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# Changes in the Ability to Detect Ordinal Numerical Relationships Between 9 and 11 Months of Age

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# Abstract

When are the precursors of ordinal numerical knowledge first evident in infancy? Brannon (2002) argued that by 11 months of age, infants possess the ability to appreciate the greater than and less than relations between numerical values but that this ability experiences a sudden onset between 9 and 11 months of age. Here we present 5 experiments that explore the changes that take place between 9 and 11 months of age in infants' ability to detect reversals in the ordinal direction of a sequence of arrays. In Experiment 1, we replicate the finding that 11- but not 9-month-old infants detect a numerical ordinal reversal. In Experiment 2 we rule out an alternative hypothesis that 11month-old infants attended to changes in the absolute numerosity of the first stimulus in the sequence rather than a reversal in ordinal direction. In Experiment 3, we demonstrate that 9month-old infants are not aided by additional exposure to each numerosity stimulus in a sequence. In Experiment 4 we find that 11-month-old but not 9-month-old infants succeed at detecting the reversal in a nonnumerical size or area-based rule, casting doubt on Brannon's prior claim that what develops between 9 and 11 months of age is a specifically numerical ability. In Experiment 5 we demonstrate that 9-month-old infants are capable of detecting a reversal in ordinal direction but only when there are multiple converging cues to ordinality. Collectively these data indicate that at 11 months of age infants can represent ordinal relations that are based on number, size, or cumulative area, whereas at 9 months of age infants are unable to use any of these dimensions in isolation but instead require a confluence of cues.

Imagine being able to differentiate a mouse from an elephant but not appreciating that one is bigger than the other. Further imagine being able to differentiate collections of two objects from collections of three objects but not appreciating that three is more than two. Both postulations are difficult for adult humans, because we have a rich appreciation of animal sizes and numbers. However, some theories of the development of numerical concepts contend that infants first comprehend only the cardinal properties of number and then later come to appreciate ordinal relationships between numbers through observing numerical transformations in their environment (see Cooper, 1984; Dehaene & Changeux, 1993; Kitcher, 1984; Strauss & Curtis, 1984). If an appreciation of the cardinal numerosity of a set of objects develops before an appreciation of ordinal relations between numerosities, then we should be able to identify an age at which infants can differentiate collections of objects based on number but fail to detect ordinal numerical relations.

A handful of studies have addressed whether young children understand ordinal numerical relationships (e.g., Brannon & Van de Walle, 2001; Bullock & Gelman, 1977; Huntley-Fenner & Cannon, 2000; Rousselle, Palmers, & Noel, 2004; Siegel, 1974; Sophian & Adams, 1987; Strauss & Curtis, 1984). These studies suggested that young children make

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ordinal numerical judgments before they are proficient at using the verbal counting system to mediate these judgments. This idea is supported by a large body of data from Wynn and colleagues that indicates that within the first year of life infants are able to track additions and deletions of objects indicating that not only are infants able to represent number, but they are also able to arithmetically manipulate these representations (e.g., McCrink & Wynn, 2004; Wynn, 1992). However, attempts to find evidence of ordinal numerical knowledge in infants younger than 12 months of age have often been unsuccessful. For example, Cooper (1984) presented infants with sequentially presented pairs of numerosities. The first and second stimuli maintained a constant ordinal numerical relationship, but the absolute values varied between trials (ranging from 1-4). On different trials infants observed one dot followed by two dots or two dots followed by four dots and looking time to the second stimulus was measured. Infants were then given test trials where the ordinal numerical relationship between the two stimuli was the same as in habituation, was reversed, or was eliminated by equating the numerical value of the first and second stimulus (e.g., three followed by three). After being habituated to pairs that increased or decreased in number, 10- to 12-month-old infants dishabituated when tested with novel pairs that contained two equal numerical values but failed to dishabituate to the novel pairs that reversed in ordinal direction. In contrast, 14- to 16-month-old infants dishabituated to both of the novel types of test trials (change in ordinal direction and elimination of ordinal relation). Cooper's data suggested a late emergence of ordinal numerical knowledge at around 14 months of age, although it is important to note that the experiment did not control for surface area.

More recently, however, Brannon (2002) found evidence that suggests ordinal numerical knowledge emerges in the first year of life. In that study, 9- and 11-month-old infants were habituated to repeating sequences of three numerosities with an ascending or descending ordinal numerical relationship (i.e., 1-2-4, 2-4-8, or 4-8-16). Once infants were habituated to a given ordinal direction, they were tested with new numerosities that increased or decreased in numerosity (i.e., 3-6-12 or 12-6-3). Surface area, element size, and density varied independently from number. Eleven-month-old infants looked longer at the new ordinal direction, whereas 9-month-old infants did not dishabituate when the ordinal direction was reversed. Brannon (2002) speculated that aspects of her procedure such as presenting infants with repeated dynamic sequences (e.g., 1-2-4, 1-2-4, 1-2-4) within a trial, three sets of overlapping numerosities between trials (i.e., 1-2-4, 2-4-8, 4-8-16), and three rather than two values in each sequence, made ordinal numerical relations more salient and accounted for younger infants' success in her task compared with Cooper's task.

Although the results of Brannon (2002) were interpreted as evidence that by 11 months of age infants can represent ordinal relations between numerosities, there is an alternative explanation. Infants may have simply attended to the first numerical value in all sequences and ignored the second and third items. Indeed, studies investigating infants' memory of serial lists demonstrate that infants are better able to recall items at the beginning of the list (Cornell & Bergstrom, 1983; Merriman, Rovee-Collier, & Wilk, 1997). Thus, infants may have succeeded in the Brannon (2002) task because they had a strong memory for the first item of each sequence of numerosities and compared these items with the first item of both the novel and familiar test sequence. This explanation is possible because the average numerical value of the first array in habituation sequences differed more from the first value in the novel test sequence than did the first value in the familiar test sequence. 1 If this alternative scenario holds, 11-month-old infants would have noticed cardinal rather than ordinal numerical changes. Experiment 2 in this article tests this alternative hypothesis and provides further evidence that 11-month-old infants do in fact represent the ordinal direction of numerical sequences.

Experiments 3 through 5 address why 9-month-old infants fail to detect a reversal in numerical ordinal direction despite the fact that even younger infants can detect twofold changes in number (e.g., Xu & Spelke, 2000). In Experiment 3, we tested whether providing 9-month-old infants with more time to form numerical representations allows them to detect ordinal reversals in numerical sequences. In Experiment 4, we explored the prior claim that at 9 months of age infants can detect nonnumerical reversals in ordinal direction but not reversals in numerical ordinal direction (Brannon, 2002). Our results rule out the insufficient time explanation, and contrary to Brannon (2002), suggest that 9-month-old infants cannot detect a reversal in a size- or area-based rule, calling into question the idea that what develops between 9 and 11 months is specific to the numerical domain. An important question that emerges from the findings of Experiments 1 through 4 is whether there are any conditions under which 9-month-old infants will succeed at detecting reversals in the ordinal direction of a sequence of stimuli. Thus a fifth experiment borrows the logic of research on intersensory redundancy (Bahrick & Lickliter, 2000; Lewkowicz, 2004) and multiple cue integration (Kirkham, Slemmer, Richardson, & Johnson, 2007) to investigate whether providing 9-month-old infants with multiple redundant cues of ordinal relationships along different quantitative dimensions would allow infants to succeed in our task.

