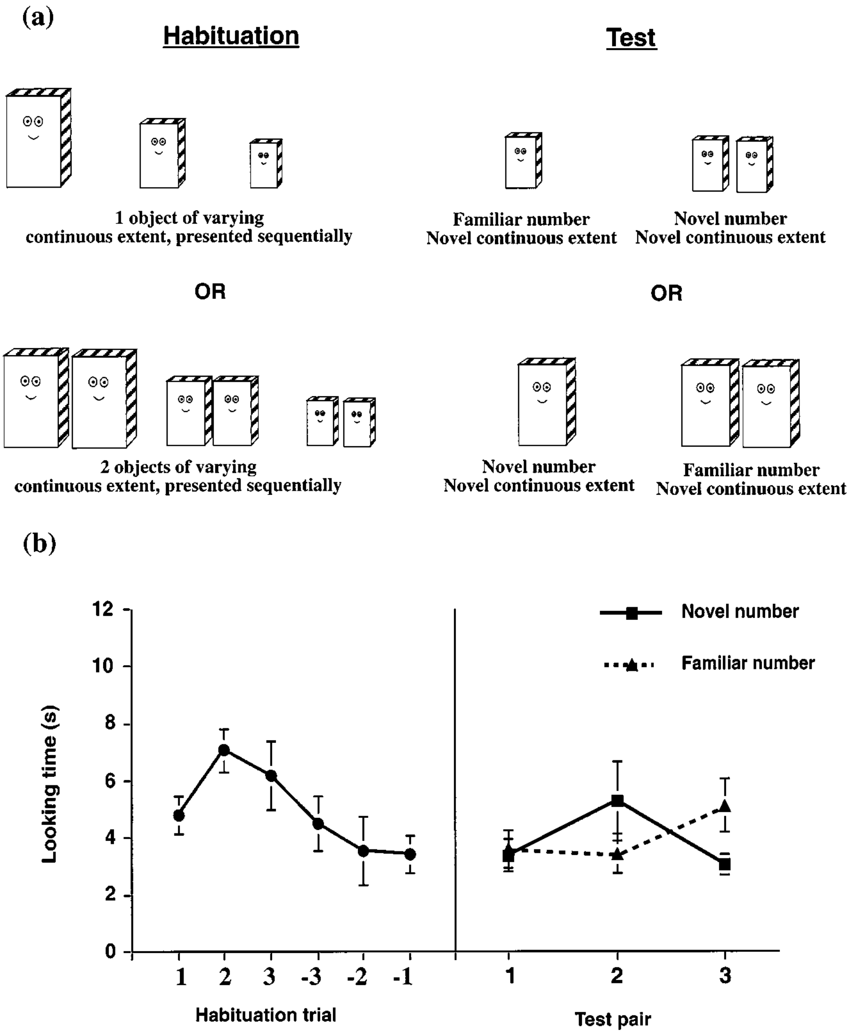

FIG. 4. (a) Displays and (b) looking times for Experiment 4, one vs two, in which continuous extent was controlled for and habituation was to varied continuous extents.

and not the absolute difference, appears to be the more relevant factor. Therefore, Experiment 4 equated the change in the proportion of total front surface area rather than that in the absolute number of square centimeters.

A new set of objects was constructed for this experiment. The objects were simple rectangular solids to allow for more precise control of front surface area. Objects were five sizes of foam blocks. The smallest, largest, and middle objects were presented during habituation (see Fig. 4a). The average total front surface area of the habituation array was 92.3 cm^2 for infants habituated to one object, and 184.6 cm^2 for infants habituated to two objects. Infants habituated to 1 object were tested with objects each with a front surface area of 63.8 cm^2, and infants habituated to two objects were tested with larger objects, each with a front surface area of 127.1 cm^2. For infants in both habituation conditions, the change in total front surface area from the habituation average to both the numerically novel display and the numerically familiar display was approximately 30%. In this way, Experiment 4 follows the design of Experiment 3, with three changes: habituation stimuli varied in total front surface area from trial to trial, test objects were adjusted to the habituation average rather than to a single value, and change was equated as a proportion.

Method

Participants. Sixteen infants participated (6 boys and 10 girls). Four additional infants were excluded from the analysis, 2 because they were more than 21 days premature, 1 whose looking times exceeded the mean by greater than 3 standard deviations, and 1 who became fussy during testing. Infants ranged in age from 6 months;13 days to 7 months; 11 days (M = 6 months;28 days). All participants included in the final analysis were healthy infants from the New York City area.

Apparatus and procedure. Infants sat in front of the same puppet stage as in Experiments 1, 2, and 3. New objects were used. The large habituation objects were 17.1 × 8.5 × 8.5 cm (front surface area 150.5 cm^2), the medium habituation objects were 13 × 6.4 × 6.4 cm (front surface area 83.2 cm^2), and the small habituation objects were 9 × 4.8 × 4.8 cm (front surface area 43.2 cm^2). The test objects were 11.4 × 5.6 × 5.6 cm (front surface area 63.8 cm^2) and 15.5 × 8.2 × 8.2 cm (front surface area 127.1 cm^2). The objects were made of painted foam and had eyes and a mouth to attract infants' attention. Because there was no effect of object color in the previous experiments, blue and green objects were used for all habituation trials and red objects for all test trials. Habituation objects alternated in color (blue and green) and in front surface area (small, medium, and large). Methods of presentation and coding were the same as in the previous experiments, with the exception that infants were allowed a maximum of 15 habituation trials rather than 12. This limit was increased from Experiments 1–3 because the varied extent during habituation was expected to increase the length of time infants needed to achieve habituation. The number of habituation trials infants saw was always a multiple of 3. This was done so as to ensure that all infants saw the same average front surface area over the course of habituation (recall that there were three different sizes of habituation objects such that total front surface area varied between trials). Thus, if infants reached the habituation criterion on the 10th trial, for example, 2 additional habituation trials were presented before the test trials began. Interobserver reliability was .95 across habituation and test trials for a random half of the participants.

