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Cognition 83 (2002) 223–240

COGNITION

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The development of ordinal numerical knowledge in infancy

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Received 19 September 2001; accepted 11 January 2002

Abstract

A critical question in cognitive science concerns how numerical knowledge develops. One essential component of an adult concept of number is ordinality: the greater than and less than relationships between numbers. Here it is shown in two experiments that 11-month-old infants successfully discriminated, whereas 9-month-old infants failed to discriminate, sequences of numerosities that descended in numerical value from sequences that increased in numerical value. These results suggest 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 develops between 9 and 11 months of age. In an additional experiment 9-month-old infants succeeded at discriminating the ordinal direction of sequences that varied in the size of a single square rather than in number, suggesting that a capacity for non-numerical ordinal judgments may develop before a capacity for ordinal numerical judgments. These data raise many questions about how infants represent number and what happens between 9 and 11 months to support ordinal numerical judgments. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Number discrimination; Ordinal; Infants

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1. Introduction

A growing body of data suggests that non-human animals and humans share a primitive non-verbal numerical system (see Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gallistel & Gelman, 2000). For example, when rhesus monkeys, young children and human adults compare the relative numerosity of visual arrays, both distance and size effects are found (e.g. Brannon & Terrace, 1998, 2000, in press; Moyer & Landaeur, 1967; Temple & Posner, 1998). The numerical distance effect is defined by faster and more accurate

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PII: S0010-0277(02)00005-7

responding when subjects compare the relative magnitude of values that are farther apart numerically, whereas the numerical size effect is characterized by higher accuracy and faster responding for smaller numerical magnitudes when numerical disparity is held constant. The distance and size effects suggest that this shared system relies on numerical representations in the form of continuous magnitudes (Dehaene et al., 1998; Gallistel & Gelman, 2000). Although adult humans clearly have alternative computational routes available (e.g. verbal counting), it appears that under some circumstances humans bypass these alternative symbolic routes and rely instead on a system that is evolutionarily primitive (e.g. Cordes, Gelman, Gallistel, & Whalen, in press; Whalen, Gelman, & Gallistel, 1999).

Although the data reviewed above suggest evolutionary continuity in the numerical representations of adult humans and animals, a more controversial question is whether there is ontogenetic continuity in numerical cognition (Carey, 2001; Gelman & Cordes, in press). Research from the habituation dishabituation of looking time, cross-modal transfer, and violation of expectation paradigms all suggest that in some sense human infants represent number (e.g. Antell & Keating, 1983; Bijeljac-Babic, Bertoncini, & Mehler, 1991; Koechlin, Dehaene, & Mehler, 1998; Simon, Hespos, & Rochat, 1995; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Treiber & Wilcox, 1984; Uller, Huntley-Fenner, Carey, & Klatt, 1999; van Loosbroek & Smitsman, 1990; Wynn, 1992; Xu & Spelke, 2000, but see Clearfield & Mix, 1999). It remains unclear however, whether the numerical abilities of infants are the developmental precursors of the non-verbal numerical system displayed by adult humans and animals. One avenue towards addressing this question is to look for common features of numerical representations in non-human animals, adult humans and human infants. For example, Xu and Spelke (2000) recently showed that 6-month-old infants discriminate 8 from 16 elements but fail to discriminate 8 from 12 elements. This pattern of data might mean that the ratio of the numerosities being compared controls discrimination, however, such an account does not explain why the same aged infants can discriminate 2 vs. 3. Another prediction of the continuity hypothesis is that infants, like adults and non-human animals, should appreciate the ordinal relationships between numerical magnitudes. The experiments described here address this second question.

Very little is known about infants' knowledge of ordinal numerical relationships. To illustrate the distinction between cardinal and ordinal numerical knowledge, imagine being able to differentiate two objects from three objects but not knowing which set is numerically greater. Some authors have argued 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). An alternative view is that infants represent numerical ordinality from the start (e.g. Wynn, 1995). The question boils down to whether for a young infant twoness is to threeness much like a blender is to a chair, or alternatively whether even for the very young infant twoness and threeness are perceived as different values along one numerical continuum.

Only a handful of studies since the landmark work of Piaget (1952) have directly addressed the development of ordinal numerical knowledge in young children. For example, Brannon and Van de Walle (2001) recently showed that children as young as 2 years of age represent the ordinal relations between numerical values as large as 4 or 5 even when surface area is controlled (see also Bullock & Gelman, 1977; Huntley-Fenner & Cannon, 2000; Siegel, 1974; Sophian & Adams, 1987; Strauss & Curtis, 1984). Thus, children make ordinal numerical judgments before they are proficient at using the verbal counting system to mediate these judgments.

Even fewer studies have specifically tested for ordinal numerical knowledge in the first year of life. One relevant type of data comes from research showing that infants keep track of the number of objects behind an occluder (e.g. Wynn, 1992). These data may be interpreted as evidence that infants are capable of addition and subtraction and that infants can represent ordinal numerical relations (Wynn, 1992, 1995, 1998). However, the available evidence may also be explained by a non-numerical account (object-file system) whereby infants represent each of the objects behind an occluder and do not possess a symbolic representation of the numerosity of the set (see Simon, 1997; Uller et al., 1999).