# **EXPERIMENT 1**

Our first experiment attempts to replicate the pattern observed in Brannon (2002) whereby 11-month-old infants but not 9-month-old infants successfully dishabituated to a reversal in the ordinal direction of a numerical sequence.

#### Method

**Participants**—Participants were 16 healthy, full-term 11-month-old infants (M age = 11 months, 3 days; range = 10 months, 15 days–11 months, 19 days) and 16 healthy, full-term 9-month-old infants (M age = 8 months, 27 days; range = 8 months, 10 days–9 months, 10 days). Ten of the 11-month-old and six of the 9-month-old infants were female. Data from an additional six 11-month-old and five 9-month-old infants were discarded because of fussiness resulting in failure to complete at least four test trials.

**Design**—The design was identical to Experiment 2 of Brannon (2002). Infants were habituated to ascending or descending sequences of three numerical stimuli (e.g., 4–8–16 or 16–8–4) and then tested with both ascending and descending sequences containing novel numerical values. Half of the infants were randomly assigned to the ascending condition. Each trial consisted of a repeating cycle that began with a black screen (1 sec) and then three consecutively presented numerical stimuli (1 sec each; see Figure 1). Following habituation, infants were given six test trials with ascending and descending sequences presented in a counterbalanced order.

**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

<sup>&</sup>lt;sup>1</sup>The average numerical value of the first stimulus in the ascending habituation sequences (1, 2, and 4) was 2.3; in contrast, the average numerical value of the first stimulus in the descending habituation sequences (4, 8, and 16) was 9.3. The ascending and descending test sequences began with 3 and 12, respectively. Thus the first numerosity in the descending test sequences (12) differed more than the first numerosity in the ascending test sequence (3) from the average of the first values in the ascending habituation sequences (2.3). The reverse was true for the average of the first values in the descending habituation sequences.

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. In the event that only one observer was available at the time of the experiment (35.9% of sessions across the five experiments), data were coded from videotape at a later date. 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 Visual Basic program, which automatically advanced the stimulus and automatically moved onto the test phase when the criterion was met. The Visual Basic program recorded infants as looking or not looking for each 100-msec interval and calculated interobserver reliability. Reliability between the two observers who coded the data live or from videotape (as conservatively computed based on agreement or disagreement at each 100-msec interval) was on average 92.44% across the five experiments (range = 91%–93.5%).

**Stimuli**—Stimuli were arrays of rainbow squares arranged in a random configuration identical to those used in Experiment 2 of Brannon (2002; see Figure 1). Stimuli were created using Canvas software and displayed in the center of the computer monitor. There were three sets of habituation stimuli. The first set contained 1, 2, and 4 elements, the second contained 2, 4, and 8 elements and the third contained 4, 8, and 16 elements. The stimulus sets for test trials contained novel numerical values: 3, 6, and 12 elements. Three different exemplars of each of the three test numerosities were used and these exemplars differed only in element configuration. Note that the numerical ratio was always one to two to ensure maximum likelihood of discrimination (Xu & Spelke, 2000). To ensure that continuous variables did not provide cues to infants, the following controls were used. The cumulative surface area of the elements within each display was held constant at  $12.5 \text{ cm}^2$  in habituation. Thus, the size of the individual elements was inversely correlated with the numerosity of the display. In addition, the size of each display was held constant at 342 cm<sup>2</sup>  $(18 \text{ cm} \times 19 \text{ cm})$  in habituation. Thus, the density of each display was positively correlated with number (e.g., 0.01, 0.02, 0.05 elements per cm<sup>2</sup> for the 4, 8, 16 displays, respectively). In the test phase, element size was held constant at 4.3 cm<sup>2</sup>. Thus in test, cumulative surface area was positively correlated with number. In addition, display size was varied such that density was held constant at 0.03 elements per cm<sup>2</sup> (19 cm  $\times$  4.9 cm, 19 cm  $\times$  9.9 cm, 19 cm  $\times$  19.7 cm for the 3-, 6-, and 12-element displays). Hence, the continuous variables that varied in the habituation phase were held constant in test and vice versa. This method of controlling for continuous variables parallels that used by Xu and Spelke (2000).2

**Procedure**—Informed consent was obtained from a parent of each participant before testing. Trials were initiated by the experimenter when the infant looked in the direction of the computer monitor. Each trial continued until the infant looked for a minimum of 2 sec and en0-ded after the infant looked for a total of 60 sec or looked away for a continuous 2 sec. Thus on a given trial an infant observed the same three numerosities presented in ascending (or descending) order repeatedly until the trial ended. This meant that infants could have seen anywhere from 1 to approximately 17 repetitions of a given numerical

<sup>&</sup>lt;sup>2</sup>Although this method of controlling for continuous variables led contour length to covary with number, the ratio of increase in contour length was not as favorable as the ratio for number. For example, during habituation the increase in contour length that accompanied a 1:2 increase in number was less than a 2:3 increase (a 5:7). Our prior work suggests that infants in the first year of life are unable to make such discriminations when this requires summing over discrete elements (Brannon, Abbott, & Lutz, 2004; Cordes & Brannon, 2007).

sequence in one trial. Across trials, the three different habituation stimulus sets were presented in a repeating random order (without replacement) until the infant met the habituation criterion (a 50% reduction in looking time over three consecutive trials, relative to the first three trials that summed to at least 12 sec) or until 16 trials were completed.3 After habituation, infants were tested with six test trials according to the same procedure. Trials alternated between novel (descending sequence for infants habituated to ascending sequences and vice versa) and familiar test sequences. Half of the infants in each condition saw the novel test sequence first.

#### Results and Discussion

The results directly replicate Experiment 2 of Brannon (2002). Thirteen 9-month-old and thirteen 11-month-old infants habituated. Average number of trials to habituation was comparable (9 months = 8.75, 11 months = 8.8). In addition, time spent looking on the first three (9 months = 14.3 sec; 11 months = 11.9 sec) and the last three habituation trials (9 months = 5.7 sec; 11 months = 5.2 sec) was equivalent for the two age groups. Paired t tests revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials for both 9- and 11-month-old infants, t(15) = 4.8, p < .001; t(15)= 3.25, p < .01, respectively. Thus 9- and 11-month-old infants seemed to attend to the stimuli to a similar degree.

A  $2 \times 2 \times 2$  mixed-factors analysis of variance (ANOVA) testing the between-subject factor of age (9 months vs. 11 months) and habituation condition (ascend vs. descend) and the within-subjects factor of test trial type (novel vs. familiar ordinal direction) on infants' looking time yielded a significant interaction between age and trial type, F(1, 28) = 5.1, p < . $05, \eta^2 p = .15$ , and no main effects or other interactions.4 This interaction was due to the fact that 11-month-old infants detected the reversal in ordinal direction of a numerical sequence, whereas 9-month-old infants did not (see Figure 2).

