Crossing the Divide: Infants Discriminate Small From Large Numerosities

Sara Cordes and **Elizabeth M. Brannon**
Duke University Center for Cognitive Neuroscience and Department of Psychology and Neuroscience.

Abstract

Although young infants have repeatedly demonstrated successful numerosity discrimination across large sets when the number of items in the sets changes twofold (E. M. Brannon, S. Abbott, & D. J. Lutz, 2004; J. N. Wood & E. S. Spelke, 2005; F. Xu & E. S. Spelke, 2000), they consistently fail to discriminate a twofold change in number when one set is large and the other is small (<4 items; F. Feigenson, S. Carey, & M. Hauser, 2002; F. Xu, 2003). It has been theorized that this failure reflects an incompatibility in representational systems for small and large sets. The authors investigated the ability of 7-month-old infants to compare small and large sets over a variety of conditions. Results reveal that infants can successfully discriminate small from large sets when given a fourfold change, but not a twofold change, in number. The implications of these results are discussed in light of current theories of number representation.

Keywords

numerical cognition; infant numerical abilities; analog magnitudes; object files

A dominant hypothesis is that human infants employ two distinct systems for representing number: an analog magnitude system and an "object file" system (e.g., Ansari, Lyons, van Eimeren, & Xu, 2007; Feigenson, Carey, & Hauser, 2002; Lipton & Spelke, 2004; van Herwegen, Ansari, Xu, & Karmiloff-Smith, 2008; Xu, 2003). This distinction was originally proposed because infant number discrimination appeared to be modulated by Weber's Law in some circumstances and limited by absolute set size in other circumstances. In contrast to the two-system proposal, other researchers suggested that there is only one nonverbal system for representing number (e.g., Gallistel & Gelman, 1992) or challenged the idea that infants represent number at all (e.g., Mix, Huttenlocher, & Levine, 2002; Moore & Cocas, 2006; Simon, Hespos, & Rochat, 1995). More recently, however, the two-system proposal has been strengthened by a series of studies that found infants unable to compare small and large values (Feigenson & Carey, 2005; Feigenson, Carey, & Hauser, 2002; Lipton & Spelke, 2004; Xu, 2003). That is, infants consistently succeed at discriminating large sets (>3 items) from large sets (e.g., 8 vs. 16), and small sets (<4 items) from small sets (e.g., 1 vs. 2), yet they consistently fail to discriminate small sets from large sets (e.g., 2 vs. 4; but see Wynn, Bloom, & Chiang, 2002). The current study probes infants' apparent difficulty at comparing small and large numerical values.

Correspondence concerning this article should be addressed to Sara Cordes, Duke University Center for Cognitive Neuroscience, Box 90999, Durham, NC 27708. scordes@duke.edu.

For sets of 4 or more elements, numerical discrimination in infancy consistently obeys Weber's Law; that is, the discriminability of two values is dependent upon their ratio, not their absolute difference. At 6 months of age, infants require a twofold difference in numerosity to discriminate a change at a wide range of absolute values greater than or equal to 4. Specifically, 6-month-old infants have been shown to discriminate 4 from 8 but not from 6; 8 from 16 but not from 12; and 16 from 32 but not from 24 (e.g., Lipton & Spelke, 2003, 2004; Wood & Spelke, 2005; Xu, 2003; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). These demonstrations have spanned two different sensory modalities (visual and auditory) with stimuli as varied as arrays of dots, jumps of a puppet, and sequences of tones. The Weber characteristic of infant numerical discriminations parallels psychometric discrimination functions for number exhibited by adult humans (e.g., Moyer & Landauer, 1967, 1973) and many other animal species (e.g., Cantlon & Brannon, 2006) and is interpreted as evidence that number is represented as continuous mental magnitudes by nonhuman animals, adult humans, and human infants (e.g., Barth et al., 2006; Cordes & Gelman, 2005; Dehaene, 2004; Gallistel & Gelman, 2000; Meck & Church, 1983; Xu, 2003).

On the other hand, infants are remarkably more precise in discriminating exclusively small sets (<4 items). Whereas 6-month-olds consistently discriminate a twofold but not a 1.5-fold change in number for large sets, a handful of cross-modal studies indicate that these young infants succeed in discriminating two from three items (a 1.5-fold change for exclusively small sets). In one of the first studies of its kind, Starkey, Spelke, and Gelman (1983, 1990) found 6- to 8-month-old infants looked longer at a display with two household items (compared to a display with three household items) when they heard two sounds and looked longer at a three-item display when hearing three sounds, despite the lack of a natural relationship between sounds and displays (but see Mix, Levine, & Huttenlocher, 1997; Moore, Benenson, Reznick, Peterson, & Kagan, 1987). Kobayashi, Hiraki, and Hasegawa (2005) created a relationship between sounds and displays by familiarizing 6-month-olds to objects dropping on a stage and making a sound upon impact. They then raised an occluder on stage and tested whether infants were able to use the number of sounds they heard to anticipate the number of objects they expected to see once the occluder was removed. Results revealed that after the occluder was removed, infants looked longer when three objects were on the stage after hearing only two impact sounds and vice versa, indicating that they detected a mismatch in the number of sounds and objects displayed. Similarly, Jordan and Brannon (2006) found successful two-versus-three discrimination when 7-month-old infants preferentially looked at the video display with the same number of women as the number of female voices they heard (in chorus). That is, when they heard two voices, infants looked to the video display with two women, and when they heard three voices, they looked to the three-woman display. In another demonstration of infant cross-modal numerical competence, Féron, Gentaz, and Streri (2006) found 5-month-olds looked longer to a display of three objects after having tactile familiarization with only three objects. Lastly, successful demonstrations that infants in this age range discriminate two objects from three is not limited to cross-modal studies. Two recent visual habituation studies have revealed infants look longer to displays with a different number of items as compared with habituation when placed in a two-versus-three comparison condition (Cordes & Brannon, 2009; Kwon, Levine, Suriyakham, & Ehrlich, 2009), again revealing that infants have significantly greater discrimination precision when sets are small as compared to when both sets are large.

The difference in precision for infant discriminations involving exclusively small sets compared with those involving exclusively large sets has led to the hypothesis that infants use two distinct systems for set representation: a ratio-dependent analog magnitude system for large sets and an object file system with a strict set-size limitation for small sets (e.g., Feigenson, Spelke, & Dehaene, 2004; Simon et al., 1995; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Xu, 2003). Object files were originally proposed in the visual attention literature to account

for how adults track objects over space and time (Kahneman, Treisman, & Gibbs, 1992; Trick & Pylyshyn, 1994). Visual attention limits the number of object files available—in infants, there are thought to be three; in adults, somewhere between three and five. The proposal is that for small sets, each entity to be enumerated is represented by a distinct object file with no symbolic representation of the cardinality of the set of objects or events. Thus, for sets of three and fewer, infants have an exact one-to-one correspondence representation of the items in a set, allowing for more precise discriminations in the small number range.

This two-system hypothesis has also been used to explain why infants consistently fail to notice numerical changes across this apparent small–large boundary. Specifically, infants have failed in at least three different paradigms to discriminate sets with favorable ratios when one set is three or fewer and the second set is four or greater. Feigenson, Carey, & Hauser (2002) placed different numbers of graham crackers into two containers in full view of infants between 10 and 12 months of age. Infants were then allowed to crawl to the container of their choice. When the number of graham crackers in both sets was three or fewer (e.g., one vs. two, two vs. three), the infants reliably crawled to the container with more food (consistent with previous findings). However, when there were four or more crackers in one of the containers, the infants responded at chance. That is, infants failed to choose the container with more crackers when the choice was between two and four crackers or three and six crackers (both of which provide a favorable ratio for discrimination, 1:2) and even when the choice was between one and four graham crackers (Feigenson & Carey, 2005).

Feigenson and Carey (2003) found a similar performance pattern using a manual search task. The manual search task is predicated on the idea that infants' search time should reflect the degree to which they expect an interesting toy to remain inside an opaque box. Twelve- to 14-month-old infants searched longer after an experimenter retrieved two toys from a box when the infants had originally seen three toys placed into the box, compared to when they had originally seen only two objects placed into the box. This positive result is interpreted to mean that infants were searching for a third object, which they expected to still be inside the box. However, search times did not differ after two toys were removed from a box in which infants had seen four toys placed, compared to when they had seen two toys placed in the box. Infants also failed to discriminate one versus four in this task, searching equally long after one toy was retrieved from a box that should contain none and from a box that should still contain three toys (Feigenson & Carey, 2005).

