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The Difficulties of Representing Continuous Extent in Infancy: Using Number Is Just Easier

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This study investigates the ability of 6-month-old infants to attend to the continuous properties of a set of discrete entities. Infants were habituated to dot arrays that were constant in cumulative surface area yet varied in number for small (< 4) or large (> 3) sets. Results revealed that infants detected a 4-fold (but not 3-fold) change in area, regardless of set size. These results are in marked contrast to demonstrations that infants of the same age successfully discriminate a 2- or 3-fold change in number, providing strong counterevidence to the claim that infants use solely nonnumerical, continuous extent variables when discriminating sets. These findings also shed light on the processes involved in tracking continuous variables in infants.

The notion that preverbal infants have a capacity to represent number is not universally accepted (e.g., Clearfield & Mix, 1999, 2001; Mix, Huttenlocher, & Levine, 2002a, 2002b; Newcombe, 2002). Although a handful of studies from the early 1980s suggested that infants could discriminate small values such as 2 versus 3 (e.g., Antell & Keating, 1983; Starkey, Spelke, & Gelman, 1983; Strauss & Curtis, 1981), these results were subsequently challenged by findings indicating that infants do not discriminate number but instead attend to continuous variables, such as contour length and area (e.g., Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002). For example, Clearfield and Mix (1999) habituated 6-month-old infants to arrays of two or three squares with a constant total contour length. Infants were then tested with arrays that were familiar in number and novel in total contour length and that were novel in number and familiar in contour length. Infants looked longer at the arrays that contained the novel contour length/familiar number compared to the arrays with a novel number/familiar contour length and only dishabituated to the change in contour length. Feigenson et al. (2002) obtained similar findings with changes in cumulative surface area rather than contour length. Such studies suggest that infants may preferentially attend to continuous variables over number and have led some researchers to question whether infants ever make purely numerical judgments (e.g., Mix et al., 2002a, 2002b; Newcombe, 2002).

In contrast, other studies that have carefully controlled continuous variables have found that infants can in fact discriminate large numerosities when continuous variables are controlled (e.g., Brannon, 2002; Brannon, Abbott, & Lutz, 2004; Lipton & Spelke, 2003; Wood & Spelke, 2005; Xu, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). For example, when element size, cumulative surface area, and density were eliminated as cues, 6-month-old infants differentiated displays of 8 and 16 elements (Xu & Spelke, 2000). An important difference between the Xu and Spelke (2000) study and the Clearfield and Mix (1999) study is that Xu and Spelke's design emphasized number as the important variable to which infants should attend by holding number constant in habituation and varying area widely and thereby making area irrelevant. In contrast, the Clearfield and Mix study made no attempt to neutralize area or contour length as cues and instead held both number and contour length constant throughout habituation and asked which infants spontaneously represented.

A requirement for the view that infants attend preferentially to continuous variables over number is that they are capable of attending to a continuous property of a set of discrete entities. However, although it is often assumed that it is easier to extract continuous variables from a set than a seemingly abstract variable such as number, a recent study

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suggests that this may not always be true. Brannon et al. (2004) habituated 6-month-old infants to displays in which cumulative surface area was held constant but number varied fivefold (between 3 and 15) in order to neutralize number as a cue. In test, infants were presented with a twofold change in cumulative area and were unable to detect this change. This finding was in direct contrast to the finding that 6-month-old infants could successfully detect a twofold change in number when habituated to stimuli of a constant number that varied fivefold in area (replication of Xu & Spelke, 2000). In other words, 6-month-old infants detected a twofold change in number when area was widely varied in habituation but failed to detect a twofold change in area when number was widely varied in habituation.

In contrast, infants are much more facile at detecting a change in area of a single element compared to the cumulative area of an array of elements (Brannon, Lutz, & Cordes, 2006). Six-month-old infants were habituated to an Elmo face of a constant size and were then tested with a 1.5-, 2-, 3-, or 4-fold change in area (smaller or larger). Results revealed that infants required at least a twofold change in area in order to successfully detect the change and the magnitude of the novelty effect that increased across a 2-, 3-, and finally, 4-fold change in area. The juxtaposition of infant abilities to detect a twofold change in area of a single element but not a twofold change in the cumulative area of a varying number of elements suggests that a larger discriminability ratio may be necessary for successful detection of a change in cumulative area for multiple items. Alternatively, it is conceivable that infants are altogether unable to represent or attend to continuous extent variables when sets contain a large number of items.

The primary goal of this research is to determine whether infants are capable of forming summary representations of the continuous extent of a set of discrete entities and to compare infants' ability to discriminate area (for single elements vs. sets of discrete elements) and number. We examined this ability separately for exclusively small sets (less than four elements) and large sets because previous research suggests that infants may rely on two different systems to represent small and large numerosities (e.g., Feigenson, Dehaene, & Spelke, 2004; Xu, 2003). A discrete, precise, object-based representational system (the object file system) may be invoked when small numbers of objects are encountered (one to three in infants and one to four in adults). A second system is thought to represent sets as approximate, continuous analog magnitudes, and this system can handle large arrays as well as small arrays. These analog magnitudes are also putatively involved in the representation of other continuous quantities such as duration (Meck & Church, 1983; vanMarle & Wynn, 2006) and surface area (Brannon et al., 2006). Analog magnitude representations obey Weber's law; that is, the ease with which two values are discriminated is dependent upon their ratio, not their absolute difference (Gallistel & Gelman, 2000). We thus chose to examine small and large sets separately in case these distinct representational systems play a part in representations of continuous set variables. By doing so, this also allows us to examine the precision with which infants represent cumulative area as a function of set size, shedding light on the processes involved in cumulative area representation.

In Experiment 1, we demonstrate that as expected infants notice a threefold change in number when continuous variables are carefully controlled. In Experiment 2, we ask the parallel question of whether infants can detect a threefold change in cumulative area when number is carefully controlled and whether this differs for small and large sets. Given negative results in Experiment 2, we next ask whether infants can detect a fourfold change in cumulative area when number is carefully controlled and whether this differs for small and large sets. We find that infants can represent a 1:4 but not a 1:3 ratio change in cumulative area and that area discrimination is not affected by set size.

Experiment 1

Many previous studies have demonstrated that 6-month-old infants can successfully discriminate a twofold change in number while failing to discriminate a 2:3 ratio change (i.e., Brannon et al., 2004; Lipton & Spelke, 2003; Wood & Spelke, 2005; Xu & Spelke, 2000). If infants' numerical discriminations follow Weber's law, then any numerical changes greater than a 1:2 ratio should be detectable at 6 months of age. To lay the foundation for testing infants' ability to discriminate changes in cumulative surface area of discrete arrays, we thought it necessary to test whether infants could in fact discriminate a 1:3 change in number because no previous study used such widely disparate numerical values. Accordingly, we tested whether infants can discriminate 7 versus 21.

Method

Participants

Participants were 16 healthy full-term 6-month-old infants (mean age = 6 months 3 days, range = 5 months 18 days to 6 months 16 days) from the Raleigh/Durham area of North Carolina. Nine of the infants were female. Data from 1 additional infant were discarded for fussiness resulting in failure to complete at least four test trials. Racial and ethnic proportions of the participants from all experiments reported here were approximately 5% Hispanic, 6% Black or African American, 2% Asian, 5% more than one race, 4% unreported, and 78% White or Caucasian.