Three different additional analyses also yielded evidence of ordinal numerical knowledge in 11-month-old infants. First, 13 of the 16 infants looked longer at the novel test trials compared to the familiar test trials (p < .05, binomial test). Second, a paired t test revealed that 11-month-old infants looked significantly longer at the novel test trials (8.6 sec), t(15) =2.79, p < .05, but not at the familiar test trials (6.6 sec), t(15) = 1.83, p = .09, compared to the last three trials of habituation (5.2 sec). Third, a second paired t test comparing the average looking time to the novel and familiar test trials revealed a significant difference, t(15) = 2.54, p < .05. Similar results were obtained when the 3 infants who did not reach the habituation criterion were excluded, t(12) = 2.93, p < .05.5

In contrast, the same three methods of analysis used to demonstrate ordinal numerical knowledge in 11-month-old infants failed to reveal ordinal numerical knowledge in 9month-old infants. First, only 8 of the 16 infants looked longer at the novel test trials compared to the familiar test trials (p > .10 binomial test). Second, a paired t test revealed that for 9-month-old infants, there was no difference in the looking time to novel (6.1 sec) or

<sup>&</sup>lt;sup>3</sup>The number of habituation trials was increased from 14 (used in Brannon, 2002) to 16 to increase the likelihood that all infants

would habituate.  ${}^{4}$ As in Brannon (2002), looking times that exceeded 3 SD were excluded. The relevant pair of test trials was replaced by the average looking times to novel and familiar trials for the remaining infants. Although the exclusion of these data points reduced variance and therefore helped the results of the ANOVA, other analyses such as binomials were unaffected. Outliers made up 3%, 3%, 5%, 2%, and 3% of the data points for Experiments 1, 2, 3, 4, and 5, respectively. <sup>5</sup>The number of infants who contributed only four test trial data points due to fussiness or fatigue was low across the five experiments

<sup>(</sup>average under 4 infants per experiment). Importantly, when these infants were excluded from the analyses, paired t tests comparing looking time to novel versus familiar stimuli remained unchanged for all experiments: Experiment 1 (9 months), t(14) = .19, p = .85; Experiment 2, t(10) = 2.82, p < .02; Experiment 4a, t(9) = .01, p = .98; Experiment 4b, t(10) = .11, p = .90; Experiment 4c, t(7) = 2.3, p < .05; Experiment 5, t(12) = 3.39, p < .01.

familiar test trials (6.2 sec) compared to the last three trials of habituation (5.7 sec), t(15) = 0.51, p = .61; t(15) = 0.54, p = .59, respectively. Third, a paired *t* test comparing the average looking time to novel and familiar test trials revealed no difference, t(15) = .15, p = .88. This finding remained true when the 3 infants who failed to reach the habituation criterion were excluded, t(12) = .24, p = .81.

# **EXPERIMENT 2**

Although Experiment 1 replicated Brannon (2002), it remains possible that 11-month-old infants succeeded in detecting the reversal in three-item numerical sequences not because they detected a reversal in numerical ordinal direction, but instead because they attended to the large change in the first value of the test sequences. The following experiment tests this alternative hypothesis. In Experiment 2, we test infants in the same paradigm described in Experiment 1 with one important exception: The numerical value of the first stimulus in the ascending and descending test sequences was equated. If infants only paid attention to the large difference in the first numerical value in Experiment 1, then they should fail to show a novelty effect in Experiment 2 because the first values were equal in the novel and familiar test sequences. On the contrary if infants show a similar novelty preference as they did in Experiment 1, this provides stronger evidence of ordinal numerical knowledge by 11 months of age.

#### Method

All aspects of the experimental apparatus, design, and procedure were identical to that of Experiment 1 except for the following.

**Participants**—Participants were 16 healthy, full-term 11-month-old infants (M age = 11 months, 0 days; range = 10 months, 16 days–11 months, 16 days). Seven of the infants were female. Data from an additional 9 infants were discarded because of fussiness resulting in failure to complete at least four test trials.

**Stimuli**—As in Experiment 1, stimuli were random configurations of rainbow squares. New sets of numerical values were used to equate the first test numerical value in both ascending and descending conditions. In the habituation phase, the first set of stimuli contained 3, 6, and 12 squares; the second contained 5, 10, and 20 squares; and the third contained 7, 14, and 28 squares. The stimulus sets for the ascending test trials contained novel numerical values: 8, 16, and 32 squares. The descending test trials contained the novel numerical values 8, 4, and 2 squares. Three different exemplars of each of the test numerosities were used and these exemplars differed only in element configuration. Note that as in Experiment 1 the numerical ratio was always one to two to ensure maximum likelihood of discrimination (Xu & Spelke, 2000). The same method used to control for continuous variables in Experiment 1 was employed. The cumulative surface area of the elements within each display was held constant at  $12.5 \text{ cm}^2$  in habituation. In addition, the size of each display was held constant at  $342 \text{ cm}^2$  (19 cm  $\times$  18 cm) in habituation. Thus, the density of each display was positively correlated with number (e.g., 0.02, 0.04, 0.08 elements per  $cm^2$  for the 7, 14, 28 displays, respectively). In the test phase, element size was held constant at 1.6 cm<sup>2</sup>. In addition, display size was varied such that density was held constant at 0.05 elements per cm<sup>2</sup> ( $2.02 \times 18$  cm,  $4.04 \times 18$  cm,  $8.08 \times 18$  cm,  $16.16 \times 18$  cm, 32.32 $\times$  18 cm for the 2-, 4-, 8-, 16-, and 32-element displays).

#### **Results and Discussion**

Fifteen of the 16 infants habituated and on average habituation required 8.6 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) = 6.74, p < .001.

Infants successfully detected the reversal in ordinal direction (Figure 3). Thirteen of the 16 infants looked longer at the novel compared to the familiar test trials (p < .05, binomial test). A  $2 \times 2 \times 2$  mixed-factors ANOVA testing the between-subject factors of habituation condition (ascend vs. descend) and first test trial (novel vs. familiar) and the within-subjects factor of test trial type (novel vs. familiar ordinal direction) on infants' looking time yielded a significant main effect for trial type, F(1, 12) = 5.14, p < .05,  $\eta^2 p = .30$ , and no other main effects or interactions were found, ps > .05, demonstrating that infants looked longer to novel compared to familiar trials. In addition, a paired *t* test revealed a significant difference between the average time infants spent looking at novel (9.34 sec) versus familiar trials (7.36 sec), t(15) = 2.19, p < .05. This result was unchanged when the 5 infants who failed to habituate were excluded from the analysis, t(10) = 2.82, p < .05. In addition, infants showed a dishabituation effect to the novel but not to the familiar test trials, t(15) = 3.37, p < .01; t(15) = 1.49, p = .15.

Lastly, we conducted a 2 × 2 mixed-factors ANOVA comparing 11-month-old infants' performance in Experiment 1 and Experiment 2 with test trial type (novel vs. familiar) as the within-subjects factor and experiment (Experiment 1 vs. Experiment 2) as the between-subject factor. The ANOVA revealed a main effect of trial type, F(1, 30) = 11.04, p < .01,  $\eta^2 p = .27$ , and importantly no main effects or interactions involving experiment, ps > .05, suggesting similar performance in the two tasks.