Younger infants have also failed to discriminate a 1:2 ratio in number involving one small and one large value in habituation and familiarization paradigms (Lipton & Spelke, 2004; Wood & Spelke, 2005; Xu, 2003). In one study, 6-month-old infants tested in the visual habituation paradigm with dot displays successfully discriminated four from eight but failed to discriminate two from four (Xu, 2003). In a second study, 6-month-old infants again succeeded at discriminating four from eight but failed at discriminating two from four puppet jumps when tempo and duration of the sequences were carefully controlled (Wood & Spelke, 2005). In yet a third study, which used a head-turn procedure with auditory stimuli, 6-month-old infants failed to discriminate two versus four but successfully discriminated four versus eight tones (Lipton & Spelke, 2004).[1]

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[1] There is only one prior study in which infants have successfully discriminated across small and large sets. Using a habituation paradigm, Wynn, Bloom, & Chiang (2002) found 5-month-old infants were able to discriminate between two and four groups of moving dots. This study demonstrates that infants can, at least under some circumstances, compare small and large sets, yet it is unclear what it is about the task or stimuli that leads to the infant success. It is also important to note that 11-month-old infants succeeded in the ordinal task used by Brannon (2002) despite sequences that contained small and large values, although it is unclear whether infants in that task necessarily attended to all values presented. Furthermore, the ordinal task did not directly address the question of set-size discrimination, and thus these findings may or may not be relevant to the question addressed in the current study.

A conundrum raised by this pattern of findings is why the analog magnitude system is not recruited to represent small values when the object file system fails. Although there is a limit to the number of object files available to the infant, there is no lower bound to the analog magnitude system. In fact, research suggests that adults, children, and nonhuman animals regularly represent small sets via magnitude representations (e.g., Brannon & Terrace, 1998; Cantlon & Brannon, 2006; Cordes, Gelman, Gallistel, & Whalen, 2001; Meck & Church, 1983; Moyer & Landauer, 1967, 1973). Only under certain circumstances in which objects must be tracked over time (e.g., Hauser, MacNeilage, & Ware, 1996; Scholl & Pylyshyn, 1999) or when verbal responses are required (e.g., Kaufman, Lord, Reese, & Volkmann, 1949; Klahr, 1973; Trick & Pylyshyn, 1994; but see Balakrishnan & Ashby, 1992) is it apparent that these populations occasionally rely upon object-file representations of small sets. Given the similarities in the behavioral data across development and across species, it seems reasonable to expect that infants should be able to represent small sets with analog magnitudes, yet the evidence suggests that they routinely fail to do so.

One possible explanation for why infants fail to compare small and large sets is that, in contrast to adults, they are entirely incapable of using analog magnitudes to represent small sets. When infants represent a small set using object files and a large one via analog magnitudes, this may create an incompatibility in representational formats that prohibits infants from comparing the two representations, thus resulting in a failure to discriminate the sets (Feigenson, Carey, & Hauser, 2002; Xu, 2003). Comparing object files and analog magnitudes may be akin to comparing apples to oranges. Under this scenario, infants will always fail to discriminate when faced with a small and a large set, regardless of task parameters. Alternatively, infants may be capable of representing small sets with analog magnitudes under some circumstances. For example, are infants still unable to compare small and large sets when they differ by a large ratio, such as 1:4?

Here we explore whether the ratio between the small and large numerosity influences infants' ability to make numerical discriminations. Four visual habituation experiments with 7-month-old infants tested small versus large numerosity discriminations while varying the ratio twofold (two vs. four and three vs. six) or fourfold (two vs. eight and one vs. four).

Experiment 1: Two Versus Eight

In Experiment 1, we tested whether infants can discriminate a fourfold change in number across small and large sets. Seven-month-old infants were tested with a two versus eight discrimination using a design modeled after Xu and Spelke (2000; Xu, 2003; Xu et al., 2005) in which continuous variables were carefully controlled.

Method

Participants—Participants were 16 healthy, full-term 7-month-old infants (mean age = 7 months 0 days; range: 6 months 13 days to 7 months 16 days) recruited from the Raleigh–Durham area. Eight of the infants were female. Data from an additional 9 infants were discarded for failing to meet the habituation criterion ($n = 2$), fussiness resulting in failure to complete at least four test trials ($n = 6$), or computer error ($n = 1$).[2] Racial and ethnic demographics of the participants from all experiments were approximately 6% Hispanic, 6% Black or African American, 2% Asian, 4% more than one race, 4% unreported, and 78% White or Caucasian; all were from primarily middle-income families.

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[2]The percentages of participants who were excluded due to fussiness and who failed to meet the habituation criterion in the current experiments were comparable to that of other published studies (e.g., Brannon, Abbot, & Lutz, 2004; Xu & Spelke, 2000). Across all four experiments, the exclusion rate due to fussiness or excessively long looking was approximately 25%.

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

Stimuli—Stimuli were created with Canvas software (Version 8.0.1) and displayed in the center of the computer monitor (see Figure 1 for example stimuli). Stimulus parameters were based on Xu & Spelke (2000); however, whereas their study involved a twofold numerical comparison, the current study involves a fourfold comparison. Stimuli were two- or eight-element arrays of black dots displayed in the center of the computer monitor. There were six habituation stimuli for each condition (two and eight), and cumulative surface area varied fivefold across the stimuli. Average element size in the two-element arrays (mean area $= 10.81$ cm^2; range $= 3.53$–17.64 cm^2) was quadruple that of the eight-element arrays (mean area $= 2.70$ cm^2; range $= 0.88$–4.41 cm^2), so that average brightness and cumulative surface area of the two-element and eight-element arrays were equated. The stimulus background was constant in size (19×18 cm^2); consequently, the density of the eight-element arrays (0.023 elements per cm^2) was quadruple that of the two-element arrays (0.00058 elements per cm^2).

In test, infants saw three novel exemplars of each numerosity. Individual element size was held constant at 5.5 cm^2. This element size was chosen so that the cumulative surface area of the two-element and eight-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 0.019 elements/cm^2 by placing the eight-element test arrays within a stimulus background (18×24 cm^2) that was quadruple the size of the two-element test arrays (18×6 cm^2). The spatial configuration of the elements changed between test stimuli.

In sum, the continuous variables that varied between the two-and eight-element arrays in habituation (i.e., density and element size) were equated in the two- and eight-element test displays, as opposed to cumulative surface area, which was held constant across the two- and eight-element habituation arrays and varied between the two- and eight-element test arrays. This design ensured that if infants looked 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 were instructed to keep their eyes closed and refrain from talking to, touching, or otherwise interacting with their infants 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 Sony color video camera 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 infant's 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 (Release 4; REAL Software, Austin, TX), which automatically advanced the stimulus and automatically moved on to the test phase when the criterion was met. The program recorded infants as looking or not looking for each 100-ms interval and calculated interobserver reliability. Reliability between the two observers who coded 75% of the data live (as conservatively computed, based on agreement or disagreement at each 100-ms interval and averaged across subjects) was 91.5% on average.

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 continuously for 2 s. The six different habituation stimuli were presented in a pseudorandom order (i.e., presentation was random except that the same habituation stimulus was never shown on two consecutive trials) until the infant met the habituation criterion (a 50% reduction in looking time over 3 consecutive trials, relative to the first 3 trials during which the infant looked for a total of at least 12 s). If the infant did not meet the habituation criterion within the first 16 trials, the subject was excluded from analyses. After habituation the infants were tested with 6 test trials according to the same procedure and alternated between familiar and novel number.

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. Only infants who met the habituation criterion were included, so not surprisingly, a paired t test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 7.2$, $p < .001$, Cohen's $d = 2.0$.

A $2 \times 2 \times 3$ mixed-factor analysis of variance (ANOVA) testing the between-subjects factor of habituation condition (two or eight dots), the within subjects factors of test trial type (novel or familiar number), and test trial pair (first, second, third) on infants' looking time revealed a main effect of test trial type, $F(1, 14) = 7.1$, $p < .05$, $h_p^2 = .34$, and no other significant main effects or interactions.[3]

The main effect of test trial type reflected the fact that infants looked significantly longer to novel ($M = 5.4$, $SE = .73$) compared to familiar ($M = 3.3$, $SE = .51$) test trials, $t(15) = 2.4$, $p < .05$, Cohen's $d = .77$. Similarly, a paired-samples t test revealed that infants looked significantly longer at the novel test trials compared to the last three habituation trials ($M = 3.5$, $SE = .34$), $t(15) = 2.2$, $p < .05$, Cohen's $d = .75$, but did not look longer at the familiar number test trials compared to the last three habituation trials, $t(15) = 0.42$, $p > .6$.[4] Although only 11 of the 16 infants looked longer overall to the novel compared to the familiar test trials (binomial, $p > .05$), 12 out of 16 ($p < .05$) looked longer on the first test trial, suggesting that the initial change in number was noticeable.