In a second paradigm more directly addressing ordinal numerical knowledge in infancy, Feigenson, Carey, and Hauser (in press) found that 10- and 12-month-old infants spontaneously chose the numerically larger of two sets of food items when amount of food was confounded with number but failed to do so when amount of food was equivalent. In addition, even when amount of food could have been used as a cue infants succeeded at 1 vs. 2 and 2 vs. 3 and failed at 2 vs. 4, 3 vs. 4 and 3 vs. 6 suggesting that the numerical ratio was not what controlled performance but instead that infants were limited by the numerical size of the values being compared. Feigenson et al. interpret their results as evidence that infants use an object-file to represent each food item and that information about surface area is preserved and used in the comparison process.

In a third paradigm, Cooper (1984) habituated infants to pairs of displays that were presented successively. The displays of each pair maintained a constant ordinal relationship between the number of elements in the first and second display but the absolute values varied between trials (values ranged from 1 to 4). Thus, on habituation trials infants were always shown a small number followed by a large number or the reverse. Infants were then tested with pairs of numerical displays where the ordinal relationship between the two displays was the same as in habituation, was reversed, or was eliminated by equating the numerical value of the first and second displays. An interesting pattern of results was obtained. Ten- to 12-month-old infants dishabituated (i.e. looked longer) when tested with the novel pairs that contained two equal numerical values but failed to dishabituate to the novel pairs that reversed in ordinal direction. In contrast, 14–16-month-old-infants dishabituated to both of the novel types of test trials (change in ordinal direction and elimination of ordinal relations). This pattern of results is tantalizing and has been widely cited because it suggests a developmental trend in ordinal numerical knowledge. Infants under 12 months of age only differentiate equal and unequal numerical relations and fail to distinguish greater than from less than relations, whereas by 14 months of age infants have ordinal numerical knowledge. However, these results are difficult to interpret because surface area was not controlled.

The current research seeks to test whether infants represent ordinal numerical relations and whether there is a lower age boundary on this ability. In Experiment 1, 9- and 11-month-old infants were habituated to three-item sequences of numerical displays presented in an ascending or descending numerical order. The sequences were dynamic in that they repeated continuously and infants' looking times were measured for the whole sequence. The absolute numerical values were varied between trials and surface area was not confounded with number. Infants were then tested with new numerical values where the ordinal relations were maintained or were reversed from that of habituation. If infants represent ordinal numerical relations they should have looked longer when the ordinal direction was reversed from that of habituation compared to when it was maintained.

2. Experiment 1

2.1. Method

2.1.1. Participants

Participants were 16 healthy full-term 11-month-old infants (mean age: 10 months 23 days, range: 10 months 14 days–11 months 14 days) and 16 healthy full-term 9-month-old infants (mean age: 9 months, range: 8 months 14 days–9 months 14 days). Seven of the 11-month-old and four of the 9-month-old infants were female. Data from five additional 11-month-old and four 9-month-old infants were discarded because of fussiness resulting in failure to complete at least four test trials.

2.1.2. Design

Infants were habituated to ascending or descending sequences of three numerical displays (e.g. 4-8-16 or 16-8-4) and then tested with both ascending and descending sequences. Half of the infants were randomly assigned to the *ascending* condition. Each trial consisted of a repeating five-frame cycle that began with a black screen followed by a brief white screen (0.5 s) and then three consecutively presented numerical displays (1 s each; see Fig. 1). On any given trial the same three numerical displays were presented repeatedly and the black and white screens were used to mark the beginning of each presentation of the sequence. Following habituation, infants were given six test trials with ascending and descending sequences presented in a counterbalanced order. As in habituation each presentation of the sequence began with the black screen and was followed by the white screen and then each of three numerosities.

2.1.3. Apparatus

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

A microcamera monitoring the infant's face and a feed directly from the stimulus presentation computer were multiplexed onto a TV monitor and VCR. One or two experienced experimenters blind to the experimental condition recorded the infants' looking behavior while viewing the live video with the display occluded. In the event that only one observer was available at the time of the experiment, when possible data were recoded from videotape at a later date and the recoded data were used rather than the live data. 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 signaled the experimenter when to end a trial and when to move on to the test phase. The Visual Basic program recorded infants as looking