Thus, although the numerical value of the first stimulus was equal for the novel and familiar test sequences, infants nevertheless detected the reversal in ordinal direction. This result provides strong evidence against the hypothesis that infants in this paradigm simply attend to the change in the first value of the sequences and provide further evidence that by 11 months of age infants appreciate ordinal relationships between numerical values.

Although Experiment 2 rules out the possibility that 11-month-old infants succeed in the ordinal task by detecting changes in the cardinal value of the first stimulus, it must be noted that it is possible that infants in Experiment 1 actually selectively attended to the cardinal value of the third numerical value in the array. However, we chose to focus on the first stimulus (*primacy*) rather than the last three (*recency*) for two reasons. First, the first stimulus is always predicted by a black screen that initiates each sequence and is thus potentially more salient (Wood & Spelke, 2005). Second, although the first stimulus always appeared first in the sequence, a trial ended whenever the infant looked away from the screen for a continuous 2 sec rather than when a sequence was complete. Thus, the third stimulus was not always the final stimulus viewed by the infant.

# **EXPERIMENT 3**

We next turned to the question of why 9-month-old infants have consistently failed to detect ordinal numerical reversals. The numerical values used in Experiment 1 should be well within the limits of 9-month-old infants' numerical discrimination ability. Infants as young as 6 months of age can discriminate large numerical values that differ by a 1:2 ratio (e.g., Brannon, Abbott, & Lutz, 2004; Lipton & Spelke, 2003; Xu, 2003; Xu & Spelke, 2000). By 9 months of age, the ratio needed for discrimination reduces to 2:3 (Lipton & Spelke, 2003). However, one possibility raised by Brannon (2002) and Wood and Spelke (2005) is that younger infants simply need more time to form numerical representations and that the

#### Method

All aspects of the experimental apparatus, design, stimuli, and procedure were identical to that of Experiment 1 except that each numerosity was presented for 2 (2-sec condition) or 3 (3-sec condition) sec rather than 1 sec. Although the duration of the numerical stimuli were increased to 2 sec or 3 sec, depending on condition, the blank screen that preceded each trial remained at 1 sec in both conditions.

**Participants**—Participants were 16 healthy full-term 9-month-old infants (M age = 8 months, 28 days; range = 8 months, 15 days–9 months, 15 days). Ten of the infants were female. Data from an additional 11 infants were discarded because of fussiness resulting in failure to complete at least four test trials. Half of the infants were assigned to the 2-sec condition.

#### **Results and Discussion**

A 2 × 2 mixed-factors ANOVA testing the between-subject factor of experimental condition (2 sec vs. 3 sec) and the within-subjects factor of test trial type (novel or familiar ordinal direction) on infants' looking time yielded no significant effect of condition  $F(1, 14) = .89, p > .05, \eta^2 p = .06$ , or any interaction, p > .05. Because performance was similar between the two conditions, for the remaining analyses, data from the two conditions were collapsed.

As in Experiment 1, 9-month-old infants rapidly habituated. Fifteen of the 16 infants habituated and on average, habituation required 8.6 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) = 5.93, p < .001.

As illustrated by Figure 4, increasing the stimulus duration did not help 9-month-old infants detect the ordinal reversal. Only 7 of the 16 infants looked longer at the novel test trials compared to the familiar test trials (p > .10 binomial test). A  $2 \times 2 \times 2$  mixed-factors ANOVA testing the between-subject factor of habituation condition (ascend vs. descend) and first test trial (novel vs. familiar) and the within-subjects factor of test trial type (novel vs. familiar ordinal direction) on infants' looking time yielded no main effect for test trial type, F(1, 12) = .96, p > .05,  $\eta^2 p = .07$ , and no other main effects or interactions, all ps > . 10. Additionally, a paired *t* test revealed that there was no difference between the average time infants spent looking at novel (5.43 sec) versus familiar trials (6.05 sec), t(15)=-.95, p = .36. When the 1 infant who failed to habituate was excluded, the finding remained unchanged, t(14) = -1.23, p = .24. Further, infants did not demonstrate a dishabituation effect to novel test trials, t(15) = 1.16, p = .26.

Finally, we conducted a 2 × 2 mixed-factors ANOVA comparing 9-month-old infants' performance when provided sequences of 1 sec stimuli (Experiment 1) and sequences of 2 sec or 3 sec stimuli (Experiment 3) using the between-subject factor of experiment (Experiment 1 vs. Experiment 3) and the within-subjects factor of test trial type (novel vs. familiar). There were no main effects (condition, trial type), ps > .10, or interaction, F(1, 30) = .173, p > .05,  $\eta^2 p = .006$ . Thus the results suggest that the failure of 9-month-old infants to detect a reversal in ordinal direction of a numerical sequence is not due to insufficient processing time for forming numerical representations. Although it is possible that longer stimulus duration made the sequences less coherent to infants, the fact that there was no

main effect of condition (stimulus duration), ps >. 10, suggests that infants' looking time to sequences with different stimulus durations did not differ.

# **EXPERIMENT 4**

Results from Experiment 3 confirm the notion that 9-month-old infants cannot yet appreciate numerical ordinal relations. However, Brannon (2002) argued that 9-month-old infants are able to represent nonnumerical ordinal relations. In Experiment 3 of that report, infants viewed a sequence of three single squares that increased or decreased in size. Nine-month-old infants dishabituated to a reversal in ordinal direction of this size-based sequence. Brannon argued that the failure of 9-month-old infants to detect a reversal in ordinal direction of a numerical sequence therefore could not be due to a general-purpose processing demand of the task. However, an untested possibility was that the 9-month-old infants detected a qualitative change in the sequence in the size-based ordinal task. Because all squares were located at the center of the screen, ascending sequences may have achieved an approaching percept (*looming*) whereas descending sequences may have yielded a retracting percept (*zooming*). This alternative explanation for 9-month-old infants' success is plausible given that the ability to discriminate zooming objects from looming objects appears early in infancy (Nanez, 1988; Yonas, Pettersen, & Lockman, 1979).

An important question thus remains as to whether 9-month-old infants can detect a change in ordinal direction for a nonnumerical sequence. In Experiments 4a and 4b we test whether 9-month-old infants can use element size or cumulative element area, respectively, to detect a reversal in ordinal direction of a sequence. To avoid the possibility of a zooming versus looming distinction and to provide a more comparable experimental design to that used in the numerical ordinal task of Experiment 1, we used arrays of elements throughout Experiment 4. In Experiment 4c, we use the same design used in 4a and 4b to test whether 11-month old infants can use area or size alone to detect a reversal in ordinal direction.

#### **Experiment 4a**

The goal of Experiment 4a was to determine if 9-month-old infants could detect an ordinal reversal in a size-based sequence when stimuli were arrays of numerosities. Element size increased threefold between stimuli while number remained constant. This led cumulative surface area to also increase threefold between stimuli. However, results from previous studies in our lab indicate that it is unlikely infants would be able to discriminate a threefold area change when this requires summing across arrays of discrete elements; thus if infants succeeded in this task, it would be most likely based on changes in element size, not cumulative area (Brannon et al., 2004; Brannon, Lutz, & Cordes, 2006; Cordes & Brannon, 2007).