When designing this study, we thought one possibility was that infants habituated to large sets would engage the analog magnitude system and easily detect the novelty of the small numerosity presented in test. In contrast, infants habituated to small sets might open object files and fail to engage the analog magnitude system when tested with large values in test, thus encountering the problem of incompatible representations. The results, however, are not consistent with that idea. Instead, infants detected the novel numerosity in the first test trials, regardless of habituation condition, revealing no asymmetry in novelty response between small–large and large–small.

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[3]When data from the two nonhabituated infants were included in the ANOVA, the results held. A main effect of test trial type, $F(1, 16) = 6.2$, $p < .05$, $h_p^2 = 28$, was found with no other significant main effects or interactions.
[4]Two looks exceeded three standard deviations of the mean duration of all test trials. These looking times were replaced with the next longest looking time for all infants. In addition, one missing test trial pair was replaced with the average looking times (across all infants) for that condition (as in Xu & Spelke, 2000).

Experiment 2: Three Versus Six

The results of Experiment 1 demonstrate that infants can discriminate a small from a large numerosity with the values two and eight. One possibility is that infants require a 1:4 ratio to discriminate small from large sets. However, the majority of the previous failures with a 1:2 ratio (and specifically, those involving habituation designs) have involved discrimination of the values two and four. Thus, another possibility is that there is something particularly difficult about this comparison because four is at the cusp of the limitations of the object file system. That is, sets of four may recruit the object-file system in infants but fail midway during the construction of object files. The recruitment of the object-file system for sets of four may prevent infants from detecting the clear mismatch between two object files and a purely analog magnitude representation. In Experiments 2 and 3, we pit predictions of our "four is special" hypothesis with those of our "greater ratio" theory by testing infants in a three versus six (Experiment 2) and a one versus four (Experiment 3) discrimination.[5] If four is an especially confusing value for infants to represent, then infants should succeed in the three versus six comparison (because it does not involve four), even though it only involves a twofold change in number. Similarly, they should fail in a one versus four comparison, despite the favorable ratio, due to difficulties in representing sets of four. On the other hand, if the value four is not the culprit and instead infants simply require a greater ratio for successful discrimination of small and large sets, we should find the opposite pattern of results.

Method

Participants—Participants were 16 healthy, full-term 7-month-old infants (mean age = 6 months 27 days; range: 6 months 14 days to 7 months 10 days). Nine of the infants were female. Data from an additional 11 infants were discarded for failing to meet the habituation criterion ($n = 7$), fussiness resulting in failure to complete at least four test trials ($n = 3$), or computer error ($n = 1$).

Design—Infants were habituated to arrays containing three or six dots that varied in surface area and were then tested with novel arrays containing three and six 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 3 for example stimuli). Stimulus parameters were again based on Xu & Spelke (2000). Stimuli were three- or six-element arrays of black dots displayed in the center of the computer monitor. There were six habituation stimuli for each condition (three and six), and cumulative surface area varied fivefold across the stimuli. Average element size in the three-element arrays (mean area = 9.1 cm^2, range = 3.5–17.6 cm^2) was double that of the six-element arrays (mean area = 4.6 cm^2, range = 1.8–8.8 cm^2), so that average brightness and cumulative surface area of the three-element and six-element arrays were equated. The stimulus background was constant in size (18×19 cm^2); consequently, the density of the six-element arrays (0.018 elements per cm^2) was double that of the three-element arrays (0.009 elements per cm^2).

In test, infants saw three novel exemplars of each numerosity. Individual element size was held constant at 6.5 cm^2. This element size was chosen so that the cumulative surface area of the three-element and six-element test stimuli differed from the average cumulative surface area

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[5]These comparisons have already been tested with the graham cracker and manual search tasks (Feigenson & Carey, 2005; Feigenson, Carey, & Hauser, 2002), in which older infants typically fail. Although these failures are robust, the cognitive and motor demands of these experimental tasks are significantly greater than those imposed by the traditional habituation designs presented here, and thus it is unclear whether the additional demands may have detrimentally influenced performance. For that reason, it was appropriate to test these specific comparisons using a less-demanding design on the young infant.

of the habituation stimuli by the same ratio. Random spatial configuration of the elements changed between test stimuli. In addition, element density of the test arrays was held constant at 0.012 elements/cm^2 by placing the six-element test arrays within a stimulus background (19×25.5 cm^2) that was double the size of the three-element test arrays (19×12.7 cm^2). The outline of the stimulus background was invisible to the infant.[6]

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

Results and Discussion

Figure 4 shows the mean looking times for the first three and last three habituation trials, the three novel test trials, and the three familiar test trials from Experiment 2. Again, because only habituated infants were included in this experiment, a paired *t* test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 5.2$, $p < .001$, Cohen's $d = 1.6$.

A $2 \times 2 \times 3$ mixed-factor ANOVA testing the between-subjects factors of habituation condition (three or six dots) and the within-subjects factor of test trial type (novel or familiar number) and test trial pair (first, second, third) on infants' looking time revealed no significant main effects or interactions.[7,8] Average looking time to the novel ($M = 4.8$, $SE = .46$) and familiar ($M = 4.2$, $SE = .36$) test trials was very similar, and only 10 of 16 infants looked longer to the novel number compared to the familiar number, suggesting that infants did not reliably detect a difference between sets of three and sets of six. Interestingly, infants did look longer to the novel, $t(15) = 3.1$, $p < .05$, Cohen's $d = 0.74$, but not the familiar test trials, $t(15) = 2.04$, $p > .05$, as compared to the last three habituation trials ($M = 3.6$, $SE = .33$), indicating that infants did at least partially notice the change in number.

These results suggest that previous infant failures in detecting a change from small to large sets are not due to a specific difficulty in representing the value four. Thus, the success reported in Experiment 1 is likely a function of the fourfold change in number from habituation to test, suggesting that in order to compare small to large sets, infants require a significantly greater ratio of change in number. To explore this hypothesis, in Experiment 3 we used a fourfold change in number across the small—large boundary with the values one and four.

Experiment 3: One Versus Four

In Experiment 3, we tested whether infants can discriminate one from four using the same design as Experiments 1 and 2. The only difference in the design of this experiment is that we used yellow happy faces instead of plain black circles, out of concern that infants would be otherwise uninterested in displays with a single element (Xu, 2003).

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[6]Although the change in the size of the background between habituation and test was significantly greater in Experiment 1 than in Experiment 2 (due to the density control), it should be pointed out that this factor did not differ between novel and familiar test trials and thus could not contribute to the pattern of success or failure in discrimination obtained in any of the experiments described here.
[7]Two looks exceeded 3 standard deviations from the mean of looking during test trials from all subjects. These values were replaced as in Experiment 1. In addition, four missing test trial pairs were replaced with the average looking for that condition.
[8]When data from the seven nonhabituated infants were included in the ANOVA, the results were similar. A marginally significant main

effect of test trial type, $F(1, 21) = 4.4$, $p = .05$, $h_p^2 = .17$, was found, but this was clearly driven by a Test Trial Type $\times$ Habituation

Condition interaction, $F(1, 21) = 10.3$, $p < .01$, $h_p^2 = .33$, which revealed an overall preference for all infants to look to the large number stimulus, regardless of habituation condition. In fact, those infants habituated to six dots looked slightly longer on average to the familiar numerosity stimuli ($M = 4.4$, $SE = .61$) as compared to the novel numerosity stimuli ($M = 4.0$, $SE = .69$), suggesting infants did not detect the change in numerosity. There were no other significant main effects or interactions.

Method

Participants—Participants were 16 healthy, full-term 7-month-old infants (mean age = 6 months 30 days; range: 6 months 12 days to 7 months 14 days). Seven of the infants were female. Data from an additional 11 infants were discarded for failing to meet the habituation criterion ($n = 5$); fussiness resulting in failure to complete at least four test trials ($n = 4$); computer error ($n = 1$); or excessively long looking times during test, resulting in two or more test trials being excluded on the basis of our method of excluding outliers ($n = 1$).

Design—Infants were habituated to arrays containing one or four circle happy faces that varied in surface area and were then tested with novel arrays containing one and four faces. 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 5 for example stimuli). Stimuli were yellow circles with happy faces in black. Stimulus parameters were based on Xu & Spelke (2000). Stimuli were one element or four elements displayed in the center of the computer monitor. There were six habituation stimuli for each condition (one and four), and cumulative surface area varied fivefold across the stimuli. Average element size in the one-element displays (mean area = 27.4 cm^2, range = 10.6–53.0 cm^2) was quadruple that of the four-element arrays (mean area = 6.9 cm^2, range = 2.7–13.2 cm^2) so that average brightness and cumulative surface area of the one-element and four-element arrays were equated. The stimulus background was constant in size (18×19 cm^2); consequently, the density of the four-element arrays (0.012 elements per cm^2) was quadruple that of the one-element displays (0.003 elements per cm^2).