Design

Infants were habituated to arrays containing 7 or 21 dots that varied fivefold in surface area and then tested with novel arrays containing 7 and 21 dots. The order of novel and familiar test trials was counterbalanced across infants.

Stimuli

Stimuli were created with Canvas software and displayed in the center of the computer monitor (see Figure 1, e.g., stimuli). Stimulus parameters were based on Xu and Spelke (2000); however, whereas their study involved a twofold numerical comparison, the current study involved a threefold comparison. Stimuli were 7- or 21-element arrays of red dots displayed in the center of the computer monitor. There were six habituation stimuli for each condition (7 and 21), and cumulative surface area varied fivefold across the stimuli. Average element size in the 7-element arrays (mean area = 7.4 cm^2, range = 2.9–14.2 cm^2) was triple that of the 21-element arrays (mean area = 2.5 cm^2, range = 0.95–4.7 cm^2) so that average brightness and cumulative surface area of the 7- and 21-element arrays were equated.

The stimulus background was constant in size (18×19 cm^2); consequently, the density of the 21-element arrays (.06 elements/cm^2) was triple that of the 7-element arrays (.02 elements/cm^2). For 8 of the 16 infants, the stimulus background was bordered by blue, so as to denote the exact size of the background (as in Xu & Spelke, 2000). For the other half of the infants, the size of the stimulus background was not outlined, so as to ensure that the change in background did not act as a cue for the infants (as in Brannon et al., 2004). Results of a preliminary 2×2 analysis of variance (ANOVA) testing the effect of background type (blue vs. none) on looking to the different test trial types (novel vs. familiar) revealed no significant main effects or interactions involving the background type ($p > .1$), indicating that background type did not influence looking time. For the remainder of the experiments reported here, the stimuli did not have a delineated background (no blue outline).

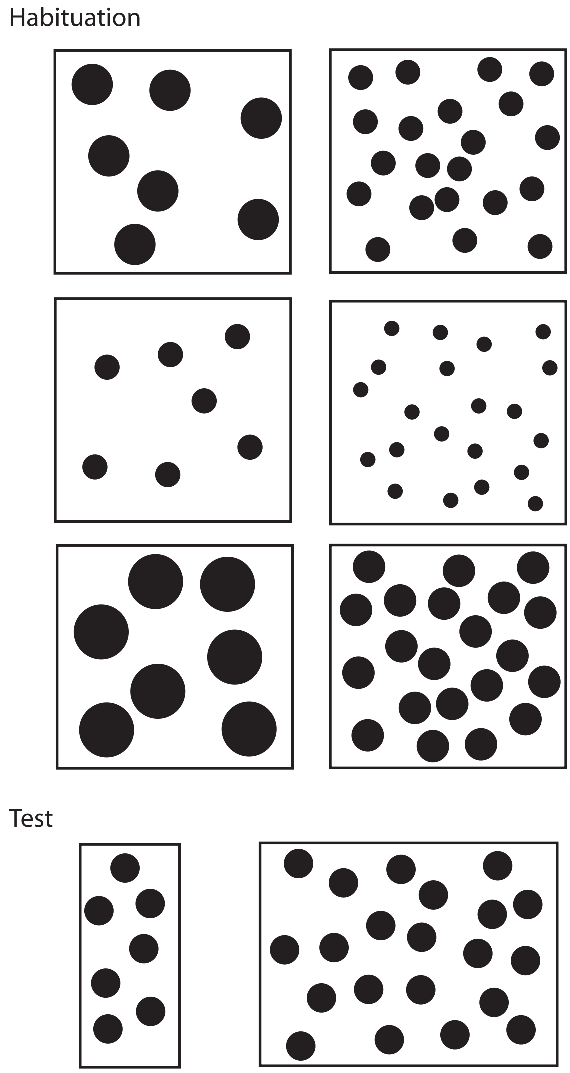

Figure 1. Schematic representation of the stimuli used in Experiment 1.
Note. Infants were habituated to displays with 7 or 21 dots (with varying area) and tested with displays of 7 and 21 dots. Dots in all experiments were red in order to attract attention to displays.

In test, infants saw three novel exemplars of each numerosity. Individual element size was held constant at 4.2 cm^2. This element size was chosen so that the cumulative surface area of the 7- and 21-element test stimuli differed from the average cumulative surface area of the habituation stimuli by the same ratio. In addition, element density of the test arrays was held constant at .049 elements/cm^2 by placing the 21-element test arrays within a stimulus background (18×24 cm^2) that was triple the size of the 7-element test arrays (18×8 cm^2). The spatial configuration of the elements changed between test stimuli.

In sum, the continuous variables that varied between the 7- and 21-element arrays in habituation (i.e., density and element size) were equated in the 7- and 21-element test displays, as opposed to average cumulative surface area, which was held constant across the 7- and 21-element habituation arrays, yet varied between the 7- and 21-element test arrays. This design ensured that if infants look longer at the novel than the familiar number test displays, this could not be attributed to the encoding of cumulative area, element size, or density.

Apparatus

Infants were seated in a high chair (or on a parent's lap) 60 cm from a computer monitor resting on a stage surrounded by blue fabric. Parents were seated next to their infants and instructed to keep their eyes closed and to refrain from talking to, touching, or otherwise interacting with their infant for the duration of the experiment. If an infant became fussy, the experimenter initiated a short break and then resumed the experiment. For an infant to remain in the final sample, the break must have been less than 1 min in duration and could not occur between a pair of test trials.

A microcamera monitoring the infant's face and a feed directly from the stimulus presentation computer were multiplexed onto a TV monitor and VCR. One or two experienced experimenters blind to the experimental condition recorded the infants' looking behavior while viewing the live video with the display occluded. Looking behavior was recorded by holding a button down when the infant was looking at the computer monitor and letting go when the infant looked away. The button input was fed into a RealBasic program, which automatically advanced the stimulus and automatically moved onto the test phase when the criterion was met. The RealBasic program recorded infants as looking or not looking for each 100-ms interval and calculated interobserver reliability. Reliability was conservatively computed based on agreement or disagreement between two observers, both blind to the experimental condition, at each 100-ms interval. Two observers were present for 71% of the participants in the studies reported in this article, and reliability was on average 92%.

Procedure

Informed consent was obtained from a parent of each participant before testing. The experimenter initiated trials when the infant looked in the direction of the computer monitor. Each trial continued until the infant looked for a minimum of 0.5 s and ended after the infant looked for a total of 60 s or looked away for a continuous 2 s. The six habituation stimuli were presented in a pseudorandom order until the infant met the habituation criterion (a 50% reduction in looking time over 3 consecutive trials relative to the first 3 trials that summed to at least 12 s) or until 16 trials were completed. After habituation, the infants were tested with 6 test trials according to the same procedure and alternated between familiar and novel number.

Data analyses

As in other studies produced by our lab and others (i.e., Brannon, 2002; Xu et al., 2005), throughout all experiments reported here, all pairs of looking times (novel and familiar) in which one or both exceeded three standard deviations of the mean duration of all test trials for that experiment were replaced with the average looking times for those particular test trials for all other infants.