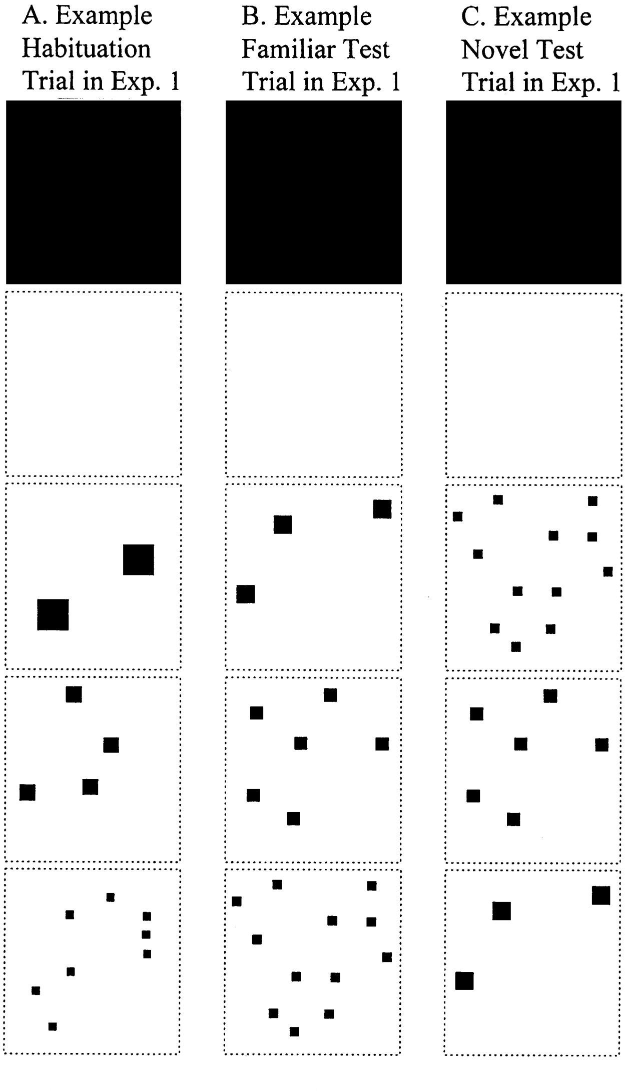


Fig. 1. The five frames of a sample (A) habituation, (B) familiar test and (C) novel test trial in Experiment 1. The dotted lines surrounding each display were not visible in the experiment. The sequence repeated, beginning with the black screen, until specific criteria were met.

or not looking for each 100 ms interval and calculated inter-observer 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 ms interval) was on average 93% (range: 89–96%) in Experiment 1, 94.5% (range: 88–97%) in Experiment 2, and 91% (range: 86–95%) in Experiment 3.

2.1.4. Stimuli

Displays were random configurations of black squares (see Fig. 1 for example displays). Displays were created with Canvas software and displayed in the center of the computer monitor. There were three sets of habituation displays. 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. Note that the numerical ratio was always 1 to 2 to ensure maximum likelihood of discrimination (Xu & Spelke, 2000). To ensure that surface area did not covary with number, one set was constructed such that cumulative surface area was equal across the three numerosities, a second set was constructed such that cumulative surface area increased with number and the third was constructed such that cumulative surface area decreased with number (the actual surface area values were 5, 10, 20; 10, 10, 10; and 20, 10, 5 cm^2). The configuration of the elements within each display was constructed using a 9×9 grid and a set of random coordinates generated by a computer program. The displays for test trials contained novel numerical values; 3, 6, and 12 elements. The cumulative surface area of the elements was 10 cm^2 for all three of the test numerosities in each trial. Three different exemplars of each of the three numerosities were used and these exemplars differed only in element configuration.

2.1.5. 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 s and ended after the infant looked for a total of 60 s or looked away for a continuous 2 s. The three different habituation displays were presented in a repeating random order 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 s) or until 14 trials were completed. After habituation the infants were tested with six test trials according to the same procedure and alternating between ascending and descending sequences.

2.2. Results and discussion

Fig. 2 shows that the pattern of habituation was similar for the 9- and 11-month-old infants. Time spent looking on the first three (9 months = 16.5 s; 11 months = 17.5 s) and the last three habituation trials (9 months = 7.8 s; 11 months = 7.6 s) was equivalent for the two age groups (Fig. 2). 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 ($t(15) = 4.27$, $P < 0.001$; $t(15) = 3.58$, $P < 0.01$). Thirteen infants habituated in each age group. Finally, on average the infants who habituated required