In test, infants saw three novel exemplars of each numerosity. Individual element size was held constant at 13.7 cm^2. This element size was chosen so that the cumulative surface area of the one-element and four-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 0.0073 elements/cm^2 by placing the four-element test arrays within a stimulus background (19×28.8 cm^2) that was quadruple the size of the one-element test arrays (19×7.2 cm^2). The spatial configuration of the elements changed between test stimuli. Again, the use of this design ensured that if infants looked 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 and procedure—The apparatus and procedure were identical to those in Experiment 1. Intercoder reliability was 95%.

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. A paired t test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 5.0$, $p < .001$, Cohen's $d = 1.17$.

A $2 \times 2 \times 3$ mixed-factor ANOVA testing the between-subjects factor of habituation condition (one or four elements) and the within-subjects factor of test trial type (novel or familiar number) and test trial pair number (first, second, third) on infants' looking time revealed a main effect of test trial type, $F(1, 12) = 16.6$, $p < .05$, $h_p^2 = .41$) and no other significant main effects or interactions.[9]

In addition to the main effect of novelty, three other analyses suggest that infants detected the change in numerosity. First, a paired-samples t test revealed that infants looked longer at the

novel ($M = 5.9$, $SE = .74$) than the familiar ($M = 4.0$, $SE = .45$) numerosities, $t(15) = 3.2$, $p < .01$, Cohen's $d = 0.79$. Similarly, a paired-samples t test revealed that infants looked significantly longer at the novel test trials compared to the last three habituation trials ($M = 3.8$, $SE = .56$), $t(15) = 3.8$, $p < .01$, Cohen's $d = 0.82$, but did not look longer at the familiar number test trials compared to the last three habituation trials, $t(15) = 0.4$, $p > .7$.[10] Finally, 14 of the 16 infants looked longer at the three novel test trials compared to the three familiar test trials. Again, we did not find a significant advantage for infants habituated to the large numerosity over those habituated to the small value, suggesting that prior activation of the analog magnitude system (in habituation) does not make the infants more inclined to represent the small sets with magnitudes.

Experiment 4: Two Versus Four

Although mean looking times in Experiment 3 were comparable to looking times in Experiments 1 and 2, it is possible that the success in Experiment 3 was related to the inclusion of more interesting stimuli (happy faces). So, in Experiment 4, we tested whether infants could discriminate two from four (a 1:2 ratio), using the same circular happy face stimuli as in Experiment 3.

Method

Participants—Participants were 16 healthy, full-term 7-month-old infants (mean age = 7 months 2 days; range: 6 months 20 days to 7 months 13 days). Seven of the infants were female. Data from an additional 18 infants were discarded for failing to meet the habituation criterion ($n = 4$), for fussiness resulting in failure to complete at least four test trials ($n = 12$), or for excessively long looks during test, resulting in the exclusion of two or more test trials ($n = 2$).

Design—Infants were habituated to arrays containing two or four circular happy faces that varied in surface area and were then tested with novel arrays containing two and four faces. 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 7 for example stimuli). Stimulus parameters were again based on Xu & Spelke (2000). Stimuli were two- or four-element arrays of yellow happy faces displayed in the center of the computer monitor. There were six habituation stimuli for each condition (two and four), and cumulative surface area varied fivefold across the stimuli. Average element size in the two-element arrays (mean area = 13.7 cm^2, range = 5.3 to 26.5 cm^2) was double that of the four-element arrays (mean area = 6.9 cm^2, range = 2.7 to 13.2 cm^2) so that average brightness and cumulative surface area of the two-element and four-element arrays were equated. The stimulus background was constant in size (18×19 cm^2); consequently, the density of the four-element arrays (0.012 elements per cm^2) was double that of the two-element arrays (0.006 elements per cm^2).

In test, infants saw three novel exemplars of each numerosity. Individual element size was held constant at 9.7 cm^2. This element size was chosen so that the cumulative surface area of the two-element and four-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 0.008 elements/cm^2 by placing the four-element test arrays within a stimulus

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[9]When data from the 6 infants who did not habituate were included in the ANOVA, the results held. A significant main effect of test trial type, $F(1, 20) = 9.6$, $p < .01$, $h_p^2 = .33$, and no other significant main effects or interactions were found.

[10]One look exceeded three standard deviations of the mean duration of all test trials and was replaced, as in Experiment 1.

background (19×25.5 cm^2) that was double the size of the two-element test arrays (19×12.7 cm^2). Random spatial configuration of the elements changed between test stimuli.

Apparatus and procedure—The apparatus and procedure were identical to those in Experiment 1. Intercoder reliability was 94.5%.

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 t test revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, $t(15) = 9.0$, $p < .0001$, Cohen's $d = 2.4$.

A $2 \times 2 \times 3$ mixed-factor ANOVA testing the between-subjects factor of habituation condition (2 or 4 dots) and the within-subjects factors of test trial type (novel or familiar number) and test trial pair number on infants' looking time revealed no significant main effects or interactions ($p > .1$).[11,12] Only 9 of 16 infants looked longer to the novel number ($M = 4.1$, $SE = .25$) compared to the familiar number ($M = 4.3$, $SE = .42$), suggesting that infants did not reliably detect a difference between two and four elements. Infants did dishabituate to both the novel, $t(15) = 3.7$, $p < .005$, Cohen's $d = 1.05$, and familiar $t(15) = 2.5$, $p < .03$, Cohen's $d = 0.90$) test trials relative to the last three habituation trials, again suggesting they noticed a change between habituation and test stimuli. Although this may be attributed to infants successfully detecting a change in number, the longer looks in test may also be a function of infants noticing the change in other stimulus properties, such as element density.

Nonetheless, these results replicate findings from other laboratories while supporting the theory that infants are unable to compare small and large sets when the sets differ by a 1:2 ratio. Instead, results of Experiments 1 and 3 suggest that infants require a greater ratio of change to detect the change in numerosity.

Combined Analyses

We conducted a $2 \times 2 \times 3$ mixed-factors ANOVA combining data from all four experiments looking at the between-subjects factor of ratio of change in numerosity (1:4 in Experiments 1 and 3; 1:2 in Experiments 2 and 4) and the within-subjects factors of test trial type (novel or familiar) and test trial pair number (first, second, third). Results revealed a main effect of test trial type, $F(1, 62) = 12.6$, $p < .005$, $h_p^2 = .17$, as well as a significant Numerosity Ratio $\times$ Test Trial Type interaction, $F(1, 62) = 8.8$, $p < .005$, $h_p^2 = .12$. Follow-up ANOVAs revealed that whereas infants in the 1:2 numerosity ratio change conditions (Experiments 2 and 4) did not look longer to novel ($M = 4.4$, $SE = .26$) as compared to familiar test trials ($M = 4.2$, $SE = .27$), $F(1, 31) = 0.29$, $p > .5$, infants in the 1:4 numerosity ratio change conditions did show a significant novelty effect: novel, $M = 5.6$, $SE = .52$; familiar, $M = 3.7$, $SE = .35$; $F(1, 31) = 15.2$, $p < .001$, $h_p^2 = .33$. In addition, infants in the 1:4 ratio conditions revealed a significant main effect of trial pair number, $F(2, 31) = 4.8$, $p < .05$, $h_p^2 = .13$. This reflected the fact that infants in this condition looked longer on the first pair of test trials ($M = 5.5$, $SE = .47$) as compared to the second ($M = 4.1$, $SE = .40$), $t(31) = 3.5$, $p < .005$, Cohen's $d = 0.56$, and third pairs ($M = 4.3$, $SE = .51$), $t(31) = 2.3$, $p = .03$, not significant with Bonferoni correction. This analysis confirms that, in contrast to discriminations in the large number range, infant

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[11]No data points exceeded three standard deviations from the mean of looking during test, but four missing test trial pairs were replaced with average looking times for that condition.
[12]Again, when data from all infants (habituators and nonhabituators) were included in the ANOVA, the same results were found. None of the main effects or interactions were significant, including that of test trial type, $F(1, 21) = .35$, $p > .5$.

discriminations of small from large sets (and vice versa) require at least a fourfold change in number.

General Discussion

The main finding from these four experiments is that young infants can compare small and large sets on the basis of number but that they require a larger ratio when comparing a small and large value than when comparing two large values. When tested with static arrays, in two different experiments, infants looked longer to the novel numerosity when number varied fourfold, but failed to detect a change when number varied twofold. Infants' success in our study at comparing small and large values that differ by a 1:4 ratio is consistent with a recent study that found that infants successfully discriminated two from eight but failed to detect a 1:4 change in surface area (Cordes & Brannon, 2009).