Results and Discussion

Figure 2 shows the mean looking time for the first three and last three habituation trials, the three novel test trials, and the three familiar test trials. A paired *t* test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 3.3$, $p < .01$. Thirteen of the 16 infants reached the habituation criterion.

A 2 × 2 × 2 mixed-factor ANOVA testing the between-subjects factors of habituation condition (7 or 21) and test trial order (novel or familiar number first) and the within-subjects factor of test trial type (novel or

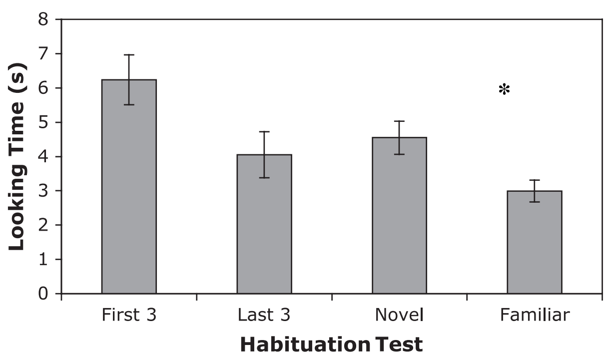

Figure 2. Average looking times for infants in Experiment 1 for the first three and last three habituation trials and for the novel and familiar test trials.
Note. Infants looked significantly longer to displays with the novel number of dots as compared with the familiar number of dots ($p < .05$).

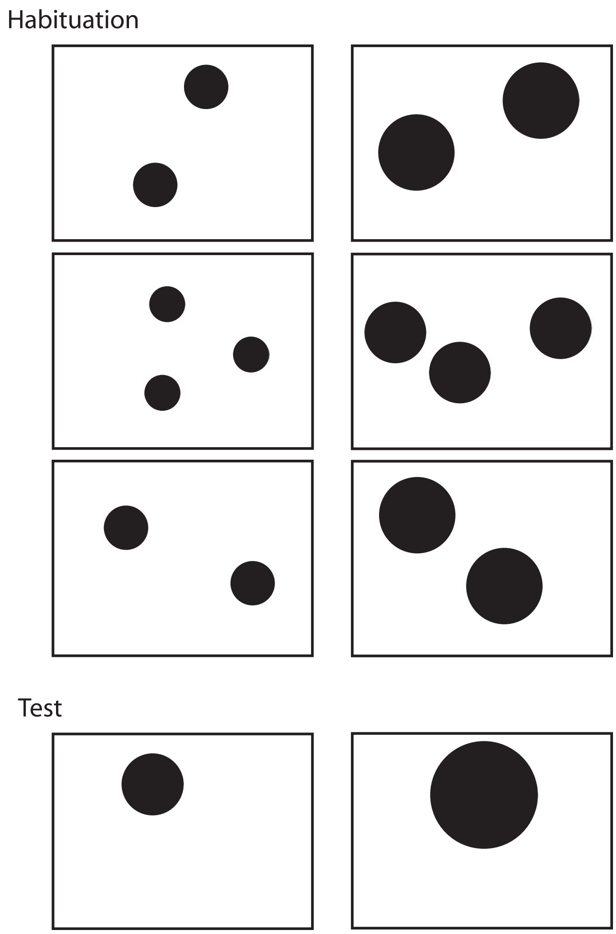

Figure 3. Schematic representation of the stimuli used in Experiment 2a.
Note. Infants were habituated to displays of two and three dots with constant cumulative surface area and tested with displays of one dot with either the same or a threefold change in cumulative surface area as compared with habituation.

familiar number) on infants' looking time during test trials revealed a significant main effect of test trial type, $F(1, 12) = 10.6$, $p < .01$, and no other significant main effects or interactions, $p > .2$. Further analyses indicated that infants detected the threefold change in numerosity. First, a paired-samples t test revealed that infants looked longer at the novel ($M = 4.6$ s) than the familiar ($M = 3$ s) test trials, $t(15) = 3.3$, $p < .01$. In addition, 12 of the 16 infants looked longer at the novel compared to the familiar test trials (binomial, $p < .05$). When these analyses were repeated using only the data from the 13 infants who met the habituation criteria, the same pattern of results emerged—we found a main effect of test trial type, $F(1, 9) = 5.4$, $p < .05$, and no other significant main effects or interactions. Thus, this experiment provides clear evidence that 6-month-old infants can detect a threefold change in number, further supporting the claim that, like adult humans and animals, numerical discriminations of large sets are ratio dependent in infants.

Experiment 2

A prerequisite of the hypothesis that infants represent continuous extent preferentially to number is that infants must be capable of summing continuous variables across discrete items. Thus, in Experiment 2, we investigated whether infants can form a representation of continuous extent across a small (less than four; Experiment 2a) or large (more than four; Experiment 2b) set of discrete entities. We used a 1:3 ratio change in area because this ratio has been found to produce a robust effect when 6-month-old infants are tested with changes in area of a single element (Brannon et al., 2006).

Experiment 2a

In Experiment 2a, we investigated whether infants were able to detect a threefold change in cumulative area across small arrays of dots (one to three). The number of dots in each array varied throughout habituation and test, preventing number from being a valid cue for discrimination.

Method

Participants. Participants were 16 healthy full-term 6-month-old infants (mean age = 6 months 6 days, range = 5 months 20 days to 6 months 17 days). Six of the infants were female. Data from an additional 5 infants were discarded because of fussiness resulting in failure to complete at least four test trials.

Design. Infants were habituated to stimuli with a small or large cumulative surface area and then tested with novel stimuli with a small and large surface area. The habituation stimuli for a given infant were of a constant cumulative surface area but alternated in numerosity between two and three dots (staying within the small number range). The test stimuli always contained a single element that alternated in size between the familiar and the novel area. The novel area was one third or three times as large as the familiar area. Half of the infants were randomly assigned to the small area condition and half to the large area condition.

Stimuli. Stimuli were created with Canvas software and displayed in the center of the computer monitor (see Figure 3, e.g., stimuli). There were six small area and six large area habituation stimuli; in each area condition, three stimuli contained two red dots and three stimuli contained three red dots. Cumulative surface area was held constant at

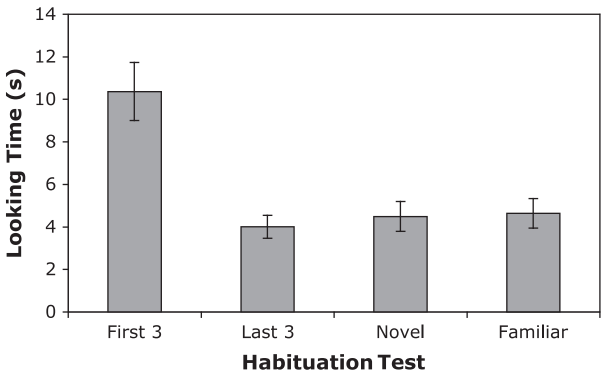

Figure 4. Average looking times for infants in Experiment 2a for the first three and last three habituation trials and for the novel and familiar test trials.
Note. Infants did not look significantly longer to test stimuli with a threefold change in cumulative surface area as compared with the familiar area stimuli ($p > .05$).