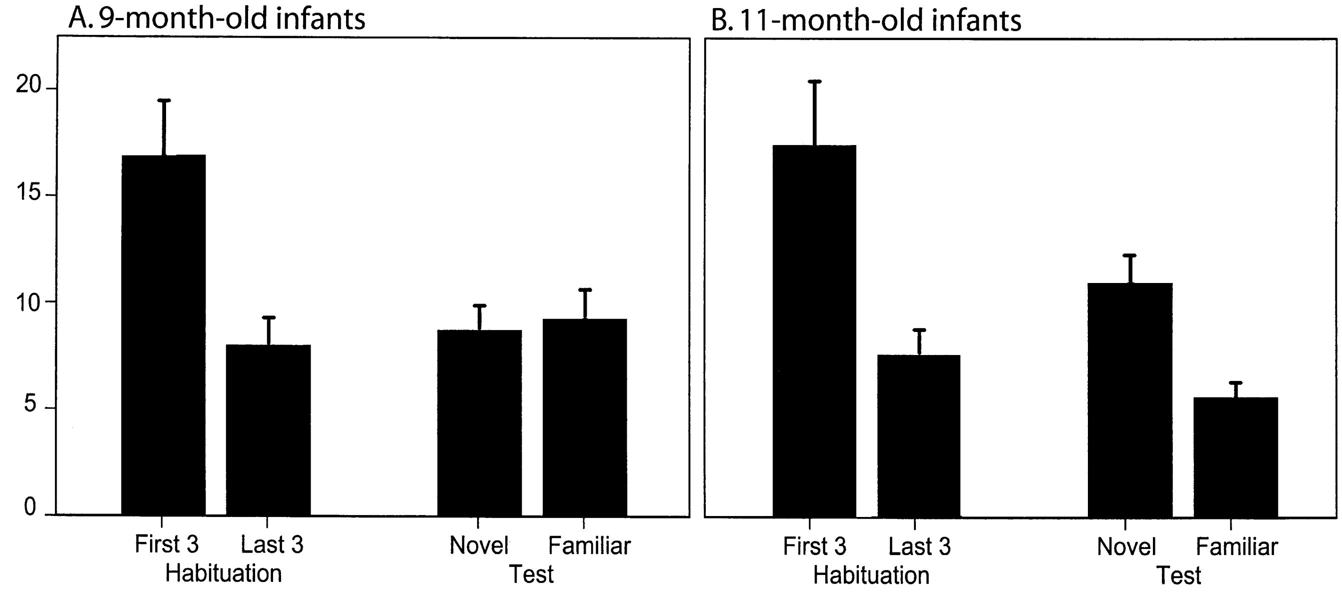


Fig. 2. Mean looking time (±SE) in Experiment 1 to the first three and last three habituation trials and to novel and familiar test trials for 9-month-old (A) and 11-month-old (B) infants.

7.77 and 7.69 trials to habituate for the 9- and 11-month-old infants, respectively. Thus, 9- and 11-month-old infants seemed to attend to the displays to a similar degree.

Eleven-month-old infants looked longer at the novel compared to the familiar test trials as judged by both a comparison of average looking time ($t(15) = 4.07$, $P < 0.001$) and by the number of infants who looked longer at the novel compared to the familiar test trials (13/16; binomial test, $P = 0.5$, $P < 0.05$) (Fig. 2). Paired *t*-tests also showed that 11-month-old infants looked significantly longer at the novel test trials ($t(15) = -2.46$, $P < 0.05$) and significantly shorter at the familiar test trials compared to the last three trials of habituation ($t(15) = 2.18$, $P < 0.05$).

In contrast, Fig. 2 shows that the 9-month-old infants failed to detect the reversal in ordinal direction of a numerical sequence. A $2 \times 2 \times 3$ analysis of variance was conducted examining the between-subject effect of age (9 and 11 months) and within-subject effects of test trial type (novel vs. familiar) and trial number (1, 2, or 3) on the time infants spent looking. The analysis revealed a two-way interaction between test trial type and trial number ($F(2, 60) = 3.34$, $P < 0.05$) and a three-way interaction between age, test trial type, and trial number ($F(2, 60) = 4.0$, $P < 0.05$) and no other main effects or interactions. The three-way interaction between test trial type, trial number and age 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. Nine-month-old infants showed no difference between their average looking time to the novel and familiar test trials ($t(15) = -0.57$, $P > 0.5$) and half of the infants looked longer at the familiar than the novel test trials. Similarly, a paired *t*-test showed that there was no difference in the time 9-month-old infants looked at the novel and familiar test trials compared to the last three trials of habituation ($t(15) = -0.41$, $P > 0.5$; $t = -0.68$, $P > 0.5$).

3. Experiment 2

The results of Experiment 1 suggest that 11-month-old infants represent the ordinal relations between numerical values and that for whatever reason 9-month-old infants do not. However, it is possible that 11-month-old infants in Experiment 1 used density rather than number to differentiate the ordinal directions of numerical sequences because density was confounded with number in the displays used in Experiment 1. In addition, in Experiment 1, element size was on average inversely correlated with number in habituation and also in test. Therefore, Experiment 2 tests 9- and 11-month-old infants with the same experimental design and procedure as Experiment 1, however all continuous variables that vary with number in the habituation phase are held constant in test and vice versa. Thus, in Experiment 2, element size, cumulative surface area, and density are all controlled.

3.1. Method

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

3.1.1. Participants

Participants were 16 healthy full-term 11-month-old infants (mean age: 10 months 30 days, range: 10 months 17 days–11 months 13 days) and 16 healthy full-term 9-month-old infants (mean age: 9 months, range: 8 months 20 days–9 months 13 days). Ten of the 11-month-old and six of the 9-month-old infants were female. Data from an additional nine 11-month-old and four 9-month-old infants were discarded because of fussiness resulting in failure to complete at least four test trials.