There are two additional points about our data that warrant discussion. First, those infants habituated to the large value were not more likely to detect a change in numerosity than the infants habituated to small values. This pattern of results rules out the possibility that early activation of the magnitude system is necessary for infants to represent small sets as analog magnitudes allowing for small and large set comparisons. In both Experiments 1 and 3, infants habituated to small values showed robust novelty effects to the large values, suggesting that exposure to a large number first was not necessary. Second, our data are not consistent with the possibility that previous failures to discriminate two versus four were due to a specific difficulty in representing the value four, given that infants successfully discriminated a one versus four contrast. Furthermore, when infants were tested with a 1:2 ratio that did not include the value four (three vs. six), infants still failed to discriminate the sets. In sum, infants did not appear to have an advantage when habituated to the large values compared to the small values, and the absolute value of the tested set sizes did not appear to control performance (failed at three vs. six and two vs. four). Why then do infants require a greater ratio of change to successfully discriminate a small from a large set compared to two large sets?

There are at least two different explanations for how infants compared small and large sets in these studies. First, infants may have initially represented small sets exclusively with object files and large sets exclusively with analog magnitudes and subsequently converted object files into analog magnitudes before the comparison process occurred. In this scenario, the fact that infants required greater than a 1:2 ratio for successful comparison might be due to increased noise in analog representations that were formed as a result of conversion from object files. Although there is no a priori reason to assume that converting object files to analog representations results in increased noise, such an assumption would explain why a fourfold change was necessary. We refer to this hypothesis as the *noise hypothesis*.

Alternatively, rather than converting object files to analog magnitudes, infants may not be so different from adults in that they instead may have represented both small and large sets with analog magnitudes from the outset. In this scenario, when the result of the analog magnitude comparison fails to exceed some threshold of change, object files trump analog magnitudes for the young infant. Thus, the infant ends up with a failed comparison of small versus large sets when the magnitude representations do not differ by some critical threshold. Although this may seem like a maladaptive process, it is possible that object files trump analog magnitude representations because they are discrete, exact representations and are thus generally more reliable for small values. Given that the precision of analog magnitude representations increases in precision over development (Halberda & Feigenson, 2008; Lipton and Spelke, 2003; Xu & Arriaga, 2007), it is not unreasonable to assume that early in infancy the benefit of object files over analog magnitudes may be important. Thus, under these assumptions, when the ratio between the small and large value exceeds a critical threshold—1:4, or possibly 1:3

(which has not been tested)—infants may be able to ignore their object file representations and successfully compare a large and small set using solely analog magnitude representations. We refer to this hypothesis as the *threshold hypothesis*.

The noise hypothesis requires a two-step process. Infants must first detect the mismatch between the representational formats used for small and large sets and subsequently convert the object file representation to an analog magnitude. This may take place regardless of the ratio of change between the sets, but the increase in noise results in discrimination failures when the small and large set differ by a 1:2 ratio. Only when the sets differ by a larger ratio (i.e., 1:4) can the infant succeed in the discrimination, because this additional noise has relatively little impact on discriminations involving such a large change in set size. In contrast, under the threshold hypothesis, no conversion is necessary. Instead, the idea is that infants routinely represent small sets with both object files and analog magnitudes, yet the object file representations trump the analog magnitude representations unless the two magnitudes being compared differ by a critical ratio. When this happens, the analog magnitude representation trumps the object files. The threshold hypothesis is consistent with prior evidence that nonhuman animals and adult humans are able to represent small values with analog magnitudes (e.g., Cantlon & Brannon, 2006; Cordes et al., 2001; Meck & Church, 1983). Thus, the threshold hypothesis implies (a) a simpler process of comparison for infants (fewer steps) and (b) continuity both across the number line (magnitudes represent both small and large values alike) and across development (infants are like adults in that they represent small sets via magnitudes). For these reasons, we prefer the threshold hypothesis as an explanation of our findings.

How can future research distinguish between the noise and threshold hypotheses? One way to explore this question is to assess small–large set discriminability as a function of the number of object files required. If, as posited by the noise hypothesis, the conversion of object files to analog magnitudes involves additional noise in the representation, the amount of additional noise would be dependent upon the number of converted object files. That is, the amount of noise in the representation should increase linearly with the number of object-files (i.e., the number of items in the small set). On the other hand, according to the threshold hypothesis, one would not expect discriminability to vary as a function of the number of items in the small or large set, so long as the ratio between the two stays constant. In the current study, we found successful small-large discrimination with a small set of 1 (Experiment 3) and a small set of 2 (Experiment 1), given a 1:4 ratio. Although these findings are in line with the threshold hypothesis, they do not necessarily negate the noise hypothesis, in that the values tested (using a 1:4 ratio) may not have been at the limits of infant discriminability. Future studies should examine infant discriminations of small and large sets either comparing the absolute values of 3 versus 12 and/or comparing a 1:3 ratio across small and large sets (e.g., 2 vs. 6). If infants succeed in discriminating 2 versus 6 but fail at discriminating 3 versus 9 and/or 3 versus 12 (after having succeeded in 1 vs. 4 and 2 vs. 8), these findings would imply decreased discrimination precision as a function of the number of object files, providing support for the noise hypothesis. On the other hand, if success is instead consistently predicted by ratio (success on all 1:4 ratio comparisons (e.g., 3 vs. 12) and a consistent pattern of success or failure on all 1:3 ratio comparisons), this would provide strong support for the threshold hypothesis.

One last point requires discussion. There have been a handful of previous studies suggesting infants preferentially attend to continuous extent over number for small sets (e.g., Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Hauser, 2002; Feigenson, Carey, & Spelke, 2002), which may lead some to question whether representations of extent played a role in the current experiments. It should first be noted that two recent studies have failed to replicate these findings; instead, infants were found to attend to both extent and number equally in the small

number range (Cordes & Brannon, 2009; Kwon et al., 2009). These recent studies, in concert with other results revealing that infants require a greater ratio of change in order to discriminate cumulative continuous extent of an array compared to numerosity (Cordes & Brannon, 2008a), cast doubt upon claims that infants actually represent extent at the expense of representing number for small sets (see Cordes & Brannon, 2008b). Furthermore, the stimuli used in the current experiments involved strenuous controls for continuous variables (as in Xu & Spelke, 2000). Cumulative surface area, element size, and density varied dramatically across habituation and were then equated and/or controlled for in test, preventing the employment of continuous variables as a cue for discrimination in our tasks. Thus, both previous research and current stimulus controls render it unlikely that representations of continuous extent played a role in this study.

In conclusion, in two experiments infants successfully discriminated static arrays on the basis of their numerosity alone when number changed fourfold, despite the fact that one value was small (less than four) and thus could be handled by an object-file system and the second value was large (four or greater) and could not be represented with object files. In contrast, infants failed to detect a change in set size when sets changed only twofold across the small–large boundary. We argue that the data suggest that infants represented both sets via analog magnitudes and, given the dramatic fourfold change in numerosity, infants attended to these analog magnitude representations over object files. The greater ratio of discriminability required for small–large comparisons as opposed to large–large comparisons (Xu & Spelke, 2000) indicates that there is a minimum threshold of change necessary for infants to ignore their object file representations and instead use analog representations of small sets.

Results of the current study raise new questions regarding the nature of the numerical comparison process. Although we favor the threshold hypothesis as a mechanism for explaining why infants require a large ratio to distinguish small from large sets, it remains possible that infants in our study instead converted object file representations into analog magnitudes. Exploring these questions with other behavioral methods such as operant learning procedures may help distinguish between the noise and threshold hypotheses. Continued exploration of these questions should help toward an understanding of how the infant's quantitative capacities develop.