**Methods**—All aspects of the experimental apparatus, design, and procedure were identical to that of Experiment 1. The stimuli, however, were configurations of rainbow squares that varied in size and total area but not in number.

**Participants:** Participants were 16 healthy, full-term 9-month-old infants (M age = 8 months, 29 days; range = 8 months, 15 days–9 months, 18 days). Ten 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.

**Stimuli:** Stimuli were random configurations of rainbow squares (see Figure 5 for example stimuli). As in Experiment 1, there were three sets of habituation stimuli and each set contained three displays. Each display increased (or decreased) in element size but not number. A threefold increase in size was used to ensure maximum likelihood of

discrimination (Brannon et al., 2006).6 The numerosities used in habituation were two, four, eight; and the numerosity used in test was six. The element sizes that were used were 0.8 cm<sup>2</sup>, 2.4 cm<sup>2</sup>, and 7.2 cm<sup>2</sup>. Thus an example habituation sequence would consist of four elements each 0.8 cm<sup>2</sup>, followed by four elements each 2.4 cm<sup>2</sup>, and finally four elements each 7.2 cm<sup>2</sup>. Because number remained constant between the displays, cumulative area increased (or decreased) threefold between displays (e.g., 1.6 cm<sup>2</sup>, 4.8 cm<sup>2</sup>, 14.4 cm<sup>2</sup> for the sequences constructed with the numerosity two).

**Results and Discussion**—As in the earlier experiments, 9-month-old infants rapidly habituated. Fourteen of the 16 infants habituated and on average, habituation required 9.4 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) = 4.16, p < .01.

Results revealed that 9-month-old infants were unable to detect the reversal in a size-based sequence that changed threefold in both element size and cumulative surface area (see Figure 6a). Eleven of the 16 infants looked longer at the novel test trials compared to the familiar test trials (p = .10 binomial test). A 2 × 2 ×2 mixed-factors ANOVA testing the between-subject factors of habituation condition (ascend vs. descend) and first test trial (novel vs. familiar); and the within-subjects factor of test trial type (novel vs. familiar) ordinal direction) on infants' looking time yielded no main effect for trial type, F(1, 12) = .50, p > .05,  $\eta^2 p = .04$ , and no other main effects or interactions, ps > .05. In addition, a paired *t* test revealed that there was no difference between the average time infants spent looking at novel (6.2 sec) versus familiar trials (5.8 sec), t(15) = .75, p = .47. When the 2 infants who failed to habituate were excluded from the analysis, this finding remained true, t(13) = .30, p = .77. Lastly, infants did not dishabituate to the novel test stimuli, t(15) = -. 38, p = .71. These results indicate that 9-month-old infants are not yet capable of forming size-based ordinal representations.

#### **Experiment 4b**

In Experiment 4a we found that 9-month-old infants could not detect a reversal in ordinal direction of a size-based sequence when element size changed threefold between stimuli. The goal of Experiment 4b was to examine whether 9-month-old infants could detect an ordinal reversal in the cumulative area of an array when element size did not covary with cumulative area. To increase the probability that infants would detect ordinal relations in cumulative area and to anticipate a necessary design feature of Experiment 5 we used a sixfold (rather than threefold) change in cumulative area. To dissociate change in cumulative area from change in element size, which would covary had we kept number constant, we had number increase and decrease within each sequence. Thus, element size increased in a nonlinear fashion (see Figure 7).

**Methods**—All aspects of the experimental apparatus, design, and procedure were identical to that of Experiment 1 except for the following.

**Participants:** Participants were 16 healthy, full-term 9-month-old infants (M age = 9 months, 4 days; range = 8 months, 13 days–9 months, 22 days). Nine of the infants were female. Data from an additional 7 infants were discarded because of fussiness (n = 4) and parental interference (n = 3) resulting in failure to complete at least four test trials.

<sup>&</sup>lt;sup>6</sup>Brannon, Cordes, and Lutz demonstrated that at 6 months of age infants require a 1:2 ratio to detect a change in the area of a single element. However, Brannon et al. (2004) demonstrated that a larger difference is needed to differentiate the cumulative, area of arrays of elements. We therefore used a 1:3 ratio to be safely within the discrimination powers of a 9-month-old infant.

Stimuli: Stimuli were random configurations of rainbow squares that varied in cumulative area (range =  $0.8 \text{ cm}^2$ -115.2 cm<sup>2</sup>). As in Experiment 1, there were three sets of habituation stimuli and each set contained three displays. In the ascending condition, each display increased in cumulative area and increased in number from the first array to the second array, then decreased from the second array to the third array (the opposite relation for cumulative area and number was true in the descending condition). The three sets of cumulative area values used in habituation were 0.8 cm<sup>2</sup>, 4.8 cm<sup>2</sup>, 28.8 cm<sup>2</sup>; 1.6 cm<sup>2</sup>, 9.6 cm<sup>2</sup>, 57.6 cm<sup>2</sup>; and 3.2 cm<sup>2</sup>, 19.2 cm<sup>2</sup>, 115.2 cm<sup>2</sup>. The cumulative area of arrays in the test sets were 86.4 cm<sup>2</sup>, 14.4 cm<sup>2</sup>, 2.4 cm<sup>2</sup>. The numerical values of the arrays used were identical to Experiment 1, but the ordinal pattern was different. For the ascending area condition, the values used in habituation were 1, 4, 2; 2, 8, 4; and 4, 16, 8. For the descending area condition, the order of numerical values was 4, 1, 2; 8, 2, 4; 16, 4, 8. Infants in both ascending and descending area conditions were tested with the numerical values 3, 12, 6 and 12, 3, 6. Because number increased then decreased between arrays, element size values increased (or decreased) in a nonlinear fashion (e.g., 0.8 cm<sup>2</sup>, 1.2 cm<sup>2</sup>, 14.4 cm<sup>2</sup> for the ascending sequence 1, 4, 2). It is also important to note that although the design of this experiment meant that number provided conflicting cues to ordinality, this parallels the conflicting changes in element size that accompanied ascending and descending numerical changes in Experiment 1. As in all the preceding experiments, three sets of exemplars were used in test and these sets differed only in configuration.

**Results and Discussion**—On average, habituation required 8.5 trials and 14 of the 16 infants habituated. 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) = 4.19, p < .01.

Nine-month-old infants were unable to detect an ordinal reversal in cumulative surface area when cumulative area changes between stimuli within a sequence were sixfold (see Figure 6b). Six of the 16 infants looked longer at the novel test trials compared to the familiar test trials (p > .10 binomial test). A  $2 \times 2 \times 2$  mixed-factor ANOVA testing the between-subject factors of habituation condition (ascend vs. descend) and first test trial (novel vs. familiar) and the within-subject factor of test trial type (novel vs. familiar ordinal direction) on infants' looking time yielded no main effect for trial type, F(1, 12) = .22, p > .10,  $\eta^2 p = .02$ , and no other main effects or interactions, ps > .05. In addition, a paired *t* test revealed that there was no difference between the average time infants spent looking at novel (6.8 sec) versus familiar trials (7.1 sec), t(15) = .44, p = .66. When the 2 infants who failed to habituate were excluded from the analysis, this finding remained true, t(13) = .75, p = .47. Lastly, infants did not dishabituate to the novel test stimuli, t(15) = .99, p = .33. Coupled with the results from Experiment 4a, the findings suggest that 9-month-old infants are not yet capable of forming size-based or cumulative area-based ordinal representations.