Results

Infants did not dishabituate to the novel number (see Fig. 4b). There was no increase in looking to the display that was novel in number and in extent, $t(1, 15) = -1.3$, $p < .11$, one-tailed, or the display that was familiar in number and equally novel in extent, $t(1, 15) = -1.3$, $p < .12$, one-tailed.

A 2 × 2 × 2 × 3 repeated-measures ANOVA examined the effects of Habituation Condition (habituation to one or two objects), Test Type (one or two objects), Test Order (1,2,1,2,1,2 or 2,1,2,1,2,1), and Test Pair on infants' looking times during test trials. The ANOVA revealed no preference for the test displays that were novel in number. There was a Habituation Condition × Test Pair interaction, indicating that infants habituated to 1 object looked longer on the second test pair, while infants habituated to 2 objects looked longer on the third test pair, $F(1, 11) = 5.43$, $p < .05$.

Discussion

Varying continuous extent over the course of habituation did not lead infants to respond to the number of objects in these displays. Rather, Experiment 4 confirmed the results of Experiment 3, in which infants neither looked longer at nor dishabituated to the novel number of objects.

Because the particular comparison tested here, one vs two objects, has not previously been empirically explored, it is possible that the one vs two comparison caused the absence of a significant looking preference. This possibility is unlikely because infants dishabituated to the change between one and two objects in Experiment 1, in which number and continuous extent were confounded. Experiment 5 nevertheless addressed this possibility directly by presenting infants with the standard two vs three comparison and testing for their response to number using the method of Experiment 4.

EXPERIMENT 5

Participants. Sixteen infants participated (7 boys and 9 girls). Four additional infants were excluded from the analysis, 2 because they were more than 21 days premature, 1 whose looking times exceeded the mean by greater than 3 standard deviations, and 1 who became fussy during testing. Infants ranged in age from 6 months;13 days to 7 months;11 days ($M = 6$ months; 28 days). All participants included in the final analysis were healthy infants from the New York City area.

Apparatus and procedure. The procedure of Experiment 5 was identical to that of Experiment 4, but used a two vs three comparison. Continuous extent was controlled for in the same way as in Experiment 4 (see Fig. 5a). The average total front surface area seen over habituation was 184.6 cm^2 for infants habituated to two objects and 276.9 cm^2 for infants habituated to three objects. Infants habituated to two objects were tested with objects of a new $12.3 \times 6.14 \times 6.14$ cm size (front surface area 75.4 cm^2), and infants habituated to three objects were tested with objects of a new $15 \times 7.5 \times 7.5$ cm size (front surface area 112.5 cm^2). For infants in both habituation conditions, the change in total front surface area from the habituation average to both the numerically novel display and the numerically familiar display was approximately 20%. Methods of presentation and coding were the same as in the previous experiments. Interobserver reliability was .95 across habituation and test trials for a random half of the participants.

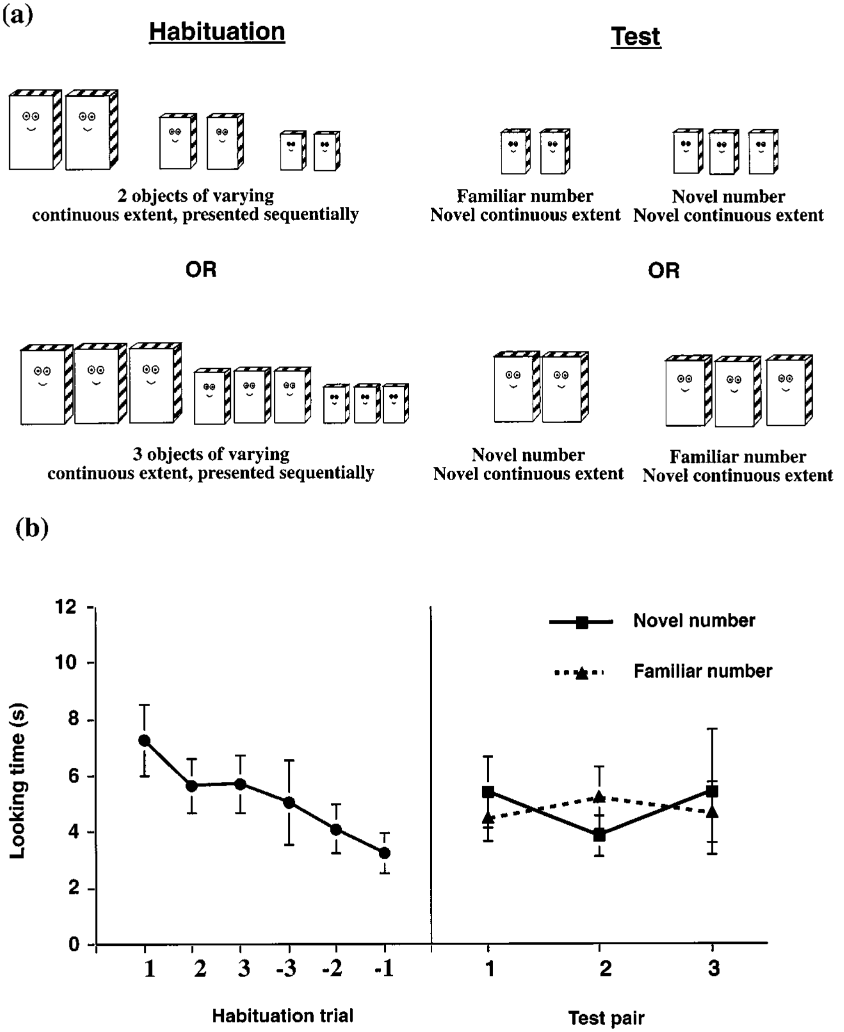

FIG. 5. (a) Displays and (b) looking times for Experiment 5, two vs three, in which continuous extent was controlled for and habituation was to varied continuous extents.