Acknowledgments

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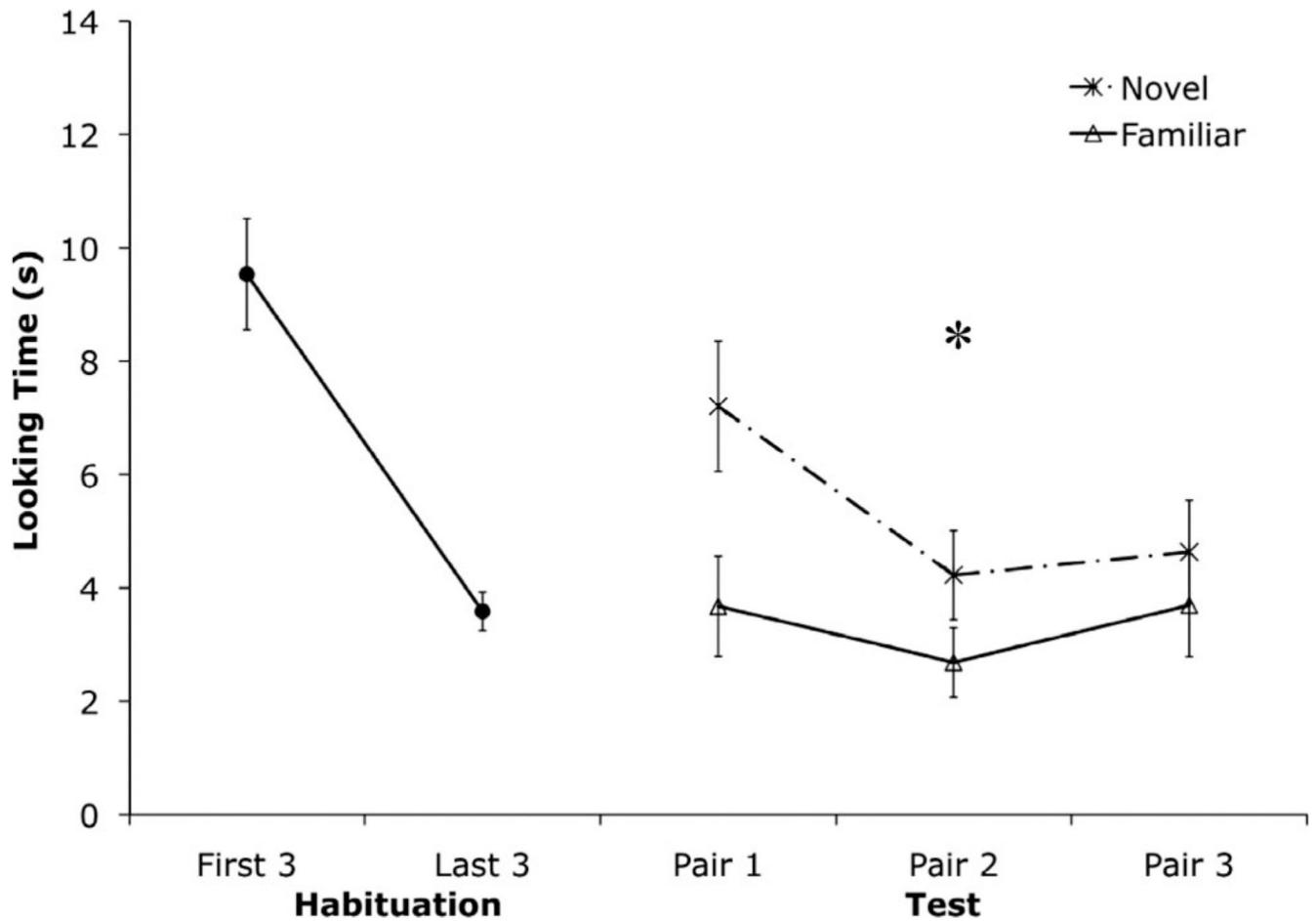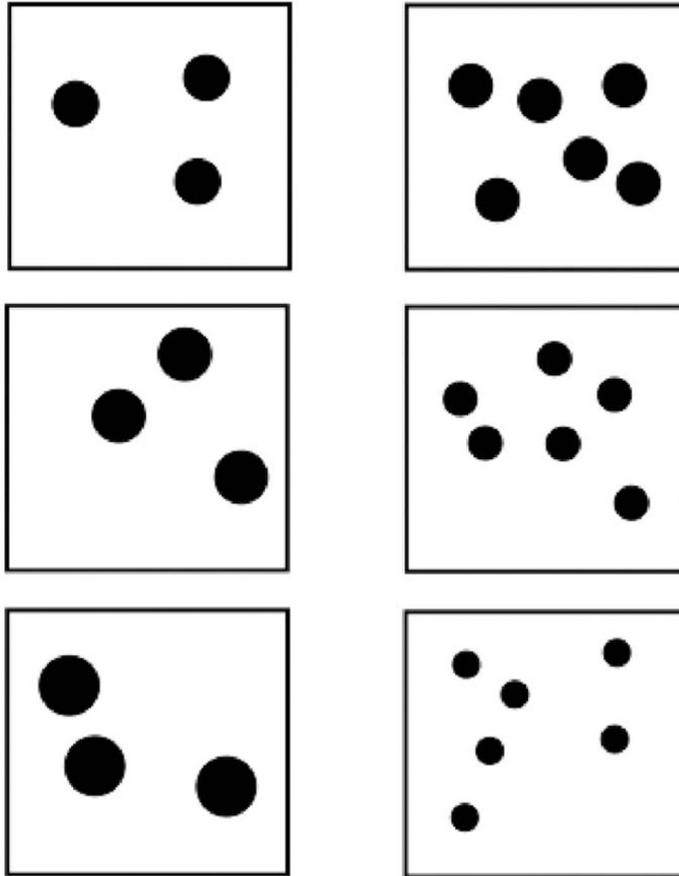
Habituation
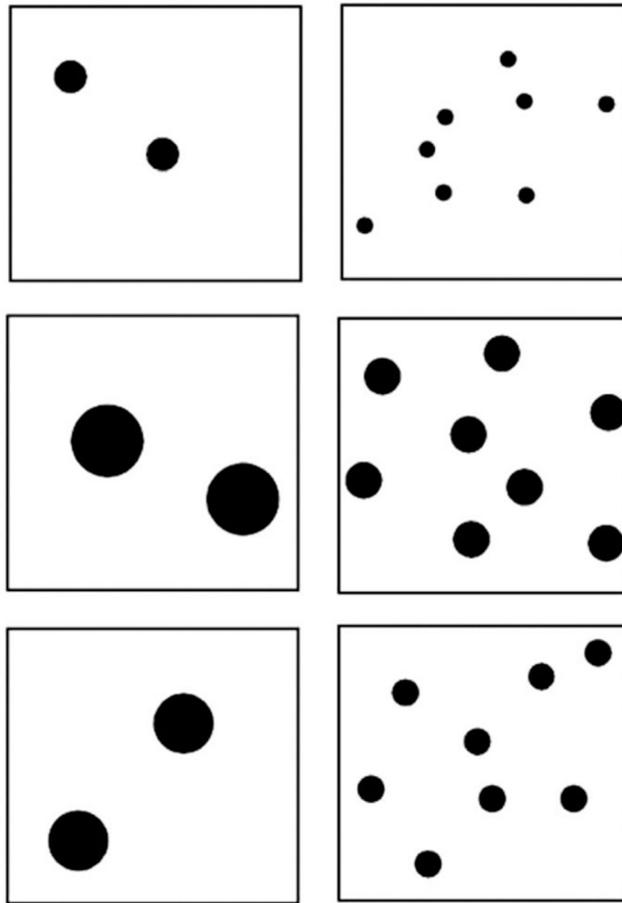
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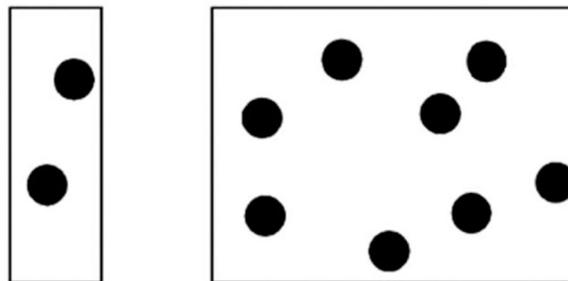
Figure 1.
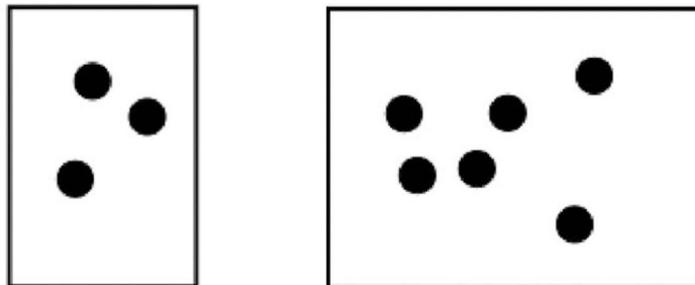Schematic representation of the stimuli used in Experiment 2.