#### **Experiment 4c**

Collectively the results of the experiments reported thus far indicate that 9-month-old infants cannot detect a number, size, or area-based reversal in an ordinal rule. In contrast, 11-month-old infants successfully detect a numerical reversal in an ordinal sequence even when size and area are carefully controlled. We next tested whether 11-month-old infants can also use size or area independently of each other and number.

**Methods**—All aspects of the experimental apparatus, stimuli, design, and procedure were identical to that of Experiments 4a and 4b.

**<u>Participants</u>**: Participants were 16 healthy, full-term 11-month-old infants (M age = 11 months, 0 days; range = 10 months, 13 days–11 months, 27 days). Seven of the infants were

female. Data from 4 additional infants were discarded because of fussiness resulting in failure to complete at least four test trials. Eight infants were tested with the stimuli used in Experiment 4a (element size-based rule) and 8 infants were tested with the stimuli used in Experiment 4b (cumulative area-based rule).

**Results and Discussion**—As in the previous experiments, infants rapidly habituated. Fourteen of the 16 infants habituated and on average, habituation required 10 trials. A 2 × 2 mixed-factor ANOVA testing the between-subject factor of condition (element size-based rule vs. cumulative area-based rule) and the within-subjects factor of trial type (first three habituation trials vs. last three habituation trials) revealed that infants in both conditions showed a significant reduction in looking time from the first three habituation trials to the last three habituation trials, F(1, 14) = 32.84, p < .001,  $\eta^2 p = .70$ , and no condition interaction, p > .05.

Unlike 9-month-old infants, 11-month-old infants successfully detected the reversal in a size- and area-based sequence. Fourteen of the 16 infants looked longer at the novel test trials compared to the familiar test trials (7 out of 8 infants in each condition, p < .05 binomial test). A 2 × 2 × 2 mixed-factor ANOVA testing the between-subject factors of habituation condition (ascend vs. descend) and first test trial type (novel vs. familiar) and the within-subjects factor of test trial type (novel vs. familiar ordinal direction) on infants' looking time yielded a significant main effect for test trial type, F(1, 12) = 13.65, p < .005,  $\eta^2 p = .53$ , and no other main effects or interactions, ps > .05. A paired *t* test revealed that infants looked longer at novel (8.8 sec) versus familiar trials (6.2 sec), t(15) = 2.66, p < .02. This finding did not change when the 2 infants who failed to habituate were excluded from the analysis, t(13)= 2.21, p < .05. In addition, infants dishabituated to novel test trials, t(15) = 3.66, p < .01, but not to familiar test trials, t(15) = .23, p = .82.

The effects were equally strong for infants tested in the element size and cumulative area conditions. A mixed-factor ANOVA examining the effect of novelty and condition (size vs. area) revealed a main effect of novelty, F(1, 14) = 6.63, p < .05,  $\eta^2 p = .32$ , and no interaction between novelty and condition, p = .78. As illustrated by Figure 8, infants in both conditions showed very similar patterns (element size condition: 8.85 sec to novel, 6.6 sec to familiar; cumulative area condition: 8.7 sec to novel, 5.9 sec to familiar).

Collectively, results indicate that by 11 months but not 9 months of age, infants can detect ordinal relationships based on size, area, or number. This was statistically supported by a 2 × 2 × 3 mixed-factor ANOVA across Experiments 1 and 4 testing the within-subjects factor of test trial type (novel vs. familiar) and the between-subject factor of age (9 months vs. 11 months) and type of ordinal information (number-based vs. size-based vs. area-based). Results revealed a significant main effect of test trial type, F(1, 42) = 12.87, p < .01,  $\eta^2 p = .23$ , with a significant interaction between test trial type and age, F(2, 42) = 8.44, p < .01,  $\eta^2 p = .17$ , and no other significant main effects or interactions, ps > .10.

# **EXPERIMENT 5**

The goal of our final study was to determine whether there are any circumstances under which 9-month-old infants can successfully detect a reversal in the ordinal direction of three successive stimuli. The memory demands of the current procedure should not have posed a problem for 9-month-old infants. Comparable habituation paradigms using repeatedly presented sequential stimuli have been used in infant numerical cognition studies (McCrink & Wynn, 2007; Wood & Spelke, 2005) and other infant research (Kirkham, Slemmer, & Johnson, 2002). For example, McCrink and Wynn (2007) tested the ability of 6-month-old infants to represent the ratio of yellow "pacmen" to blue "pellets." Infants were presented

with sequences of five arrays, where each array contained a different number of yellow and blue objects but maintained the same yellow-to-blue object ratio. Thus to abstract ratio, infants had to compare the array that was visually present with previously viewed arrays. Further, Kirkham et al. (2002) habituated 2-month-old infants to sequences of different shapes whose ordering followed a statistically predictable pattern. Two-, 5-, and 8-month-old infants later preferred novel sequences that contained identical stimulus components but whose ordering violated the pattern presented in habituation. Detecting novel orderings of familiar components indicates that by 2 months of age infants are able to integrate successively presented stimuli in memory.

A second ability that is central to the current paradigm is the ability to perceive ordinal relationships between stimuli. Previous studies suggest that this ability emerges prior to 9 months of age. For example, by 9 months of age infants begin to exhibit delayed imitation that often preserves the order of events (Carver & Bauer, 1999). Even younger infants show evidence of memory for the order of mobiles presented in the conjugate mobile paradigm (e.g., Gulya, Rovee-Collier, Galluccio & Wilk, 1998). In addition, using the visual habituation paradigm, Lewkowicz (2004) showed that infants as young as 4 months of age are capable of perceiving serial order among three items when given visual and auditory information.

These studies show that infants are able to perceive order between specific items or actions, but our research addresses a different question. We ask whether 9-month-old infants can represent the ordinal relationships between values on a quantitative dimension such as number, size, or cumulative area such that they can detect reversals in ordinal direction even for novel values along the same dimension.

An interesting finding from the Lewkowicz (2004) study is that infants' detection of serial order is aided when presented with multimodal rather than unimodal cues. Lewkowicz (2004) habituated 4- and 8-month-old infants to video clips of three distinct objects sequentially emerging from a spout. On impact, each object emitted a unique sound. Infants were then tested for their ability to detect auditory, visual, and auditory-visual changes in the order of objects. Results indicated that 4-month-old infants detected the change in ordinal relationship when tested with multimodal stimuli but not when presented with unimodal stimuli. In contrast, 8-month-old infants succeeded at detecting a change in ordinal relationship even when unimodal stimuli were tested. This finding fits nicely with other research that suggests providing multiple cues boosts infant perception (for review, see Bahrick & Lickliter, 2000; Bahrick, Lickliter, & Flom, 2004).