Results

Infants did not dishabituate to the novel number (see Fig. 5b). There was no increase in looking to either the display that was novel in number and extent, $t(1, 15) = -1.47$, $p < .09$, one-tailed, or to the display that was familiar in number and novel in extent, $t(1, 15) = -.46$, $p < .33$, one-tailed. The trend was, however, in the right direction, with infants showing a greater increase in looking to the test display that was novel in both number and extent.

A $2 \times 2 \times 2 \times 3$ repeated-measures ANOVA examined the effects of Habituation Condition (habituation to two or three objects), Test Type (two or three objects), Test Order (2,3,2,3,2,3 or 3,2,3,2,3,2), and Test Pair on infants' looking times during the test trials. The ANOVA revealed no preference for the test displays that were novel in number. The only significant finding was a three-way interaction between Habituation Condition, Test Type, and Test Pair, $F(2, 22) = 3.68$, $p < .05$. Only infants who were habituated to two objects looked longer at the novel number on the first and last test pairs.

The possibility that a small effect would not be found due to lack of power was explored by collapsing across Experiments 4 and 5, which differed only in the numerical change presented. A $2 \times 2 \times 2 \times 3$ ANOVA examined the effects of Experiment (Experiment 4 or 5), Test Type (novel number or familiar number), Test Order (novel number presented first or second), and Test Pair on infants' looking times during the test trials. No significant influences on looking were found, and most importantly there was no preference to look at the novel number, $F(1, 26) = .01$, $p < .94$.

Discussion

We found no evidence that infants dishabituated to the numerical change between 2 and 3. This confirms the findings of Clearfield and Mix (1999) and throws into doubt that number is a relevant variable in any of the habituation studies using small sets of visible objects.

Although infants dishabituated to the novel continuous extent (and not to the novel number) in Experiment 2, they failed to dishabituate to changes in extent in Experiments 3, 4, and 5. Again, we suggest that this lack of response derives from the fact that (a) the change in extent between habituation and test was smaller in Experiments 3, 4, and 5 than it was in Experiment 2; and (b) continuous extent was varied during habituation in Experiments 4 and 5, leading infants to habituate to changes in this variable.

Evidence that infants were, in fact, encoding continuous extent comes from their patterns of habituation. In Experiments 1, 2, and 3, infants saw a single continuous extent throughout habituation. This contrasts with Experiments 4 and 5, in which infants saw three different extents during habituation. If infants encode any variable that correlates with continuous extent, then varying extent during habituation should increase the number of trials needed to achieve the habituation criterion. This was the case. When a single extent was presented during habituation, 38 of 56 infants (67.5%) habituated within 12 trials (collapsed across Experiments 1, 2, and 3). When extent varied, only 15 of 32 infants (46.9%) habituated within the same number of trials (collapsed across Experiments 4 and 5). It was for this reason that the maximum number of habituation trials in Experiments 4 and 5 was increased to 15; 23 of 32 infants (71.9%) met the habituation criterion by this point, comparable to the percentage of infants who habituated by 12 trials in Experiments 1–3.[4] These habituation patterns suggest that infants indeed represented total front surface area or some correlated dimension of continuous extent, but that the change in extent between habituation and test was not large enough to cause dishabituation. Despite this indirect evidence for sensitivity to continuous extent, there was again no evidence for a response to number.

As discussed above, the habituation procedure may provide different opportunities for encoding than other methodologies. Habituation provides a long period in which to encode the physical properties of stimuli. In Experiments 1–5, objects remained visible for 1 to 60 s on every trial, and infants saw at least 6 and up to 15 habituation trials. Infants in number experiments do not always have such lengthy visual access to objects. In Wynn's transformation studies objects appear very briefly before they are occluded, allowing only a few seconds to encode individual object properties. Furthermore, infants never see an array with the total continuous extent of the transformation outcome because the transformation occurs behind an occluding screen. It is possible that limiting the length of time that objects are visible or the exposure to the outcome may affect which aspects of the array are encoded. When physical properties such as size and color are only briefly available, infants may represent only the number of individuals rather than the total continuous extent.

Experiments 6 and 7 test this hypothesis. Experiment 6 replicates Wynn's (1992) findings with 7-month-old infants and with the stimuli used in Experiments 1–3. Experiment 7 asks whether infants' expectations in the transformation paradigm were based on number or on extent.

EXPERIMENT 6

Experiment 6 validates our procedure by replicating the standard transformation experiment. Following the procedure of Wynn (1992), infants were presented with addition or subtraction events. Infants saw a single size of object throughout the experiment, leaving number and continuous extent completely confounded (see Fig. 6a). Half of the infants saw an addition event in which one small object + one small object resulted in two small objects (expected in both number and extent) vs one small object (unexpected in both number and extent). The other group of infants saw a subtraction event in which two large objects − one large object resulted in one large

[4] Failure to respond to numerical changes in Experiments 4 and 5 was not, however, due to insufficient habituation by the infants who did not meet the habituation criterion. Difference scores for both infants who habituated and for infants who did not were calculated between average looking time to the last three habituation trials, and to the first novel-number and familiar-number test trials. The increase in looking to either trial type was not different for habituators (novel number: +1.08 s vs familiar number: +1.53 s) and nonhabituators (novel number: +0.36 vs familiar number: +0.20 s).