Figure 2.
Average looking times for infants in Experiment 1 (two vs. eight) for the first three and last three habituation trials and for the novel number and familiar number test trials. Error bars signify standard error of the mean. * $p < .05$.
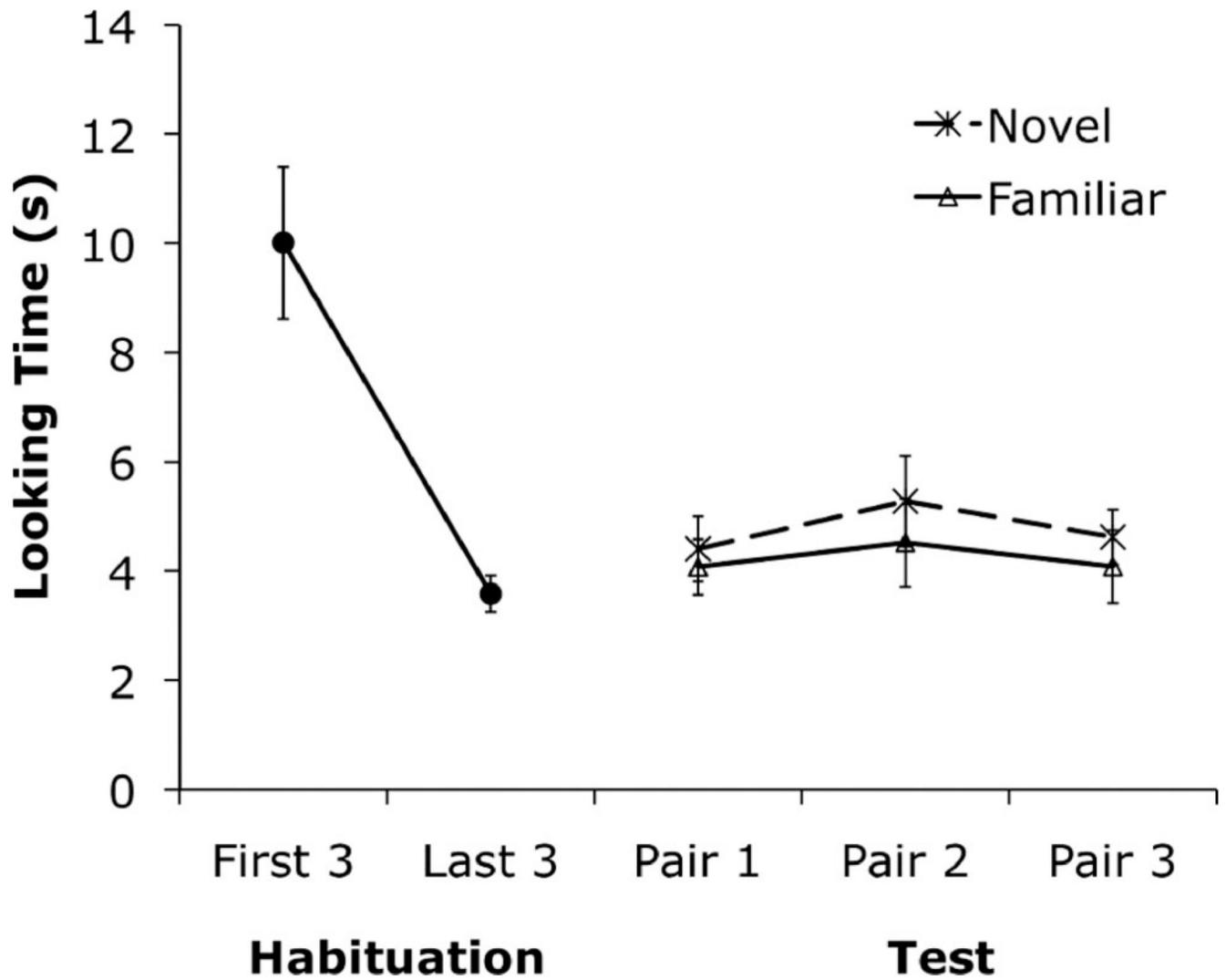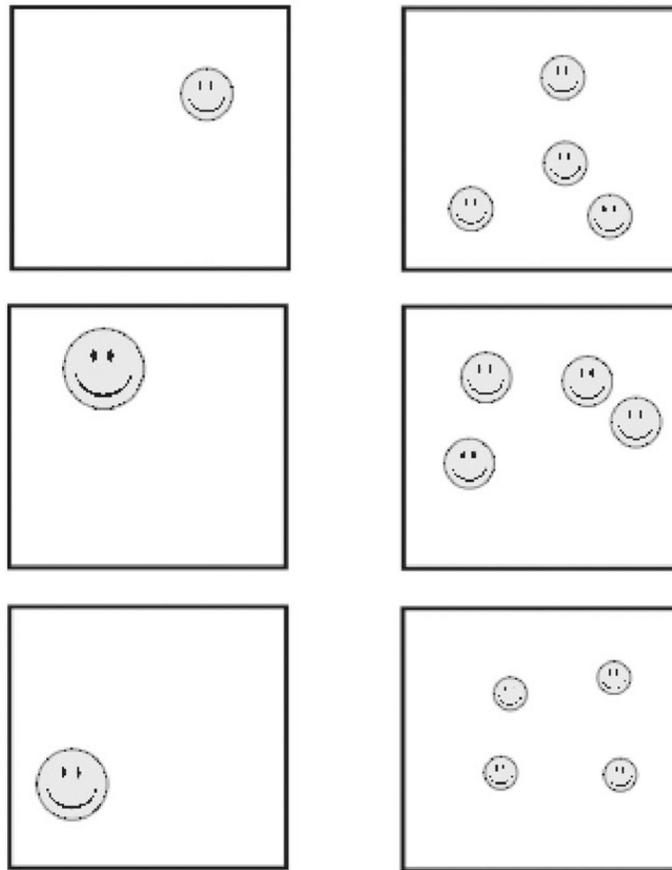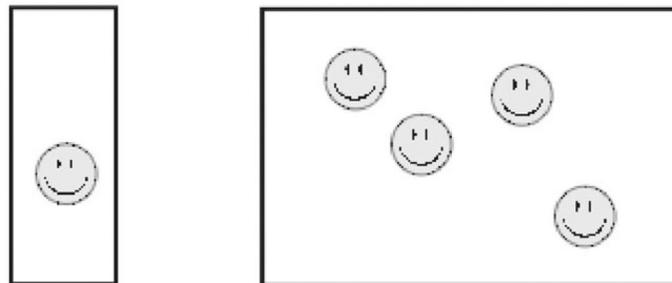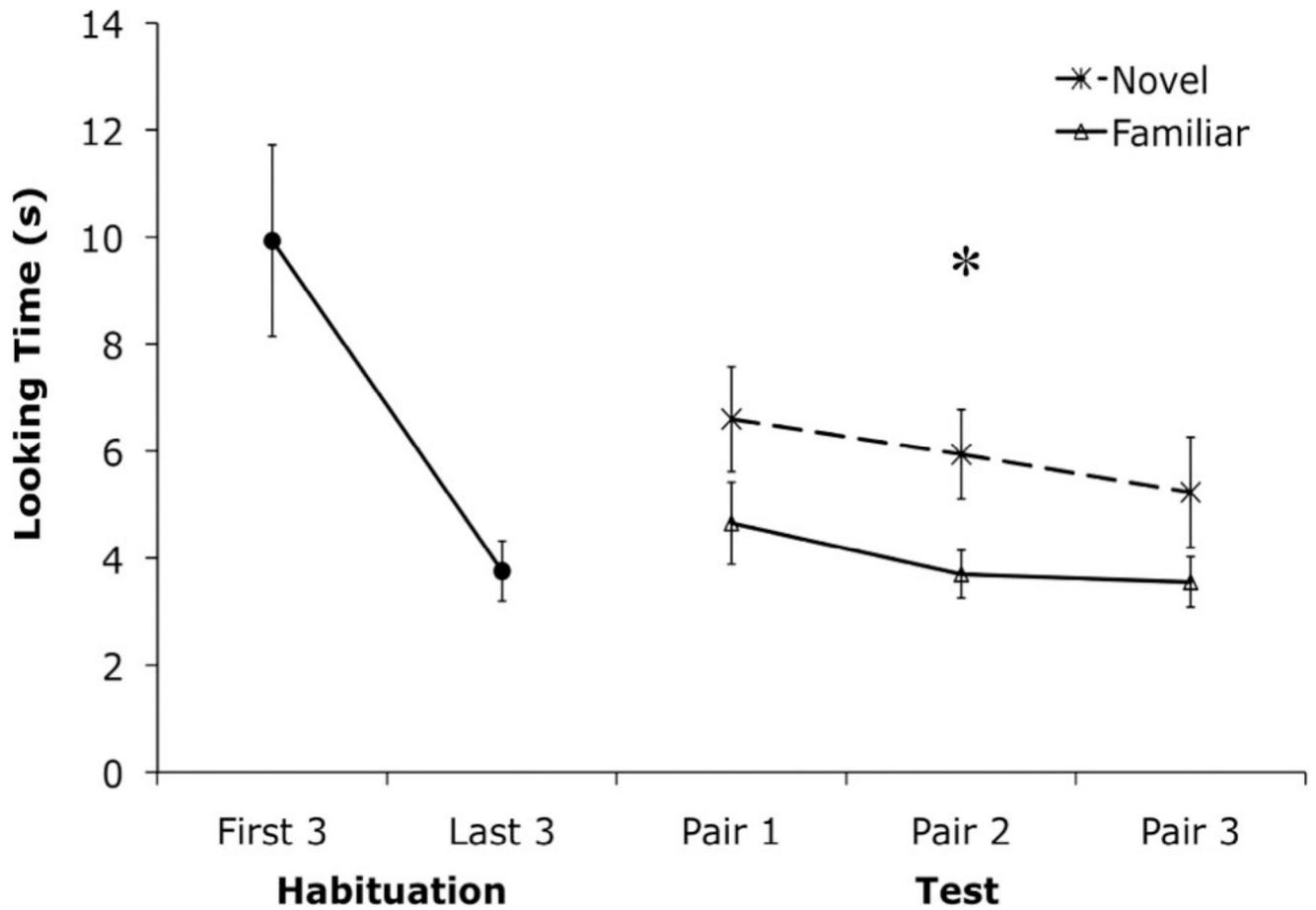
Figure 3.
Schematic representation of the stimuli used in Experiment 2.