Further, recent work by Kirkham and colleagues demonstrates that infant perception can also be aided by multiple visual cues as opposed to cues from multiple sensory modalities. Kirkham et al. (2007) found that 11- but not 8-month-old infants were capable of perceiving violations of a red circle's statistically defined spatial pattern. However, when presented with multiple visual cues (shape, color, and location) that predicted the location of a stimulus, 8-month-old infants also succeeded. Thus in this study and the Lewkowicz study already described, younger infants seem to require multiple cues to succeed at tasks that older infants solve with a single cue. Taking insight from these literatures, Experiment 5 tested whether providing multiple cues to ordinality allows 9-month-old infants to detect a reversal in ordinal direction. Deviating from the literature previously described, however, we use redundant correlated ordinal relationships: numerosity, element size, and cumulative area.

#### Method

All aspects of the experimental apparatus, design, and procedure were identical to that of Experiments 1 through 4 except for the following.

**Participants**—Participants were 16 healthy, full-term 9-month-old infants (M age = 9 months, 0 days; range = 8 months, 13 days–9 months, 17 days). Eleven of the infants were female. Data from an additional 8 infants were discarded because of fussiness resulting in failure to complete at least four test trials.

**Stimuli**—Stimuli were random configurations of rainbow squares (see Figure 9 for example stimuli). As in Experiment 1, there were three sets of habituation stimuli and each set contained three displays. The numerosities used in both habituation and test were identical to Experiment 1. However, element size was positively correlated with number. That is, element size increased (or decreased) threefold between displays in a set (element sizes from Experiment 5 were used: 0.8 cm<sup>2</sup>, 2.4 cm<sup>2</sup>, and 7.2 cm<sup>2</sup>). Given that number increased twofold and element size increased threefold this meant that cumulative surface area of the display increased sixfold (e.g., 0.8 cm<sup>2</sup>, 4.8 cm<sup>2</sup>, 28.8 cm<sup>2</sup> for the numerosities 1, 2, 4). Test stimuli contained the novel numerical values: 3, 6, and 12 elements. Three exemplars of each test value were used and these exemplars differed only in configuration.

#### **Results and Discussion**

As in the previous experiments, infants rapidly habituated. Fifteen of the 16 infants habituated and on average, habituation required 8.37 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) = 6.41, p < .001.

As shown in Figure 10, 9-month-old infants succeeded in detecting the reversal in ordinal direction when multiple cues provided redundant ordinal information. Fourteen of the 16 infants looked longer at the novel test trials compared to the familiar test trials (p < .05 binomial test). A 2 × 2 × 2 mixed-factor ANOVA testing the between-subject factors of habituation condition (ascend vs. descend) and first test trial type (novel vs. familiar) and the within-subject factor of test trial type (novel vs. familiar ordinal direction) on infants' looking time yielded a significant main effect for test trial type, F(1, 12) = 13.65, p < .005,  $\eta^2 p = .53$ , and no other main effects or interactions, ps > .05. Furthermore, a paired *t* test revealed that infants looked longer at the novel (7.44 sec) versus familiar test trials (5.24 sec), t(15) = 3.9, p < .01. Results excluding the 2 infants who failed to habituate showed the same effect, t(13) = 3.51, p < .01. Finally, 9-month-old infants dishabituated to novel test stimuli, t(15) = .18, p = .85.

To compare 9-month-old infants' performance in the multiple-cue ordinal task and the number ordinal task in Experiment 1, we conducted a  $2 \times 2$  mixed-factor ANOVA with the between-subject factor of ordinal task (number [Experiment 1] vs. multiple cues [Experiment 5]) and the within-subjects factor of test trial type (novel vs. familiar). Results revealed a significant interaction between type of ordinal information and test trial type, F(1, 30) = 4.46, p < .05,  $\eta^2 p = .13$ , but no significant main effects, ps > .05. Further, to compare 9-month-old infants' performance in the multiple-cue task with the element size and cumulative area tasks (Experiments 4a & 4b) we conducted a  $2 \times 3$  mixed-factor ANOVA with the between-subject factor of ordinal task (multicue [Experiment 5] vs. element size [Experiment 4a] vs. cumulative area [Experiment 4b]) and the within-subjects factor of test trial type (novel vs. familiar). Results of the ANOVA revealed a significant main effect for test trial type, F(1, 45) = 4.49, p < .05,  $\eta^2 p = .09$ . Importantly, a significant interaction between test trial type and ordinal task was also found, F(2, 45) = 4.05, p < .05,  $\eta^2 p = .15$ .

As demonstrated by the *t* tests reported previously, this interaction is due to the fact that infants in the multiple-cue study discriminated the novel ordinal sequences from the familiar ones, whereas infants in the element size and cumulative area studies did not.

These results suggest that 9-month-old infants are, in fact, capable of forming ordinal representations across a sequence of three stimuli and that the failure of 9-month-old infants tested in this paradigm was not due to a deficit in a more general-purpose cognitive ability to integrate successive stimuli. Instead it appears that 9-month-old infants require a stronger signal to form ordinal representations. Presenting multiple convergent quantitative cues allows infants to detect ordinal relationships that they are unable to detect when number, element size, or cumulative area are available in isolation.

# **GENERAL DISCUSSION**

Experiments 1 and 2 together confirm the conclusion made by Brannon (2002) that infants as young as 11 months of age are sensitive to the ordinal relations between numerical values. This finding is important because it demonstrates that preverbal infants have conceptual numerical knowledge. Although some may argue that even with the evidence provided in this article we should not attribute conceptual numerical knowledge to an 11-month-old infant, we use the term *conceptual* as employed by Gallistel and Gelman (1992) who argued that "animals (or human infants) may be said to have a concept of number insofar as they may be shown to mentally manipulate numerons in processes that are isomorphic to some or all of the operations that define the system of arithmetic: ordering, addition, subtraction, multiplication, and division" (p. 45). Without question, a child's numerical concept becomes much more sophisticated and undergoes elaboration and change between 11 months of age and adulthood; nevertheless by 11 months of age, infants are not representing numerosities as unrelated categories, but instead as values along an ordered continuum. In this sense they already possess a concept of number.

Together with the findings of Brannon (2002), our results suggest an important possibility in the development of infants' quantitative understandings: The ability to discriminate two values along a given quantitative dimension may emerge earlier than the ability to appreciate the ordinal relationships between such values. For example, we know that infants as young as 6 months of age can discriminate a 1:2 ratio change in number or element size and yet our results suggest that 3 months later infants may still be unable to represent the ordinal relationships between these values (e.g., Brannon et al., 2006; Xu & Spelke, 2000). An alternative explanation, however, is that this apparent contradiction between studies that show successful numerical discrimination and our studies that show inability to detect reversals in ordinal direction reflect the more complicated information-processing demands in our task. Future research should address these issues by attempting to reduce the task demands for young infants.