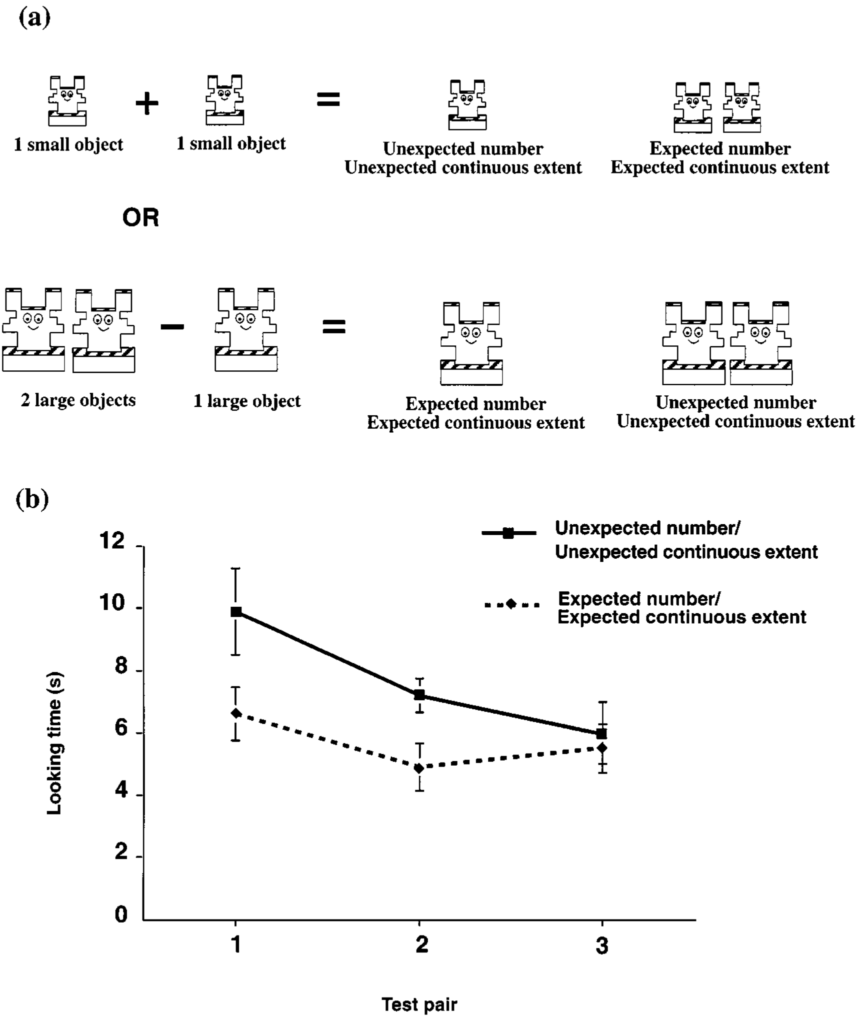

FIG. 6. (a) Displays and (b) looking times for Experiment 6, array transformations in which number and continuous extent were confounded.

object (expected in both number and extent), vs two large objects (unexpected in both number and extent).

Method

Participants. Sixteen infants participated (10 boys and 6 girls). Three additional infants were excluded from the analysis, two due to fussiness, and one whose parent influenced looking during the session. Infants ranged in age from 6 months;15 days to 7 months;16 days (M = 7 months;2 days). All participants were healthy infants from the New York City area.

Apparatus and procedure. Infants sat in front of the same puppet stage as in Experiments 1–5. The stimuli were the small (front surface area 38.9 cm^2) and large (80.5 cm^2) Lego objects from Experiments 1–3. Infants were randomly assigned to either the addition or subtraction condition. The experiment began with two baseline trials to assess any initial preference to look at one or two objects. The experimenter lowered the screen to reveal one object on the stage, and looking time was recorded. The trial began when infants looked at the stage area for at least 0.5 s and lasted until they looked away for at least 2 continuous s. When the trial ended, the experimenter raised the screen, placed an additional object on the stage out of the infant's view, and lowered the screen again. Order of presentation (one or two objects first) was counterbalanced across infants, and the color and shape of the object seen during the baseline trials was always different from the color seen during the test trials. Object size remained constant throughout all phases of the experiment.

Following baseline trials, infants saw six transformation trials. The outcomes of these trials alternated between expected and unexpected, with object color and order of outcome presentation counterbalanced across participants. Each trial began with an empty stage. Infants in the addition condition saw the experimenter's hand emerge from the opening on the left side of the stage, holding a small object. The experimenter said, ''(Baby's name), look at this,'' and made certain that the infant was attending to the object. She placed the object in the center of the stage and withdrew her hand and then raised the screen to hide the object from the infant's view. Then the experimenter's hand reappeared holding a second, identical object. The experimenter said, ''(Baby's name), look at this,'' and again made certain that the infant saw the object. Her hand passed behind the screen and reemerged empty. The screen was lowered to reveal either one or two small objects, and infants' looking was recorded according to the same criteria used in the baseline trials. Infants saw objects of only one color throughout the test trials, different from that seen in the baseline trials.

Infants in the subtraction condition saw a similar sequence of events. The experimenter placed two large objects sequentially on the stage. The screen was raised to cover them, and the experimenter's hand reentered the stage. The experimenter made certain the infant saw her empty hand and then passed her hand behind the screen and re-emerged holding a large object. The experimenter said, ''(Baby's name), look at this,'' and removed the object through the opening in the stage. The screen was then lowered to reveal either one or two large objects. Methods of coding were the same as in Experiments 1–5. Average interobserver reliability was .93 across baseline and test trials for a random half of the participants.