Figure 4.
Average looking times for infants in Experiment 2 (three vs. six) for the first three and last three habituation trials and for the novel number and familiar number test trials. Error bars signify standard error.
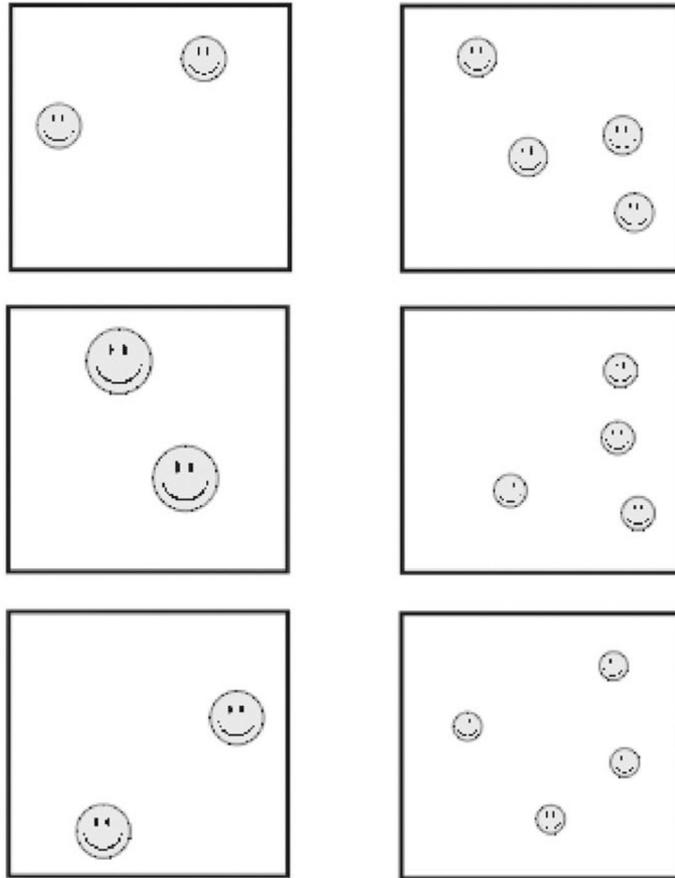
Habituation

Test

Figure 5.
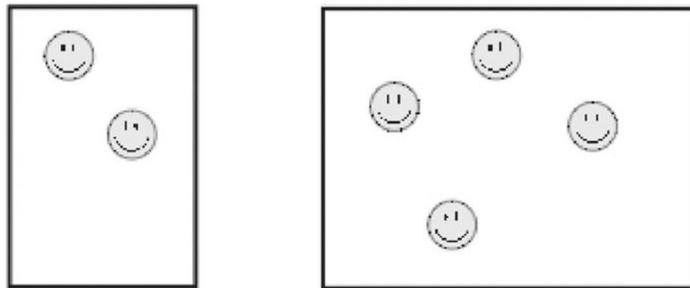Schematic representation of the stimuli used in Experiment 3.

Figure 6.
Average looking times for infants in Experiment 3 for the first three and last three habituation trials and for the novel number and familiar number test trials. Error bars signify standard error of the mean. * $p < .05$.
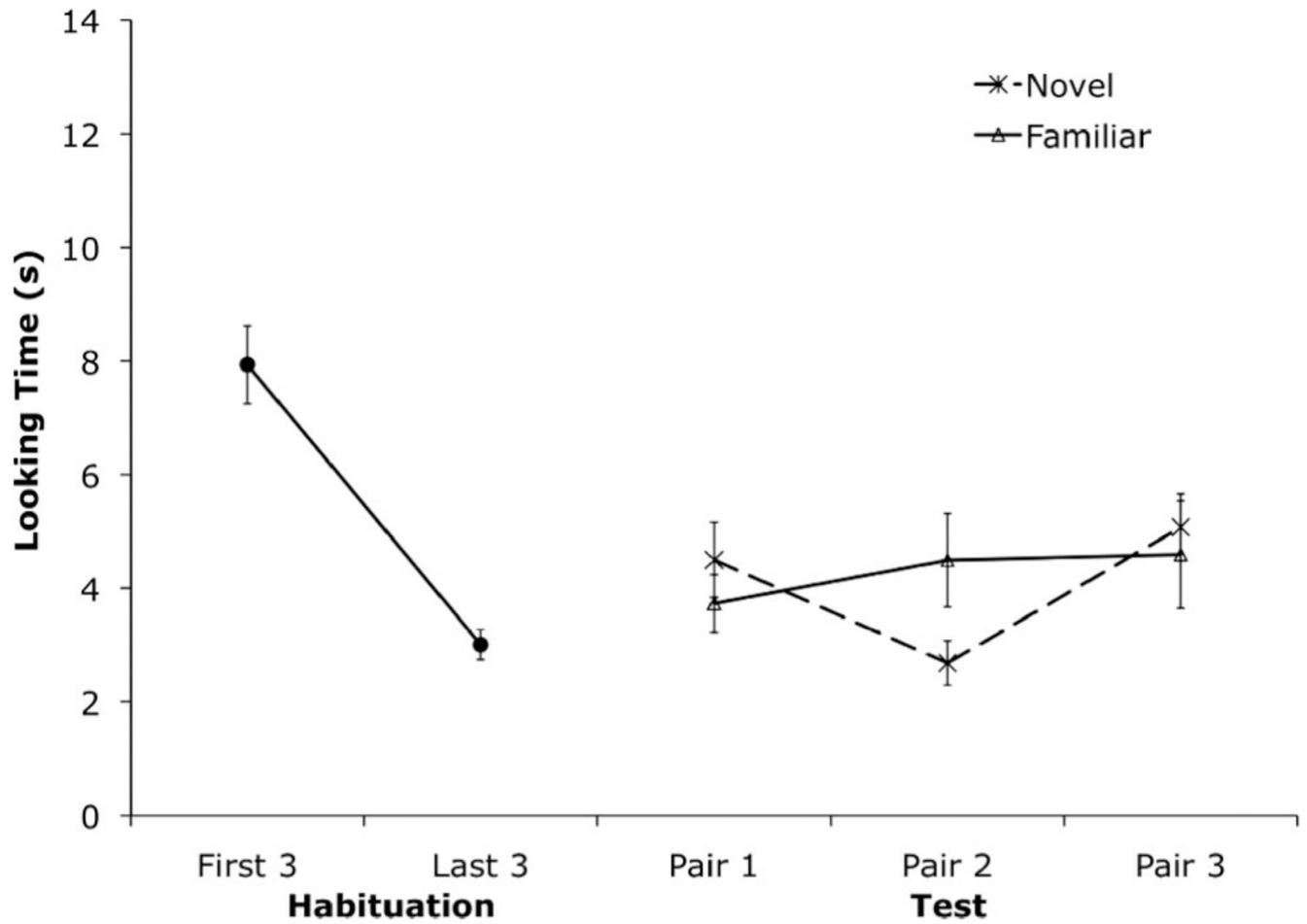
Figure 7.
Schematic representation of the stimuli used in Experiment 4.

Figure 8.
Average looking times for infants in Experiment 4 (two vs. four) for the first three and last
three habituation trials and for the novel number and familiar number test trials.