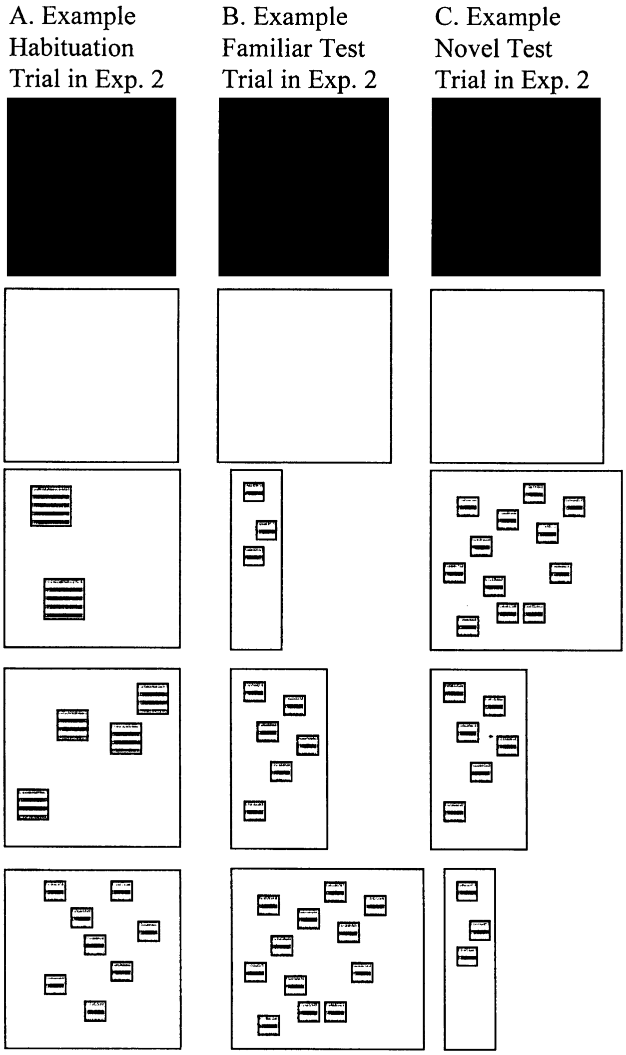
3.1.2. Stimuli

As in Experiment 1, displays were random configurations of squares, however, they were rainbow colored squares (see Fig. 3). The numerical values used in the habituation and test phases were the same as in Experiment 1. In contrast to Experiment 1, in Experiment 2 the cumulative surface area of the elements within each display was held constant at 12.5 cm^2 in the habituation phase. 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^2 (18×19 cm) in habituation. Thus, the density of each display was positively correlated with number (0.01, 0.02, and 0.05 elements per cm^2 for 4, 8, and 16 element displays, respectively). In the test phase, element size was held constant at 4.3 cm^2 and display size was varied such that density was held constant at 0.03 elements per cm^2 (19×4.9, 19×9.9, and 19×19.7 for 3 6 and 12 element displays). Thus, the continuous variables that varied in habituation were held constant in test and vice versa. This method of controlling for density and surface area parallels that used by Xu and Spelke (2000).

3.2. Results and discussion

Fig. 4 shows that the results of Experiment 2 parallel the results of Experiment 1. The pattern of habituation was similar for the 9- and 11-month-old infants. Time spent looking on the first three (9 months = 13.0 s; 11 months = 11.8 s) and the last three habituation trials (9 months = 4.6 s; 11 months = 4.7 s) was similar. 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 ($t(15) = -5.13$, $P < 0.001$; $t(15) = -3.76$, $P < 0.01$). Twelve 11-month and 14 9-month-old infants habituated. Finally, on average the infants who habituated required 7.9 and 9.3 trials to habituate for the 9- and 11-month-old infants, respectively. Thus, as in Experiment 1, 9- and 11-month-old infants seemed to attend to the displays to a similar degree.

As in Experiment 1, 11-month-old infants looked longer at the novel than the familiar test trials and 9-month-old infants failed to respond differentially to the two types of test trials. A $2 \times 2 \times 3$ analysis of variance was conducted examining the between-subject effect of age (9 and 11 months) and within-subject effects of test trial type (novel vs. familiar) and trial number (1, 2, or 3) on the time infants spent looking. The analysis revealed a main effect of age ($F(1,30) = 4.45$, $P < 0.05$) and a three-way interaction between age, test trial type, and trial number ($F(2,60) = 4.74$, $P < 0.02$) and no other main effects or interactions. The interaction between test trial type, trial number and age was again 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 Fig. 4). Paired *t*-tests revealed that 9-month-old infants looked significantly longer at both the novel and the familiar test trials compared to the last three trials of habituation ($t(15) = 3.07$, $P < 0.01$; $t(15) = 2.2$, $P < 0.05$). The same was true for 11-month-old infants ($t(15) = 4.5$, $P < 0.01$; $t(15) = 4.8$, $P < 0.01$). However, 11-month-old infants looked significantly longer at the novel compared to the familiar test trials ($t(15) = 2.37$, $P < 0.05$), whereas 9-month-old infants showed no difference in the time they looked at familiar and novel test trials ($t(15) = 0.37$, $P > 0.5$).



A. Example Habituation Trial in Exp. 2

B. Example Familiar Test Trial in Exp. 2

C. Example Novel Test Trial in Exp. 2

Fig. 3. Achromatic elements are shown here, however, elements were rainbow colored in the actual experiment. The five frames of a sample (A) habituation, (B) familiar test and (C) novel test trial in Experiment 2. The solid lines surrounding each display were visible in the experiment.