Results

Infants showed no preference to look at one or two objects during the baseline trials. Infants looked for an average of 9.3 s ($SD = 7.3$) at the one-object display, and 9.2 s ($SD = 9.4$) at the two-object display, $t(1, 15) = .034$, $p < .97$. Infants in both the addition and subtraction conditions preferred the unexpected outcomes of the transformation trials (see Fig. 6b). A $2 \times 2 \times 2 \times 3$ ANOVA examined the effects of Transformation Condition (addition vs subtraction), Test Order (1,2,1,2,1,2 vs 2,1,2,1,2,1), Outcome Type (expected vs unexpected), and Test Pair on looking times. There was a main effect of Outcome Type, $F(1, 18) = 4.83$, $p < .03$, one-tailed. This reflects that infants in both conditions looked longer at outcomes that were unexpected in number and extent than at those that were familiar in both. The only other significant finding was a main effect of Test Pair, $F(1, 16) = 8.99$, $p < .01$, two-tailed. Infants looked longest on the first test pair, and looking time decreased as the experiment progressed.

Discussion

Experiment 6 confirms the finding that infants look longer at the unexpected results of simple transformations. However, Experiment 6 includes the same confound as other transformation studies. Because number is confounded with continuous extent, the outcome that is expected on the basis of number is also expected on the basis of total front surface area, total surface area, total volume, total contour length, and all other correlated variables. Only by unconfounding number and extent can we determine whether infants' expectations are based on a representation of cardinal values.

EXPERIMENT 7

Experiment 7 separates the transformation outcomes so they are expected on the basis of either number *or* continuous extent, but not both (see Fig. 7a). Infants in the addition condition saw one small object + 1 small object, just as in Experiment 6. The difference lies in the test outcomes. On half of the trials one small object + one small object resulted in two large objects. In this case, the total number of objects is expected, since 1 + 1 indeed equals 2. But the total front surface is unexpected: Each object is larger, so the total front surface area is twice as much as would be expected ($38.9\ cm^2 + 38.9\ cm^2 \neq 161.1\ cm^2$). The other half of the time, one small object + one small object resulted in one large object. In this outcome, the total number of objects on stage is now unexpected, since $1 + 1 \neq 1$, but the total front surface area is expected. Since the front surface area of two small objects combined is approximately the same as that of the single large object, the one-object outcome represents the expected total front surface area ($38.9\ cm^2 + 38.9\ cm^2 \approx 80.5\ cm^2$).

Simon et al. (1995) report a transformation study using a similar design, manipulating the variable of object identity rather than continuous extent. To determine whether infants were forming specifically numerical expectations, as opposed to expectations about whether an outcome was physically possible, Simon et al. showed infants one Ernie doll + one Ernie doll. Test outcomes were two Ernies (expected in number and identity), one Ernie and one Elmo (expected in number, unexpected in identity), one Ernie (unexpected in number), or one Elmo (unexpected in both). In this study, unexpected number drove infants' responding, whereas unexpected identity did not. Infants looked longer at the numerically unexpected outcomes, but there was no increase in looking to outcomes in which the identity of the objects had been switched. The numerically unexpected outcomes were also unexpected in continuous extent, however, and changes in extent may be more salient than the change in identity from Ernie to Elmo, where the toys are complex objects. Therefore, the question remains open as to whether infants use continuous extent in forming expectations about object transformations in the Wynn paradigm.

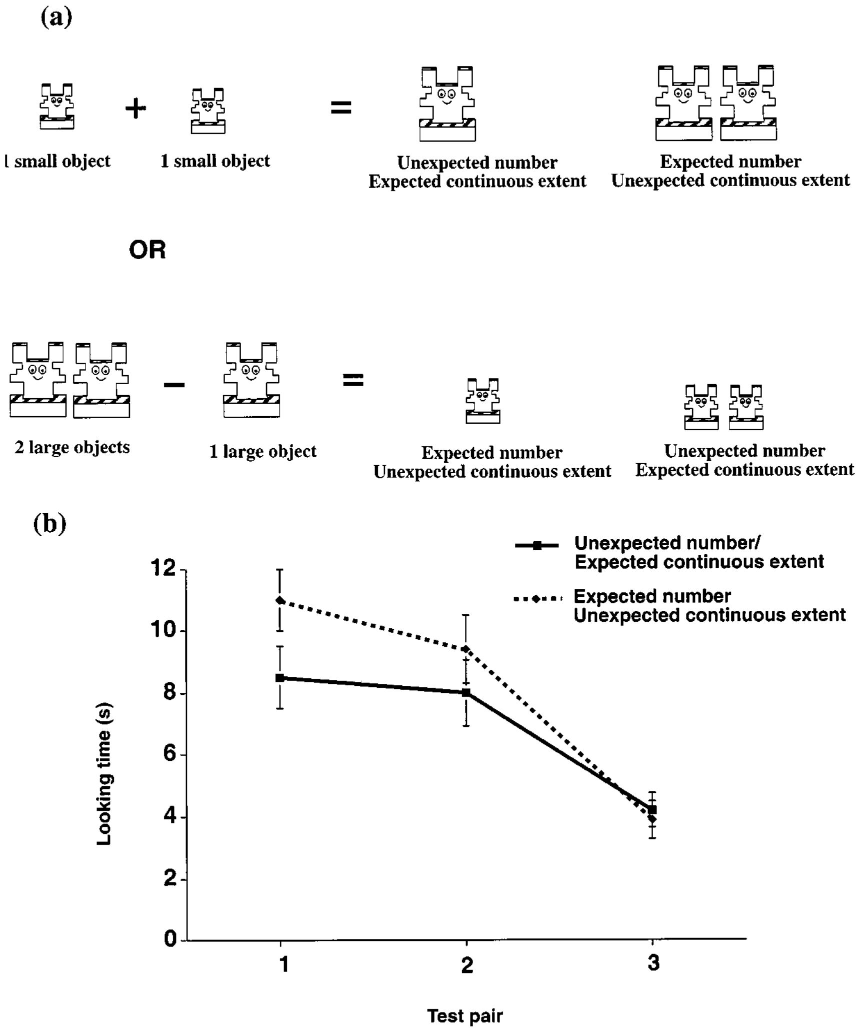

FIG. 7. (a) Displays and (b) looking times for Experiment 7, array transformations in which outcomes expected in number were pitted against outcomes expected in continuous extent.