50 cm^2 for the small area condition and 150 cm^2 for the large area condition. Following habituation, infants were presented with six test trials that alternated between one small dot (50 cm^2) and one large dot (150 cm^2). The order of novel and familiar test trials was counterbalanced across infants.

Apparatus and procedure. The apparatus and procedure were identical to those in Experiment 1.

Results and Discussion

Figure 4 shows the mean looking time for the first three and last three habituation trials, the three novel test trials, and the three familiar test trials. A paired-samples t test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 7.3$, $p < .01$. All 16 infants reached the habituation criterion.

A 2 × 2 × 2 mixed-factor ANOVA testing the between-subjects factors of habituation condition (small or large area) and test trial order (novel or familiar area first) and the within-subjects factor of test trial type (novel or familiar area) on infants' looking time during test trials revealed no significant main effects or interactions, $p > .2$. There was no evidence to suggest that infants in this experiment detected the threefold change in cumulative area from habituation to test. This conclusion was supported by further analyses. A paired-samples t test revealed that infants did not look longer at the novel ($M = 4.5$ s) than the familiar ($M = 4.6$ s) test trials, $t(15) = 0.21$, $p > .8$, and only 7 of the 16 babies looked longer at the novel compared to the familiar test trials (binomial, $p > .75$). Infants did not dishabituate to novel or familiar test trials, $t(15) = 0.60$, and $t(15) = 0.65$, respectively, all ps $> .5$, indicating that they did not notice the change in numerosity from habituation to test.

Experiment 2b

Results of Experiment 2a suggest that infants were unable to detect a threefold change in cumulative area when habituated and tested with small arrays of dots. In Experiment 2b, we tested whether 6-month-old infants could discriminate a 1:3 ratio change in the cumulative surface area of large numbers of dots (10–15).

Method

Participants. Participants were 16 healthy full-term 6-month-old infants (mean age = 6 months 4 days, range = 5 months 12 days to 6 months 18 days). Ten of the infants were female. Data from an additional 3 infants were discarded because of fussiness resulting in failure to complete at least four test trials.

Design. The design of Experiment 2b was similar to Experiment 2a. Infants were habituated to arrays with 10 and 15 elements (maintaining the 2:3 ratio of number in habituation) and tested with arrays that contained 7 and 21 elements. The novel area displays were one third or three times the area of the habituation displays. Half of the infants were randomly assigned to the small area condition and half to the large area condition. The numerical test values (7 and 21) were chosen to be roughly equidistant to both the arithmetic mean (12.5) and the geometric mean (12.25) of the habituation values while still maintaining the balanced change in area.

Stimuli. Stimuli were created with Canvas software and displayed in the center of the computer monitor (see Figure 5, e.g., stimuli). There were six small and six large area habituation stimuli, and three stimuli in each condition contained 10 red dots and three contained 15 red dots. Cumulative surface area was held constant at 50 cm^2 for the small area condition and 150 cm^2 for the large area condition. Following habituation, infants were presented with six test trials that alternated between 7 (cumulative area = 50 cm^2) and 21 dots (cumulative area = 150 cm^2). Dot size was held constant at 7.14 cm^2 in the test stimuli.

Apparatus and procedure. The apparatus and procedure were identical to those in Experiment 1.

Results and Discussion

Figure 6 shows the mean looking time for the first three and last three habituation trials, the three novel test trials, and the three familiar test trials.

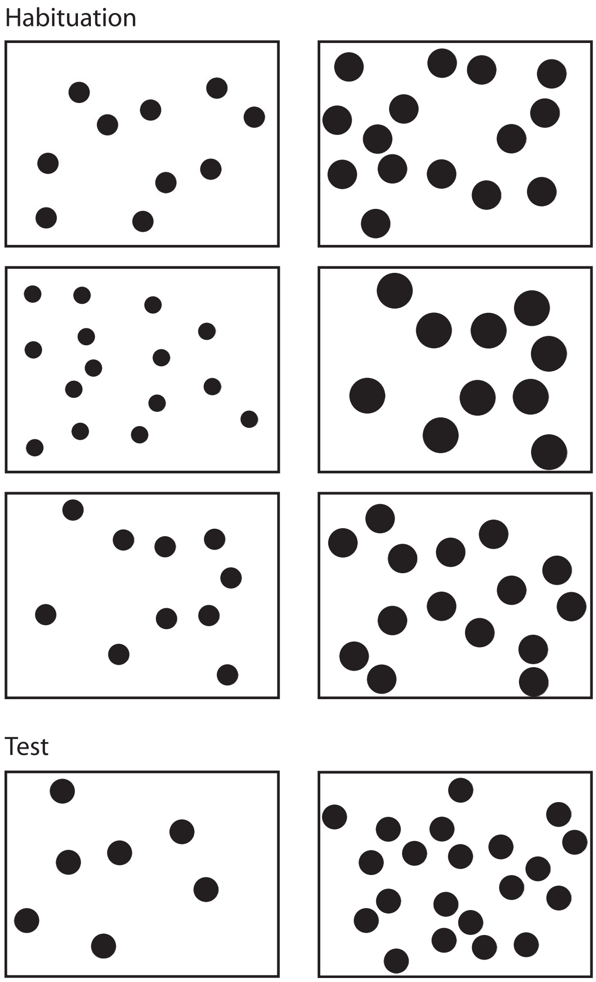

Figure 5. Schematic representation of the stimuli used in Experiment 2b.
Note. Infants were habituated to displays of 10 and 15 dots with constant cumulative surface area and tested with displays of 7 and 21 dots with either the same or a threefold change in surface area.

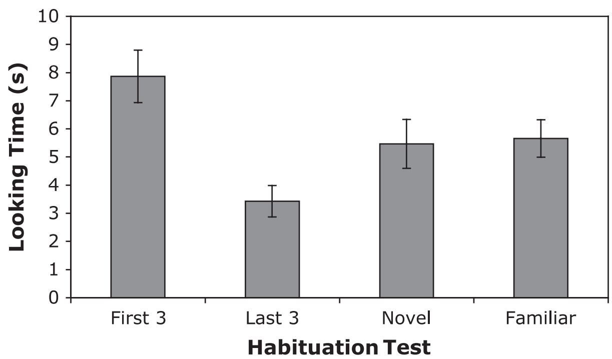

Figure 6. Average looking times for infants in Experiment 2b for the first three and last three habituation trials and for the novel and familiar test trials.
Note. Infants did not detect the threefold change in surface area across large sets of dots ($p > .05$).

A paired-samples *t* test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 7.75$, $p < .001$. Fifteen of 16 infants reached the habituation criterion.

A $2 \times 2 \times 2$ mixed-factor ANOVA testing the between-subjects factors of habituation condition (small or large area) and test trial order (novel or familiar area first) and the within-subjects factor of test trial type (novel or familiar area) on infants' looking time revealed no main effects or interactions, $p > .45$. Repeating the same ANOVA with only those 15 babies who habituated again yielded no main effects or interactions. There was no main effect of test trial type, and only 6 of the 16 infants looked longer to the novel test trials as compared with the familiar (binomial, $p > .05$), thus confirming that infants did not represent the cumulative surface area of the large arrays and were unable to detect the threefold area change. Interestingly, infants did dishabituate in test, suggesting that they noticed the change in number, $t(15) = 2.41$, $p < .05$.