The second and more original contribution of this article concerns the nature of ordinal representations at 9 and 11 months of age. Collectively our results indicate that 9-month-old infants are unable to detect changes in the ordinal direction of a number-based (Experiments 1 & 3), size-based (Experiment 4a), or area-based (Experiment 4b) sequence when these cues are presented in isolation; however, they successfully represent ordinal relations and detect a reversal when all three cues provide convergent and redundant information (Experiment 5). In contrast, 11-month-old infants succeed at detecting ordinal relationships when number (Experiments 1 & 2), size, or area (Experiment 4c) increase or decrease independently.

Thus our results suggest that the ability to represent ordinal relationships of numerical values and nonnumerical quantities follows a similar developmental trajectory. This finding mirrors a growing body of literature demonstrating that infants' discrimination abilities for magnitudes such as number, time, and area show similar limits (Brannon et al., 2006; Feigenson, 2007; vanMarle & Wynn, 2006; Xu & Spelke, 2000) and follow a similar developmental pattern (Brannon, Suanda, & Libertus, 2007; Lipton & Spelke, 2003; Xu & Arriaga, 2007).

Our results also suggest that 9-month-old infants can succeed at our paradigm when multiple ordinal cues are present. These results are important in demonstrating that the reason for 9-month-old infants' failures at this paradigm is not solely due to task demands. However, an interesting and important issue raised by these findings is why 9-month-old infants require multiple redundant cues to appreciate ordinal relations in our task. It may be tempting to argue that these data support the thesis put forth by Mix, Huttenlocher, and Levine (2002) that continuous and discrete quantities are initially undifferentiated in infancy and that a young child's conceptual task is to discover the distinct nature of discrete and continuous quantities. However, at least two aspects of our data speak against this claim. First, it is important to note that infants did not detect ordinal reversals in continuous quantities any earlier than they detected ordinal reversals in numerosity. Instead, as already described, it appears that there is no privilege to nonnumerical or numerical information.

Second, a critical aspect to the task and stimulus design of our experiments is that to detect an ordinal reversal in a single quantitative dimension (number, area, or size) infants need to ignore nonmonotonic changes in the irrelevant dimensions. For example, in the habituation stimuli used in Experiment 1, number increased or decreased, whereas cumulative surface area was held constant and thus element size was inversely related to number. In the habituation stimuli used in Experiment 4b cumulative area increased or decreased, whereas number increased and then decreased (or vice versa). The difficulty for 9-month-old infants may be in extracting ordinal relations from a single dimension in the face of conflicting changes in other quantitative dimensions. This may not be surprising given that even adults show interference from variations in continuous variables when comparing relative numerosities (Hurewitz, Gelman, & Schnitzer, 2006). Specifically, when adults are asked to judge which of two arrays contained more circles, they were quicker and more accurate when the array with more circles also had larger circles. Thus 9-month-old infants' failure in the single cue ordinal tasks may be due to a need for multiple redundant cues or alternatively a result of being unable to filter out conflicting cues. Unfortunately, our results do not distinguish between these two explanations.

Although our results clearly demonstrate that 9-month-old infants are better able to compare and contrast three stimuli based on their ordinal relationships when they are provided multiple redundant cues to ordinality, they leave open the question of whether there are any circumstances under which infants at this age could detect ordinal relationships along a quantitative dimension when only a single dimension is available in our paradigm. For example, perhaps increasing the ratio between successive numerical values (e.g., 1:3 or 1:4) or providing infants with more than three exemplars in each numerical sequence would allow 9-month-old infants to extract numerical ordinal direction even when nonnumerical cues were controlled.

In apparent contradiction with our findings, Feigenson and colleagues have found that by 10 months of age infants can use the ordinal relationships between quantities of food to make foraging decisions (Feigenson & Carey, 2005; Feigenson, Carey, & Hauser, 2002). In these studies, 10- to 12-month-old infants reliably choose the larger of two food quantities but only when quantities consist of three or fewer graham crackers. This set size limitation has

been interpreted as evidence that infants open an "object file" for each element in a visual array (e.g., Hauser & Carey, 1998; Leslie, Xu, Tremoulet, & Scholl, 1998; Simon, 1997). In the object-file model there is no symbol that represents the numerosity of a set; instead, each element is represented by a file stripped of object features, such as color and shape. The model posits that the visual system contains a limited number of object files that can be assigned to an object and this accounts for the set-size limitation observed in this task and other tasks. There are multiple differences between our paradigm and that used by Feigenson and colleagues. For example, her paradigm involves a comparison of only two values rather than three, involves food rather than two-dimensional arrays of squares, and the youngest infants in her experiments are at an intermediate age between infants who succeed and fail in our task. Although any of these factors may contribute to differences in performance, most important, our experiments include both small and large numerosities and thus cannot be explained by an object-file model. An interesting possibility then is to see whether 9-month-old infants would succeed in our paradigm if tested with exclusively small numerical values.

In conclusion, our results provide strong evidence that by 11 months of age infants represent the greater than and less than relations between purely numerical values or values along continuous dimensions such as surface area or element size. In contrast, 9-month-old infants are unable to use any of these three ordinal relationships in isolation and instead can only detect reversals in ordinal direction when multiple redundant cues are available. Our findings thus highlight an important change that takes place between 9 and 11 months of age in the ability to extract ordinal relationships between values along a quantitative dimension. However, many questions remain as to the precise changes that take place and the mechanisms of these changes.

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## FIGURE 1.

The four frames of a sample (a) habituation, (b) familiar test, and (c) novel test trial in Experiment 1 (figure is provided in color online).



# FIGURE 2.

Mean looking time  $(\pm SE)$  in Experiment 1 to the first three and last three habituation trials and to novel and familiar test trials for (a) 9-month-old and (b) 11-month-old infants.



## FIGURE 3.

Mean looking time  $(\pm SE)$  in Experiment 2 to the first three and last three habituation trials and to novel and familiar test trials.



# FIGURE 4.

Mean looking time ( $\pm$  SE) in Experiment 3 to the first three and last three habituation trials and to novel and familiar test trials.



## FIGURE 5.

The four frames of a sample (a) ascending habituation trial in Experiment 4a; (b) ascending test trial (familiar) in Experiment 4a; and (c) descending test trial (novel) in Experiment 4a (figure is provided in color online).



## FIGURE 6.

Mean looking time  $(\pm SE)$  in (a) Experiment 4a (size-based) and (b) Experiment 4b (areabased) to the first three and last three habituation trials and to novel and familiar test trials.



#### FIGURE 7.

The four frames of a sample (a) ascending habituation trial in Experiment 4b, (b) ascending test trial (familiar) in Experiment 4b, and (c) descending test trial (novel) in Experiment 4b (figure is provided in color online).



# FIGURE 8.

Mean looking time ( $\pm$  *SE*) in Experiment 4c, separated by condition, to the first three and last three habituation trials and to novel and familiar test trials.



#### FIGURE 9.

The four frames of a sample (a) ascending habituation trial in Experiment 5, (b) ascending test trial (familiar) in Experiment 5, and (c) descending test trial (novel) in Experiment 5 (figure is provided in color online).



### FIGURE 10.

Mean looking time ( $\pm$  *SE*) for 9-month-old infants in Experiment 5 to the first three and last three habituation trials and to novel and familiar test trials.