Method

Participants. Sixteen infants participated (9 boys and 7 girls). Five additional infants were excluded from the analysis, 1 due to fussiness, 1 due to experimental error, 2 whose parents were judged to have influenced looking during the session, and 1 who did not look at the display. Infants ranged in age from 6 months;13 days to 7 months;15 days (M = 6 months; 30 days). All participants were healthy infants from the New York City area.

Apparatus and procedure. Infants sat in front of the same puppet stage and saw the same stimulus objects as in the previous experiment. Methods of presentation were the same, with the exception of the transformation outcomes. Unlike in Experiment 6, trials did not alternate between the simple ''expected'' and ''unexpected'' outcomes. Instead, they alternated between meeting expectations on the basis of number and meeting expectations on the basis of total front surface area. Methods of presentation and coding were the same as in Experiment 6, with each infant seeing objects of one color during the baseline trials, and objects of a different but constant color during the transformation trials. Baseline objects were of the same size as the outcome objects. Inter-observer reliability was .94 across baseline and test trials for a random half of the participants.

Results

As in Experiment 6, infants showed no preference to look at 1 or 2 objects during the baseline trials, $t(1, 15) = 1.4$, $p < .20$. Infants looked for an average of 6.8 s (SD = 4.5) at the one-object display, and 5.5 s ($SD = 3.9$) at the two-object display. For the transformation trials, infants looked longer at the outcomes that were unexpected in continuous extent (see Fig. 7b). A $2 \times 2 \times 2 \times 3$ ANOVA examined the effects of Transformation Condition (addition or subtraction), Test Order (1,2,1,2,1,2 or 2,1,2,1,2,1), Outcome Type (expected in number or expected in extent), and Test Pair. There was a main effect of Outcome Type, with infants looking longer at outcomes that were unexpected in extent than those that were unexpected in number, $F(1,8) = 5.56$, $p < .05$, two-tailed. There was also a main effect of Test Pair, $F(1, 16) = 3.64$, $p < .05$, with infants looking least on the last test pair. No other main effects or interactions were found.

The pattern of looking in Experiment 7 was significantly different from that in Experiment 6, when number and extent were confounded. A $2 \times 2 \times 2 \times 2 \times 3$ ANOVA examined the effects of Experiment (Experiment 1 or Experiment 2), Outcome Type (expected or unexpected in number), Transformation (addition or subtraction), Test Order (1,2,1,2,1,2 or 2,1,2,1,2,1), and Test Pair on infants' looking times during the test trials. The analysis revealed a marginally significant Experiment × Outcome Type interaction, $F(1, 19) = 4.83$, $p < .053$, two-tailed, showing that whether infants looked longer at the numerically unexpected outcome depended on whether number and extent were confounded. When number and extent were confounded in Experiment 6, infants looked longer at the outcomes that were unexpected in number and extent than at outcomes that were familiar on both counts. When number and extent were unconfounded, infants looked less long at the outcomes that were unexpected in number than at those that were unexpected in extent. The only other effect was a main effect of Test Pair. Infants' looking declined significantly as the experiment progressed, $F(2,38) = 9.4$, $p < .001$, two-tailed.

Discussion

Experiment 7 extends the findings of Experiments 2–4, providing no evidence for a response to number. This is a surprising result, given that the transformation task was designed to assess numerical knowledge and that previous findings have been interpreted as evidence for such knowledge. In studies that confound number and continuous extent, infants look longer when 1 + 1 = 1 and when 2 − 1 = 2 (Experiment 6 in this series; Koechlin et al., 1998; Simon et al., 1995; Uller et al., 1999; Wynn, 1992). Eliminating the confound resulted in a different pattern: infants looked longer when 1 + 1 = 2 than when 1 + 1 = 1. In this situation, the numerical outcome is expected but the visible surface area has doubled. It was to this violation of continuous extent that infants appeared to respond.

The convergence of these transformation results with the habituation results from Experiments 1–5 is especially striking given the procedural differences between the two tasks. In habituation studies, infants have extensive visual access to the continuous extent of the object array, allowing them ample opportunity for encoding. In transformation studies, on the other hand, infants never see the resulting continuous extent when one object is added to (or subtracted from) an existing, briefly presented array.