Experiment 3

Results of Experiment 2 in conjunction with data from Brannon et al. (2004) indicate that infants are unable to track a two- or threefold change in cumulative area over changing numbers of elements. Given that 6-month-old infants are able to detect a two- (Xu & Spelke, 2000) and threefold (Experiment 1) change in number, these results contradict claims that continuous variables are more salient to infants than numerosity (i.e., Clearfield & Mix, 1999). This finding also contrasts with 6-month-old infants' ability to detect a twofold change in surface area of a single element.

One explanation for infants' failure to detect a threefold change in cumulative area is that infants may be completely unable to track cumulative surface area of discrete arrays. Alternatively, the process of representing cumulative area may be a noisier one than that for tracking the area of a single element. It seems intuitive that the representation of cumulative surface area across multiple elements is a significantly more complex process than that of the representation of a single element's area, and thus, infants may require a greater proportion of change in order to detect a difference in this variable across displays. Accordingly, in Experiment 3, we investigated whether a fourfold change in cumulative area would enable infants to succeed in our task. Again, this idea was explored with exclusively small sets and then exclusively large sets.

Experiment 3a

In Experiment 3a, we investigated whether infants were able to detect a fourfold change in cumulative area across small arrays of dots (one to three).

Method

Participants. Participants were 16 healthy full-term 6-month-old infants (mean age = 5 months 26 days, range = 5 months 16 days to 6 months 19 days). Nine of the infants were female. Data from an additional 4 infants were discarded because of fussiness resulting in failure to complete at least four test trials.

Design. Infants were habituated to stimuli with a small or large cumulative surface area and then tested with novel stimuli with a small and large surface area. The habituation stimuli for a given infant were of a constant cumulative surface area but alternated in numerosity between two and three dots. The test stimuli always contained a single element that alternated in size between the familiar and the novel area. The novel area was one fourth or four times as large as the familiar area. Half of the infants were randomly assigned to the small area condition and half to the large area condition.

Stimuli. Stimuli were created with Canvas software and displayed in the center of the computer monitor (see Figure 7, e.g., stimuli). There were six small area and six large area habituation stimuli; in each area condition, three stimuli contained two red dots and three stimuli contained three red dots. Cumulative surface area was held constant at 50 cm^2 for the small area condition and 200 cm^2 for the large area condition. Following habituation, infants were presented with six test trials that alternated between one small dot (50 cm^2) and one large dot (200 cm^2). The order of novel and familiar test trials was counterbalanced across infants.

Apparatus and procedure. The apparatus and procedure were identical to those in Experiment 1.

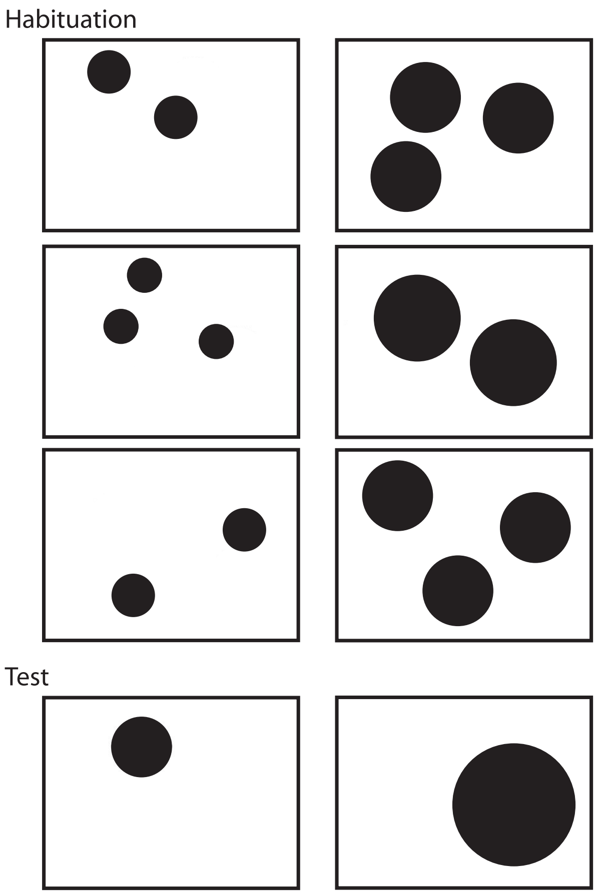

Figure 7. Schematic representation of the stimuli used in Experiment 3a.
Note. Infants were habituated to displays of two and three dots with constant cumulative surface area and then tested with one dot of either the same or a fourfold change in cumulative surface area.

Results and Discussion

Figure 8 shows the mean looking time for the first three and last three habituation trials, the three novel test trials, and the three familiar test trials. A paired-samples t test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 4.3$, $p < .001$. Ten of the 16 infants reached the habituation criterion.

A 2 × 2 × 2 mixed-factor ANOVA testing the between-subjects factors of habituation condition (small or large area) and test trial order (novel or familiar area first) and the within-subjects factor of test trial type (novel or familiar area) on infants'

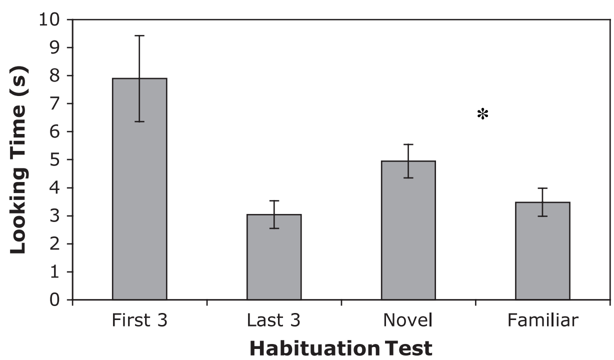

Figure 8. Average looking times for infants in Experiment 3a for the first three and last three habituation trials and for the novel and familiar test trials.
Note. Infants detected the fourfold change in cumulative surface area for the small sets of dots, as results revealed they looked significantly longer to novel test trials than to familiar ($p < .05$).

looking time during test trials revealed a main effect of test trial type, $F(1, 12) = 8.9$, $p < .02$, and no other significant main effects or interactions ($p > .3$). Three different analyses revealed evidence of infants' ability to recognize a change in cumulative area. First, a paired-samples *t* test revealed that infants looked longer at the novel ($M = 4.9$ s) than the familiar ($M = 3.5$ s) test trials, $t(15) = 3.1$, $p < .01$. Second, 12 of the 16 babies looked longer at the novel compared to the familiar test trials (binomial, $p < .05$). Third, a paired-samples *t* test revealed that infants looked significantly longer at the novel test trials than at the last three habituation trials, $t(15) = 3.4$, $p < .01$, whereas the difference between looking to the familiar test trials and the last three habituation trials was not significant, $t(15) = 0.87$, $p > .39$. When the analyses were redone with only the 10 infants who habituated, the same pattern of results emerged—we found a main effect of test trial type, $F(1, 6) = 10.4$, $p < .02$, and no other significant main effects or interactions. Infants looked longer at the novel than the familiar test trials, $t(9) = 3.3$, $p < .01$, and dishabituated to the novel, $t(9) = 3.4$, $p < .01$, but not the familiar area test trials, $t(9) = 1.0$, $p > .33$.