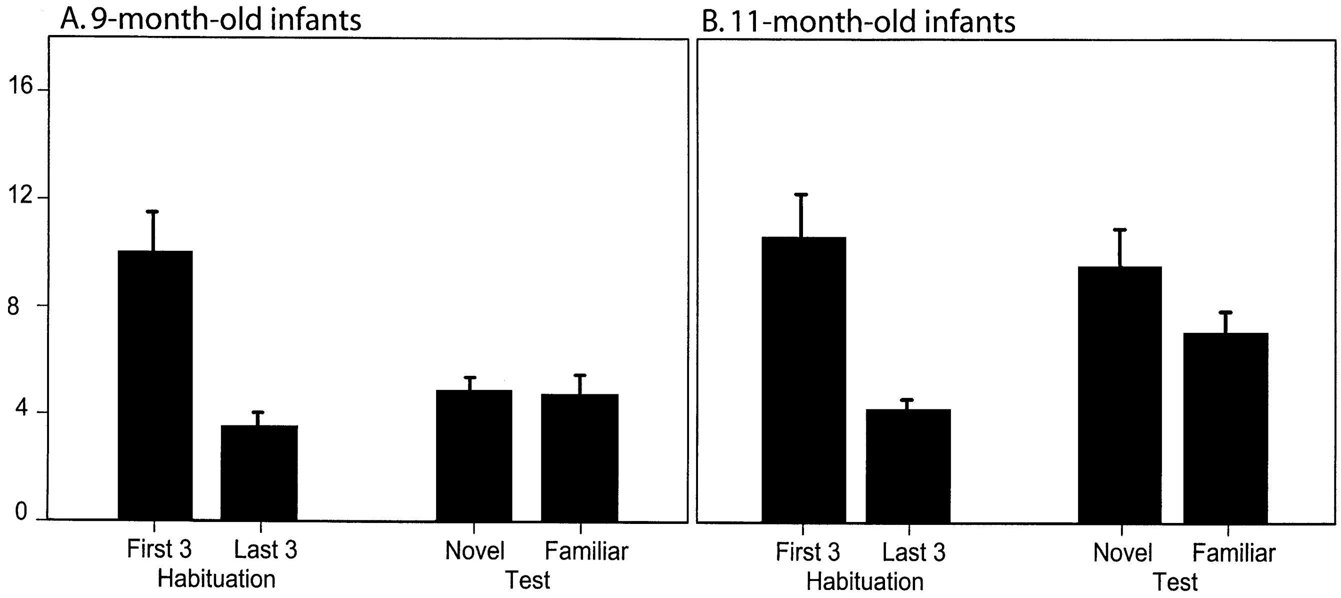


Fig. 4. Mean looking time (±SE) in Experiment 2 to the first three and last three habituation trials and to novel and familiar test trials for 9-month-old (A) and 11-month-old (B) infants.

Thus, both 9- and 11-month-old infants looked longer at the test trials compared to the final habituation trials regardless of novelty. This is likely explained by the fact that the test displays were very different from the habituation displays. The size of the displays increased in the ascending test sequences and decreased in the descending test sequences, whereas the size of the displays was constant in habituation (see Fig. 3). The important result, however, is that 11-month-old infants looked longer at novel test trials relative to familiar test trials and 9-month-old infants did not. Thus, Experiment 2 replicates the results from Experiment 1 and suggests that 11-month-old infants detected the reversal in ordinal direction of a numerical sequence and 9-month-old infants did not.

4. Experiment 3

Experiments 1 and 2 collectively suggest that a change occurs between the 9th and 11th months of life to support the ability to make numerical comparisons. However, these results can not answer whether the failure of 9-month-old infants is numerical in nature or instead depends on a more general cognitive ability such as the ability to contrast any two rapidly and successively presented visual displays. To test this alternative possibility, 9-month-old infants were tested in another version of the same task where displays differed in the size of a single square rather than in number. If 9-month-old infants are unable to make ordinal comparisons between any type of displays then they should again fail in this task. In contrast if 9-month-old infants' deficiency relative to 11-month-old infants is numerical in nature then they may succeed in Experiment 3.

4.1. Method

All aspects of the experimental apparatus, design, and procedure were identical to that of Experiments 1 and 2.

4.1.1. Participants

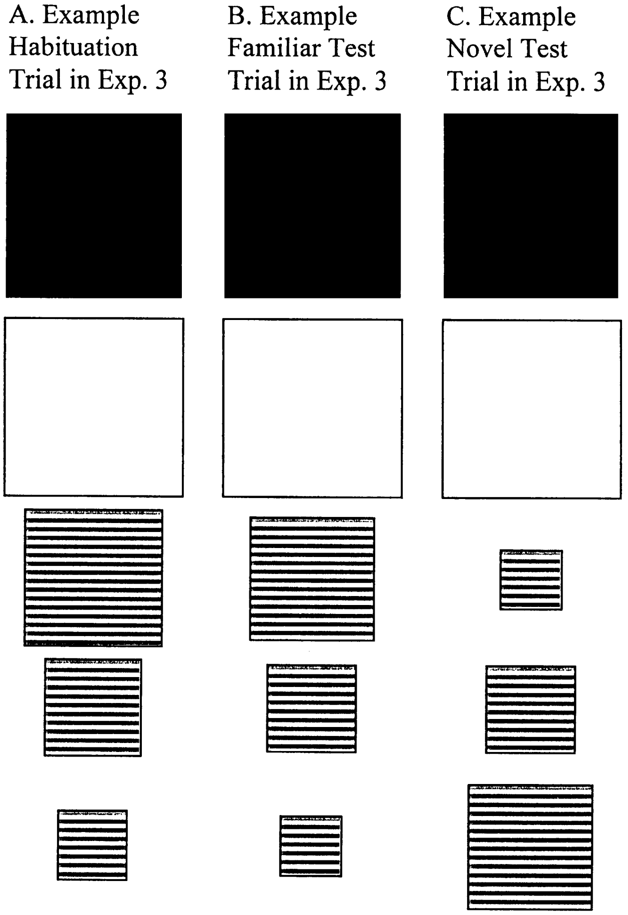
Participants were 16 healthy full-term 9-month-old infants (mean age: 8 months 28 days, range: 8 months 16 days–9 months 16 days). Five of the infants were female. Data from six additional infants were discarded because of fussiness resulting in failure to complete at least four test trials.