GENERAL DISCUSSION

In the present studies, we asked whether phenomena that had been taken as evidence that infants encode the number of objects in array might instead reflect sensitivity to some continuous stimulus dimension of the array. These experiments were not designed to explore which dimensions of continuous extent infants are sensitive to. We manipulated total front surface area of three-dimensional objects and in doing so manipulated other dimensions that were correlated with total front surface area, such as volume, contour length, total spatial envelope, and brightness of the array. All were dissociated from number in our experiments. Experiment 1 replicated the standard finding of dishabituation to changes in number and extent when the two covary. The next four experiments examined infants' responses when number was isolated from total front surface area and correlated continuous dimensions. Experiment 2 suggests that infants represent one or more dimensions of continuous extent: Infants dishabituated to a change in the total front surface area of an array, providing a conceptual replication of Clearfield and Mix (1999). However, there was no evidence in any of the experiments that infants respond to changes in number. Infants did not dishabituate to a change in number in Experiment 2, and when changes in continuous extent were equated across test trials in Experiment 3, there was no difference between looking to displays that were novel in number and those that were familiar in number. In Experiment 4, varying continuous extent over habituation did not induce a numerical response to a one vs two change either, and Experiment 5 extended this finding to a two vs three comparison. This pattern of results is supported by Experiments 6 and 7, which tested infants in a transformation paradigm. When number and extent covaried, infants differentiated outcomes that were unexpected in both number and extent from those that were expected in both. But when the two were unconfounded, infants again looked longer at the outcome with unexpected continuous extent than at that with unexpected number.

Thus, contrary to our expectations, infants presented with small sets of three-dimensional objects in which continuous extent was controlled for did not demonstrate sensitivity to number, either in the habituation or the transformation paradigm. These results contrast with positive demonstrations of numerical ability in which infants discriminate numbers of large sets such as 8 vs 16 and 16 vs 32 dots (Xu & Spelke, 2000; Xu, 2000), collections of dots (Wynn & Bloom, 1999), syllables (Bijeljac-Babic et al., 1991), and puppet jumps (Wynn, 1996), where number was not confounded with continuous extent. How might we reconcile the lack of a numerical response in the present series of experiments with these successes?

Here we turn to the models that have been proposed to account for numerical ability. One possible mechanism for encoding number is the analog-magnitude model first offered by Meck and Church (1983) to account for findings from the animal literature (see also Dehaene & Changeux, 1993; Gallistel & Gelman, 1992; Wynn, 1995). In this model, the number of individuals in a set is represented by a neural magnitude that is proportional to number. Number is represented as on a number line. A variety of analog-magnitude models have been proposed, differing in the process by which the underlying magnitude is computed. The best known is Meck and Church's ''accumulator'' model, which will suffice to illustrate how these models work (but see Church & Broadbent, 1990, and Dehaene & Changeux, 1993 for alternative analog-magnitude models). The accumulator model proposes a stream of impulses, a gate, an accumulator, and a readout mechanism. Each time the infant sees an item to be enumerated, the gate allows a fixed burst of impulses into the accumulator. The more items to be enumerated, the more ''energy'' stored in the accumulator. After the infant has seen the last item to be enumerated, the readout mechanism stores the resulting magnitude in memory; this magnitude represents the number of items in the set. Analog-magnitude representations of number clearly were not implicated in the present series of tasks. If infants were storing an accumulator value and evaluating test arrays on the basis of accumulator value matches or mismatches, there should have been a response to number. Instead, we found converging evidence for a lack of numerical response.

An alternative class of models, termed the ''non-numerical'' model by Simon (1997), the ''object-file'' model by Uller et al. (1999), and the ''object-indexing'' model by Leslie, Xu, Tremoulet, and Scholl (1998) suggests that infants may succeed in some ''number'' tasks via a nonnumerical (or ''protonumerical'') method. The model posits that infants use a mental token to represent each to-be-enumerated item. These tokens derive from a general object-tracking attentional mechanism such as Treisman's ''object-files''

(Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992) or Pylyshyn's ''FINSTs'' (Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999). There appears to be an upper limit of three or four object-files available at any one time. In the case of Wynn's original transformation experiments (1992), infants would activate one token (hereafter termed ''object-file'') for the first mouse and then activate another when a mouse is added. Infants now have two object-files open. When the screen drops and only one mouse is present, infants align their mentally stored object-files with the object on the stage, compare on the basis of one-to-one correspondence, and find a mismatch. Longer looking time is due to the numerical mismatch between the object-file representations (or attentional indexes, see Leslie et. al, 1998) and the actual visible outcome. This model too finds no support in our present data. There was no evidence of comparisons among sets on the basis of one-to-one correspondence, for infants did not respond to novelty in the habituation paradigm on the basis of numerical mismatches, nor did they respond to violations of numerical expectancies in the transformation tasks.

If infants were using neither an analog-magnitude nor an object-file representation in the habituation and transformation tasks, then what accounts for our pattern of results? Recall that in Experiments 1 and 6, in which number and continuous extent were confounded, infants demonstrated a response to the change between habituation and test trials. In Experiments 2 and 7, when number and extent were pitted against each other, infants responded to the change in continuous extent only. One possibility is that infants kept a ''running total'' of some variable of continuous extent during the experiment. That is, perhaps infants incremented an accumulatorlike mental device, but rather than incrementing once per each item, they incremented according to some measure of continuous extent, thereby increasing the magnitude more for larger items than for smaller items. This would allow infants to compare the total extent stored in memory with that present on stage.

Several findings suggest that this type of running total does not underlie infants' behavior. First, Starkey and Cooper (1980) demonstrated that infants discriminate two vs three visual items, but fail to distinguish four vs six. If infants were forming a running total of continuous extent, then a four vs 6 comparison should be no more difficult than a two vs three comparison. Second, infants in a $1 + 1$ transformation experiment by Uller (Uller, 1995) differentiated outcomes that were equally expected on the basis of extent. Infants saw one small block plus one small block and were presented with outcomes of two small blocks vs one large block. The one-large block consisted of two smaller blocks stacked together. Infants preferred this one-large-block outcome. If infants represented this event only as a running total of continuous extent, then the two outcomes were equally expected and therefore should have resulted in equal looking times. The fact that infants looked longer at the one-large block demonstrates that infants must have tracked more than only total extent in this task (in fact, infants probably responded to the sheer novelty of the never-before-seen one-large block). Together, these results lead us to reject the possibility that infants relied solely on a running total of continuous extent.