An important question is whether infants were attending to cumulative surface area or another continuous aspect of the displays such as changes in cumulative perimeter or changes in element size. The fact that there was no Habituation Condition × Test Trial Type interaction suggests that infants were not tracking cumulative contour length but rather cumulative area. The small area test displays (overall contour = 25.1 cm) differed from the small area habituation displays (39.4 cm) by a greater proportion than the large area test displays (50.1 cm); thus, infants habituated to the small area would have showed longer looking to the familiar as opposed to novel area displays if they tracked overall contour as opposed to cumulative area of the displays. Infants habituated to small arrays did not show a preference for the familiar area but instead showed longer looking to the novel area that was more similar in overall contour length to the habituation displays.

If infants attended to changes in individual element size, this could explain why infants habituated to small values looked longer to the large area test stimuli because the small area habituation elements were on average 20.8 cm^2, whereas the element in the small and large area test stimuli were 50 cm^2 and 200 cm^2, respectively. However, attending to a change in element size would not explain why infants who were habituated to the large area stimuli looked longer at the novel area test stimulus because the average size of the elements in the large area habituation stimuli was 83 cm^2, which is actually closer to the size of the element in the small area test stimulus (50 cm^2) than the element in the large area test stimulus (200 cm^2). In fact, 7 of the 8 infants habituated to the large area looked longer to the novel than to the familiar stimuli (binomial, $p < .05$). Thus, the lack of an interaction indicates that infants were likely assessing cumulative area and not cumulative perimeter or individual element size.

In sum, Experiment 3a suggests that 6-month-old infants can form a representation of the cumulative surface area of a small number of discrete elements. In the following experiment, we used the identical design but asked whether 6-month-old infants are able to form a representation of the cumulative surface area of a large number of discrete elements.

Experiment 3b

Results of Experiment 3a suggest that infants were able to detect a fourfold change in cumulative area when habituated and tested with small arrays of dots. In Experiment 3b, we tested whether 6-month-old infants could discriminate a 1:4 ratio change in the cumulative surface area of large numbers of dots (10–15).

Method

Participants. Participants were 16 healthy full-term 6-month-old infants (mean age = 6 months 0 days, range = 5 months 16 days to 6 months 19 days). Nine of the infants were female. Data from an additional 4 infants were discarded because of fussiness resulting in failure to complete at least four test trials.

Design. The design of Experiment 3b was similar to Experiment 3a. Infants were habituated to arrays with 10 and 15 elements and tested with arrays that contained 6 and 24 elements. The novel area test stimuli were one fourth or four times the area of the habituation displays. Half of the infants were randomly assigned to the small area condition and half to the large area condition.

Stimuli. Stimuli were created with Canvas software and displayed in the center of the computer monitor (see Figure 9, e.g., stimuli). There were six small and six large area habituation stimuli, and three stimuli in each condition contained 10 red dots and three contained 15 red dots. Cumulative surface area was held constant at 50 cm^2 for the small area condition and 200 cm^2 for the large area condition. Following habituation, infants were presented with six test trials that alternated between 6 (cumulative area = 50 cm^2) and 24 dots (cumulative area = 200 cm^2). Dot size was held constant at 8.3 cm^2 in the test

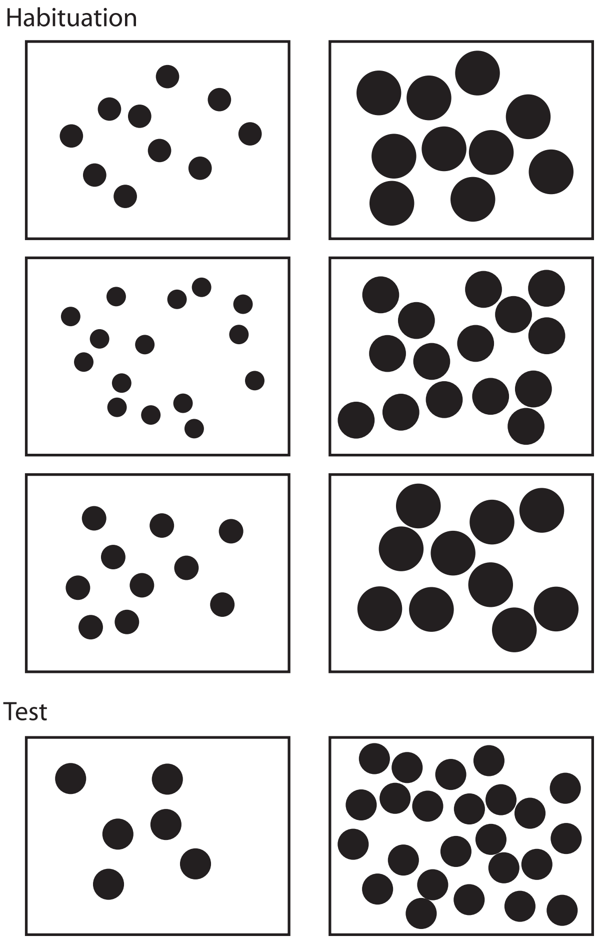

Figure 9. Schematic representation of the stimuli used in Experiment 3b.
Note. Infants were habituated to displays of 10 and 15 dots of constant cumulative surface area and then tested with displays of 6 and 24 dots of the same and a fourfold change in area.

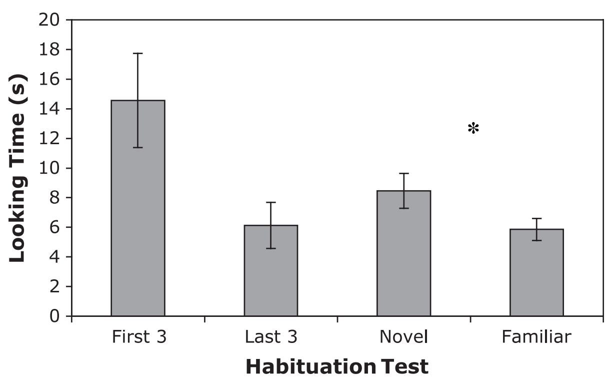

Figure 10. Average looking times for infants in Experiment 3b for the first three and last three habituation trials and for the novel and familiar test trials.
Note. Infants looked significantly longer to the novel than the familiar test trials ($p < .05$), indicating that they noticed the fourfold change in surface area for the large sets of dots.

stimuli, the geometric mean between the two dot sizes in habituation. The numerical test values (6 and 24) were chosen to be approximately half and double the average of the habituation values (12.5) while still maintaining the balance in area. The order of novel and familiar test trials was counterbalanced across infants.

Apparatus and procedure. The apparatus and procedure were identical to those in Experiment 1.

Results and Discussion

Figure 10 shows the mean looking time for the first three and last three habituation trials, the three novel test trials, and the three familiar test trials. A paired t test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 4.7$, $p < .01$. Fifteen of the 16 infants reached the habituation criterion.