4.1.2. Stimuli

Fig. 5 shows that stimuli were single squares that varied in size (range 8–64 cm^2) and were displayed in the center of the computer monitor. The habituation displays were rainbow colored squares as in Experiment 2 (Fig. 5). Rainbow squares were used because a single black square was unlikely to hold attention for the duration of the experiment. The three sets used in habituation contained squares that were 64, 32, 16; 48, 24, 12; and 32, 16, 8 cm^2. The test set contained three novel squares that were 24, 12, and 6 cm^2.

4.2. Results and discussion

Fig. 6 shows that as in Experiments 1 and 2 infants rapidly habituated. Twelve of the



A. Example Habituation Trial in Exp. 3

B. Example Familiar Test Trial in Exp. 3

C. Example Novel Test Trial in Exp. 3

Fig. 5. Achromatic elements are shown here, however, elements were rainbow colored in the actual experiment. The five frames of a sample (A) habituation, (B) familiar test and (C) novel test trial in Experiment 3.

16 infants habituated and on average habituation required 8.27 trials. Paired *t*-tests revealed a significant reduction in looking time from the first three habituation trials to the last three habituation trials ($t(15) = 4.02$, $P < 0.01$) (Fig. 6).

In contrast to Experiments 1 and 2, Fig. 6 illustrates that 9-month-old infants successfully detected the reversal in ordinal direction of a sequence of differently sized squares. Thirteen of the 16 infants looked longer at the novel test trials compared to the familiar test trials (binomial test, $P = 0.5$, $P < 0.05$) (Fig. 6). A paired *t*-test revealed that on average infants looked significantly longer at the novel test trials compared to the last three trials of habituation ($t(15) = -3.98$, $P < 0.01$), whereas there was no difference between their looking times to the familiar test trials compared to the last three trials of habituation ($t(15) = -60$, $P > 0.4$). And finally, infants' average looking time to the novel test trials

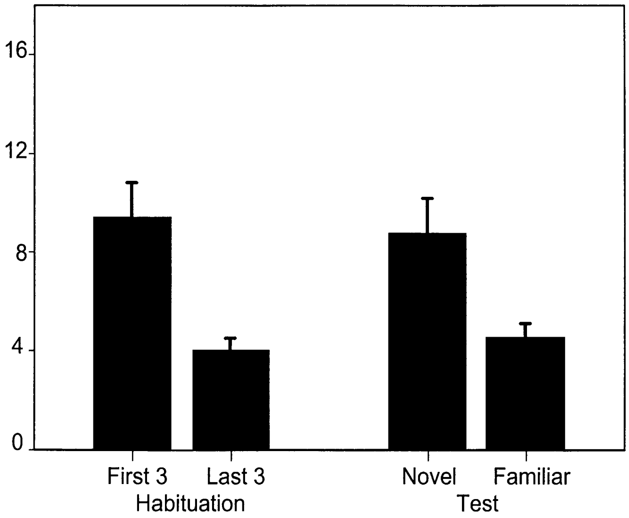


Fig. 6. Mean looking time (±SE) to the first three and last three habituation trials and to the three novel and three familiar test trials for 9-month-old infants in Experiment 3.

was significantly longer than their looking time to the familiar trials ($t(15) = 4.02$, $P < 0.01$).[1]

Nine-month-old infants successfully detected a reversal in the ordinal direction of a non-numerical size-based sequence in Experiment 3 but failed to detect the reversal in ordinal direction of a numerical sequence in Experiments 1 and 2. If the failure of this age group to detect the ordinal reversal in numerical sequences was due to a deficit in some general-purpose cognitive ability such as memory capacity or the ability to contrast any two rapidly presented successive visual displays, then 9-month-old infants should have failed in Experiment 3. Their success suggests that the cognitive change that occurs between 9 and 11 months of age is numerical in nature.[2]

5. General discussion

The results of Experiments 1 and 2 suggest that infants as young as 11 months of age are sensitive to the ordinal relations between numerical values. Such a finding would be important because it would demonstrate that preverbal infants within the first year of

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[1] One infant looked for the full 60 s on one of the novel trials. This was the only case of a looking time that exceeded 3 standard deviations of the mean. The relevant pair of test trials was replaced by the average looking times to the novel and familiar trials for the remaining 15 infants. While the elimination of that single 60 s looking time reduced variance and therefore helped the results of the ANOVA, the other analyses were unaffected. Furthermore, the outlier was observed on a novel trial and was therefore in the predicted direction.