How, then, can we resolve the puzzle of infants' responses in our tasks and in previous number tasks? Above we rejected the object-file model as it has been formulated in the literature. However, we believe that a modification of the model can account for the present data, receives support from other data as well, and contributes to a resolution of the puzzle of when number is encoded by infants and when it is not. Suppose that when infants observe events involving small numbers of objects, they open one object-file for each object in the event. When spatiotemporal evidence concerning object individuation is available, as in all the present experiments, the number of object-files opened will be determined by such evidence. Spatially distinct objects, or objects moving on distinct trajectories, will be represented by separate object-files. Suppose also that the format of representation is imagistic and that once an object-file has been opened, information about an object's properties, such as its size, is bound to it. Such representations can be stored in working memory, and various computations can be performed over them. One such computation could be establishing one-to-one correspondence, as previous formulations of the object-file model have stated, but another could be comparison according to other properties of the images, including overall continuous extent of the objects in the images.

Two experiments, one with rhesus macaques (Hauser, Carey, & Hauser, 2000) and one with 10- and 12-month-old infants (Feigenson, Carey, & Hauser, 2000), provide evidence for this version of the object-file model. In these experiments, participants were shown items of food sequentially placed into two opaque containers (e.g., 1 + 1 into the left container; 1 + 1 + 1 into the right container). The dependent measure was which container was approached. Infants and monkeys succeeded in choosing the greater number when set sizes were small (in the case of infants, one vs two and two vs three) but failed with larger sets (three vs four and three vs six). It is the failure at three vs six that provides evidence for object file representations. The hallmark of analog-magnitude representations is their sensitivity to Weber's law; discriminability is a function of the ratio of the two quantities. A hallmark of object-file representations is their set-size signature: successful representation within the limits of parallel individuation and failure outside those limits. The ratio of 6:3 is larger than 3:2, yet infants fail at the former while succeeding at the latter, a result that is inconsistent with analog-magnitude representations. But because of the inherent limits on parallel individuation, and therefore the number of objects that can be represented in an object-file model, the object-file account predicts that performance will fall apart with numbers greater than three or so. In these choice experiments, then, the sets were represented by object-file models. However, as is rational given the task, infants' comparison of these representations was on the basis of total continuous extent. Given a choice between one very large cracker and two small ones, infants chose the single larger cracker, thereby maximizing the total quantity of edible food obtained. Thus, in computing the more/less relationship, infants relied on the property information bound to the object-files they had opened and not on one-to-one correspondence.

What these data show is that even though infants are comparing sets on the basis of total amount of cracker, they are not estimating the amount of each cracker and summing, for that would be an analog magnitude representation of amount, and infants should succeed at three vs six. Rather, they form object-file representations of the individuals in each set and then compare those representations on the basis of total continuous extent. Starkey and Cooper's (1980) demonstration that infants succeed at discriminating two vs three, but fail to distinguish four vs six is therefore predicted by this version of the object-file model. The object-file model explains infants' divergent performance in terms of the upper limit on available object-files. While two and three are within the range of object-file representations, four and six exceed the limit. Whether infants are comparing object-files via one-to-one correspondence (comparing number) or comparing the physical properties of the object-file representations (e.g., comparing continuous extent), once the limit has been exceeded the object-file representations themselves are not successfully created. In this way, the total number of objects presented can affect even nonnumerical comparisons.

The difference between the accumulator model and the object-file model is in their representational roles. The accumulator model (and other analog magnitude models of number representations) is a dedicated number representational system; it creates symbols for number alone. It has no other role in general cognitive function. Any information about the physical properties of a stimulus, such as size or color, is discarded within this system. The object-file model, on the other hand, has been suggested as a more general cognitive mechanism underlying object-based attention and working memory. While some numerical information is derivable from object-file representations, in the sense that one-to-one correspondence can be drawn between object-files, its primary purpose is not quantitative (as of now there is no direct evidence that infants compare object-files via one-to-one correspondence, but this is still an open question). Rather, it functions to track objects as they move and change. An important additional characteristic is that property information can be bound to an object-file once it has been opened.

What determines when the accumulator model is deployed and when object-files are deployed? We suggest that when small sets of objects are encountered, parallel individuation occurs and one object-file is created for each object in the visible set. In this case, number is not particularly salient (although numerical information could be derived from the representation in the form of one-to-one correspondence). Two occasions when an analog-magnitude mechanism is more likely to be deployed are (1) when the number of individuals grossly exceeds the limits of parallel individuation, and (2) when the stimuli are not objects. The cases reviewed above in which infants demonstrate sensitivity to number and in which dimensions of continuous extent were controlled for all fall into these categories (large number discrimination: Xu & Spelke, 2000; Xu, 2000; discrimination of sets of nonobject stimuli: Wynn & Bloom, 1999; Bijeljac-Babic et al., 1991; Wynn, 1996). When there are too many objects to be tracked using object-file representations, infants may instead rely on an analog-magnitude mechanism to represent large sets and their approximate cardinal values. When collections, sounds, or events are presented, object-files are unlikely to be opened because there are no objects to be tracked.

The present series of studies suggest that representations of surface area, or other continuous variables correlated with surface area, underlie infants' behavior in at least two types of tasks, both of which were thought to bear on numerical representations. These results force us to question the conclusion that number is easily and spontaneously encoded when infants view small sets of objects. Infants appear to rely on multiple mechanisms, some nonnumerical, in tasks that have been interpreted as addressing numerical competence.

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(Accepted February 3, 2001; published online July 19, 2001)