A 2 × 2 × 2 mixed-factor ANOVA testing the between-subjects factors of habituation condition (small or large area) and test trial order (novel or familiar area first) and the within-subjects factor of test trial type (novel or familiar area) on infants' looking time revealed a main effect of test trial type, $F(1, 12) = 5.7$, $p < .05$, a main effect of habituation condition, $F(1, 12) = 9.0$, $p < .05$, and no other significant main effects or interactions, $p > .2$. The main effect of habituation condition revealed that infants habituated to the small area stimuli ($M = 9.1$) looked significantly longer overall in test than those habituated to the large area stimuli ($M = 5.2$). The main effect of test trial type indicated that infants looked significantly longer to the novel ($M = 8.5$) than the familiar ($M = 5.9$) area stimuli. This result was supported by a follow-up paired-samples t test comparing the average looking time to the novel and familiar test trials, $t(15) = 2.4$, $p < .05$. In addition, 12 out of 16 infants looked longer to the novel area compared to the familiar area test trials (binomial, $p < .05$). When this ANOVA was repeated using only the data from the 15 babies who habituated, results again revealed a main effect of test trial type, $F(1, 11) = 5.1$, $p < .05$, and a main effect of habituation condition, $F(1, 11) = 10.4$, $p < .01$.

Again, the question of whether infants were attending to changes in continuous variables other than cumulative area is of interest. The advantage of this particular design allows us to completely rule out the possibility that infants were attending to changes in individual element size, as element size was the same in the small and large test stimuli (true for Experiment 2b also). It is, however, possible that infants detected changes in overall contour because unlike Experiment 3a changes in overall contour were in fact confounded with changes in cumulative extent. Two reasons lead us to believe that infants were more likely to have attended to area compared to contour length in this design. First, overall contour varied during habituation, such that infants would have had to not only represent the cumulative contour of each display but then compute the average overall contour representation, conceivably a much more difficult task than forming a representation of cumulative area that did not vary across habituation arrays (a two-step vs. a one-step process). In addition, if it were the case that infants detected changes in contour instead of changes in cumulative area, this means that infants would have had to detect a significantly smaller change in contour (1:2.8-fold change) than in area (1:4-fold). Contour would have to be both more discriminable and more salient to infants than cumulative area—a finding not supported by the literature (Clearfield & Mix, 2001). Thus, it seems very unlikely that infants used contour as the basis for discrimination in this task.

Combining data from Experiments 2 and 3, we ran a $2 \times 2 \times 2$ ANOVA on the between-subjects factors of cumulative area ratio (1:3 [Experiment 2] vs. 1:4 [Experiment 3]) and set size (small [Experiments 2a and 3a] vs. large [Experiments 2b and 3b]) and the within-subjects factor of test trial type (novel vs. familiar). Results revealed a main effect of test trial type, $F(1, 60) = 6.17$, $p < .05$; a main effect of set size, $F(1, 60) = 8.62$, $p < .01$; and a Test Trial Type × Ratio interaction, $F(1, 60) = 8.67$, $p < .01$. There were no other significant main effects or interactions, $p > .15$. The main effect of set size revealed that infants habituated and tested with large set sizes tended to look longer overall ($M = 6.4$) compared with infants tested with small set sizes ($M = 4.4$). The main effect of test trial type revealed that across all four experiments, infants looked longer at the novel test trials ($M = 5.8$) as compared with the familiar test trials ($M = 4.9$). This result is tempered, however, by the Test Trial Type × Ratio interaction we obtained. Although, on average, there was an overall preference for novelty, the interaction revealed that this preference was due to results of Experiments 3a and 3b, in which the cumulative area ratio was 1:4. In these experiments, infants preferred novel test trials ($M = 6.7$) over familiar ones ($M = 4.7$). In contrast, in Experiments 2a and 2b, in which there was a threefold change in cumulative area, infants showed no preference for novel test trials ($M = 5.0$) over familiar ones ($M = 5.2$), confirming our previous findings that infants required a 1:4 change in cumulative surface area in order to detect a change. In addition, the lack of an interaction of set size with other variables in this ANOVA highlights the fact that the same ratio of discriminability is required for small and large sets alike for infants to succeed in our task. In conclusion, evidence from Experiments 2 and 3 suggests that infants are capable of representing cumulative surface area over a small and large number of items as long as there is at least a fourfold change in area.

General Discussion

Collectively, results reveal that infants can detect a fourfold change in the cumulative area of a set however fail to notice a smaller threefold change. These results are in marked contrast with infants' more sensitive discrimination capacities for area with single element arrays where infants of the same age were able to detect a twofold change (Brannon et al., 2006). Similarly, 6-month-old infants' inability to detect a threefold change in cumulative area contrasts with the finding that infants successfully discriminate a two- or threefold change in *number* when continuous variables vary over habituation. Thus, both the number and the area of a single element appear to be more salient and more discriminable than cumulative area to the 6-month-old infant. The finding that cumulative area representations have significantly compromised precision relative to other quantity discriminations in infancy is consistent with the finding that 3- and 4-year-old children have difficulty in choosing the sets of cookies with the larger total amount (Sophian, 2000).

Our results also suggest that cumulative area discriminations, much like those for numerosity (Brannon et al., 2004; Lipton & Spelke, 2003; Wood & Spelke, 2005; Xu & Spelke, 2000), time (Brannon, Libertus, Meck, & Woldorff, in press; Brannon, Suanda, & Libertus, 2007; vanMarle & Wynn, 2006), and the area of a single element (Brannon et al., 2006), are ratio dependent, even in infancy (see Feigenson, 2007, for review). Although in the case of these other variables there appears to be a single common critical ratio necessary for successful discrimination (1:2), results of the current study suggest that the discrimination of continuous variables across multiple entities requires at least double that ratio (1:4) for successful detection. These results strongly suggest that the formation of representations of cumulative area across discrete sets is a significantly noisier process than the formation of representations of numerosity.

Of note is that these results are at odds with previous findings by Feigenson et al. (2002) and

Clearfield and Mix (1999) in which 7-month-old infants discriminated sets with a 2- and 2.5-fold change in cumulative surface area, respectively (Clearfield & Mix's design controlled for contour, as opposed to surface area, so that the change in cumulative surface area in their stimuli was 2.5:1). Although both these studies used a similar habituation paradigm, there is one significant difference between the design of their studies and that of ours. In their studies, number and surface area were confounded (both held constant) in habituation, such that infants saw the exact same stimuli (in different configurations) from trial to trial. Subsequently, these two variables were pitted against each other in test. For example, in Feigenson et al. (2002, Experiment 2), infants were habituated to one large object and then tested with one small object (familiar number, novel continuous extent) and two small objects (novel number, familiar continuous extent). Results revealed that infants looked longer to the displays with novel continuous extent, suggesting that they noticed a change in the cumulative surface area of the display. In contrast, in our experiments, set size varied across habituation trials and this may have made similarities in continuous extent across displays less salient to the infants. If this is the case, this result brings up an important point—although infants require constant set size in habituation in order to detect a twofold change in cumulative surface area, they do not need continuous variables to be constant in order to detect a twofold change in number. When habituation displays vary in continuous extent variables (e.g., Experiment 1; Xu & Spelke, 2000), infants are still able to form a representation of number. This again suggests that for 6-month-old infants, number may, in fact, be more salient than continuous extent when presented with discrete arrays.

At first glance, our results may seem inconsistent with recent findings by Hurewitz, Gelman, and Schnitzer (2006) who found that cumulative surface area interfered with numerical judgments when the two were in conflict. In their task, adults were asked to judge which of the two sets had more circles while the circle varied in size, such that on some trials, the overall cumulative surface area was greater for the side with fewer circles (incongruent) and on other trials, the cumulative area of the side with fewer circles was smaller in area (congruent). Participants took significantly longer to respond on incongruent trials as compared with congruent, suggesting that cumulative surface area spontaneously interfered with numerical judgments. These results should be interpreted with caution, however, as the differences in numerosity and cumulative area were not closely matched. For example, on some trials, subjects were required to ignore a 20-fold difference in surface area when making a numerosity comparison that involved only a 2-fold change. Nevertheless, these findings suggest that adult humans are sensitive to the continuous properties of a set, even when making numerical judgments and that future research is needed to examine the interaction between area and number over development and into adulthood.

A crucial question for the interpretation of our results is whether we can be certain that infants detected a change in area as opposed to another continuous variable (e.g., element size, overall contour, density). Although our experiments did not directly address whether or not infants can also represent cumulative perimeter or individual element size, the pattern of results we obtained are inconsistent with the idea that infants attended to these other continuous dimensions when discriminating the sets in our study. In Experiment 3a (small – small 1:4 ratio), if infants had used overall contour as the basis for discrimination, then those infants habituated to the small area condition would have looked significantly longer to the small area (i.e., familiar) test stimuli because these stimuli revealed the greatest proportion of change in overall contour from habituation to test. The pattern was not observed. If infants attended to element size instead of cumulative area, then we would expect those infants habituated to the large area stimuli to look longer to the large area test (familiar) stimuli because these stimuli had a greater proportion of change in element size compared to habituation than the small area test stimuli. Again, we did not observe that pattern. Thus, it seems likely that infants' success in Experiment 3a reflected their use of cumulative area as opposed to contour or element size.

The design of Experiment 3b (large – large 1:4 ratio) prevented infants from using element size as a basis for discrimination in this task because element size was held constant across test displays. Although it is possible that overall contour played a part in infants' success in Experiment 3b because changes in contour were confounded with changes in cumulative surface area, this seems unlikely because infants would have had to form a representation of contour over habituation displays that varied on this dimension. In addition, the proportion of change in contour from habituation to test (1:2.8) was less than the 1:4 ratio change in cumulative surface area, suggesting that in order for contour to have been the dimension of discrimination, this variable must have been significantly more salient to infants than cumulative area. Thus, it seems unlikely that infants relied on cumulative perimeter or element size in Experiments 3a and 3b.

Another possibility is that infants may have relied on density rather than cumulative surface area. Density can be measured in a variety of ways; however, in each case, it would be correlated with cumulative surface area in our designs. If density is defined as the proportion of red to white space in the displays, such a calculation would require representing cumulative red and white area. However, a given ratio change in area corresponds with a dramatically greater change in density, suggesting infants' sensitivity to density would be even lower than their sensitivity to cumulative area and thus still be in marked contrast with their sensitivity to number. On the other hand, if density were defined as average interelement distance, this measure was also correlated with cumulative area; however, it was not held constant in habituation (due to random configurations) and thus seems an unlikely dimension for infants' attention. Indeed, this would require infants to first take the average interelement distance for each stimulus and then average variable averages over habituation and test stimuli. In addition, it is unclear how this variable could be meaningful for the test stimuli in Experiments 2a and 3a, which contained a single element. Furthermore, estimates of average interelement distance should become more variable with larger set sizes (each additional element requires the computation of several more distances)—which is inconsistent with our lack of a set-size effect.

A noteworthy aspect of the results of our study is that the ratio critical for successful discrimination was identical for small and large sets. That is, 6-month-old infants fail to discriminate a threefold change in cumulative area for small sets and for large sets, and they succeed with a fourfold change for both small and large sets. Although it is possible that the design of our study lacks the sensitivity to detect subtle differences that may exist between the precision of cumulative area representations of small versus large sets, currently, there is no evidence in the available data to suggest the existence of such a set-size effect. The data in fact suggest that cumulative area representations are formed via a set-size independent process and that these representations are ratio dependent. The ratio dependence suggests that cumulative area, for both small and large sets, is represented via mental magnitudes, much like those used to represent other quantities such as time and number. The similar ratio of discriminability for small and large sets also provides a window into the process by which these magnitude representations are formed. If representations of cumulative area were formed via successive summations of representations of individual element areas stored in memory, then previous work on the addition of mental magnitudes (Barth et al., 2006; Cordes, Gallistel, Gelman, & Latham, 2007) would predict an increasing compromise in precision of these representations with increasing set size. That is, the more elements in the display, the more representations stored in memory, and the more summations to perform, leading to greater noise in the final representation, thus requiring a greater proportion of change for successful discrimination. This does not appear to be the case. Our results therefore suggest that the process by which these representations were formed did not involve iterative summations of values in reference memory. On the contrary, our results suggest that infants represented cumulative area via a single accumulation process—similar to how representations of time and number are thought to accumulate over time or space (Meck & Church, 1983).

Considering the lack of a set-size effect, it is surprising that infants required a fourfold change in cumulative surface area when presented with multiple elements, given that infants in Brannon et al. (2006) only required a twofold change to detect a change in the area of a single element. If the precision of cumulative area representations is not compromised with increasing set size, then what makes the jump from one element (Brannon et al., 2006) to two and three elements (Experiment 3a) so special? There are a number of possibilities to explain this. First, as outlined by Brannon et al., it is possible (although rather unlikely) that infants in their study used other stimulus dimensions (such as element diameter or distance from screen edge) as a basis for discrimination. The use of these alternative stimulus dimensions as a basis for discrimination in our study was not, however, a viable option. Another possibility is that the formation of a cumulative area representation is a more complex and noisy process than that of representing the area of a single element. The discrepancy in infant abilities to represent the area of a single item versus the area of multiple items mirrors the finding by Sophian (2000) in which she found that young children chose the larger of two sets based upon the single largest item. Although our findings suggest that the process is not made noisier by the additional elements in a multielement display perhaps the initial jump to summing area as opposed to simply representing it contributes noise to the representation. Last, it is also possible that the discrepancy in precision we have found is a function of other differences in experimental design. For example, set size in the Brannon et al. study did not vary across habituation or test—infants always saw one-item displays. Similar to the Feigenson et al. (2002) and

Clearfield and Mix (1999) designs, number and surface area were confounded in habituation in contrast to our design. As discussed earlier, when number is constant, continuous extent variables may become more salient to the infant than when number is variable.

In summary, our results reveal that although 6-month-old infants are able to represent the cumulative area of a discrete set of items when number is controlled, a fourfold change is necessary in order for them to notice the change. In contrast, infants can readily discriminate a two- and threefold change in *numerosity* when strict controls on continuous variables are employed. Results suggest that cumulative area and number are represented via similar mental magnitudes, both with a single accumulation process. Why is it that infants require a twofold greater change in cumulative area compared with number in order to detect a change in sets of discrete items? Although it appears that infants are capable of representing both number and cumulative area of sets, our results indicate that cumulative area changes are simply less salient and/or more difficult to detect than number changes for a 6-month-old infant.

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