[2] At first blush Experiment 3 might be interpreted as contrasting a receding from a looming stimulus and not involving ordinal non-numerical judgments. However, 9-month-old infants are well-equipped to resolve conflicting depth cues (e.g. binocular disparity and pictorial depth cues) to determine that the computer screen is not three-dimensional (Yonas, Arterberry, & Granrud, 1987).

life appreciate that 16 is numerically more than 8 rather than simply discriminating that 16 is different from 8. It could also be argued that such a finding would be evidence that infants have numerical *concepts* because it would demonstrate an ability to perform computations on numerical representations (see Gallistel and Gelman, 1992 for a distinction between numerical categories and numerical concepts). The results of Experiments 1 and 2 also show that by 11 months of age infants have a numerical processing system other than that described by object-file theory or the subitization hypothesis because the numerical values used in Experiments 1 and 2 exceed the range that can be handled by either theory.

However, the results do not necessitate ordinal numerical knowledge in 11-month-old infants. It is possible that 11-month-old infants only attended to the first or last numerical value in the sequence and did not actually represent the ordinal direction of the sequence. For example, if infants only noticed the first numerosity in the sequence, infants habituated to ascending sequences would have formed representations of 1, 2, and 4 and contrasted those values (or perhaps the average value) with 3 for the ascending test sequence and 12 for the descending test sequence. Infants would then have dishabituated because 12 is numerically more disparate from 1, 2, and 4 than is 3. Similarly, infants in the descending group would have formed representations of 4, 8 and 16 and detected that these values are numerically more disparate from 3 than from 12. This alternative explanation seems unlikely for two reasons. First, infants attended to multiple sequences on each trial and would have had to selectively attend to one-third of each sequence. Second, 9-month-old infants failed in Experiments 1 and 2 which suggests that they did not selectively attend to one value since Xu and Spelke's data show that even 6-month-old infants can discriminate absolute values in this range. Nevertheless, to determine whether 11-month-old infants attended to the ordinal direction of the sequence or the absolute value of some portion of the sequence, I am currently conducting an experiment where the first (or last) display in the novel and familiar test sequence is equated (e.g. 4-2-1 vs. 4-8-16; note that it is only possible to equate the first or the last value, not both). Success in such a task would be more definitive evidence that 11-month-old infants represent ordinal numerical relations.

A second finding was that 9-month-old infants in Experiments 1 and 2 failed to detect a reversal in the ordinal direction of a numerical sequence but did successfully detect a reversal in the ordinal direction of a size-based sequence. This pattern of results suggests that 9-month-old infants are able to represent the ordinal relations between continuous variables such as size but not the ordinal relations between numerosities. But why would magnitude representations formed in response to number be more difficult to contrast than analog representations formed in response to a continuous dimension such as size? Such an interpretation would suggest that the two types of magnitude representations differ or that the comparison process itself differs for magnitude representations that originate from numerical and non-numerical displays.

Another possibility is that 9-month-old infants have trouble representing number in this experimental design. As described earlier, infants as young as 6-months of age discriminate 8 from 16, thus it is likely that 9-month-old-infants are also capable of discriminating the numerosities used in Experiments 1 and 2 (Xu & Spelke, 2000). However, it is possible that the current design did not elicit numerical representations in 9-month-old infants. For example, the current design differs from the standard habituation design in that here each numerical display was only presented for 1 s. Perhaps at 9-months of age infants need more time to form numerical representations. Or perhaps number is less salient for 9-month-old infants compared to 11-month-old infants. Future work should explore these questions and more broadly investigate the relationship between the development of numerical and non-numerical ordinal judgments.

It is interesting to note that the Dehaene and Changeux (1993) neural network model predicts that ordinal numerical knowledge develops between 9 and 11 months of age. Their model posits that infants have a numerosity detection system in place early in development but that the ability to represent the ordinal relations between numerosity detectors develops at around 10 months of age as dendritic density increases in the prefrontal cortex (e.g. Diamond, 1988; Huttenlocher, 1990). Although it is certainly possible that the prefrontal cortex is needed to contrast two values in working memory, such an account leaves unexplained why 9-month-old infants succeeded in detecting the reversal in a non-numerical ordinal sequence; presumably working memory should be equally involved in non-numerical and numerical ordinal comparisons.

As reviewed earlier, other researchers have reported later onset of ordinal numerical abilities than that reported here (Cooper, 1984; Strauss & Curtis, 1984). There are at least three possible reasons why the current paradigm might have revealed a younger onset of ordinal knowledge than that reported by Cooper (1984). First, the current paradigm employed a three-item sequence rather than a two-item sequence. Second, the sequences repeated indefinitely and looking time was measured to the whole dynamic sequence rather than to a single static display. Finally, three different sets of absolute values were used in habituation and these spanned the values 1–16. Together these three features of the current experimental design may have made the ordinal numerical relations salient to the infants and produced conditions to facilitate generalization.

Another inconsistency between the current results and previous research is that here 11-month-old infants seem to discriminate all values between 1 and 16 that differ by a 1:2 ratio (although we did not test 5 vs. 10, or 7 vs. 14). In contrast, Feigenson et al. (in press) found that 10-month-old infants failed to choose a bucket with 4 cookies as opposed to 2 cookies or buckets with 6 cookies as opposed to 3 cookies. It is possible that the paradigms and displays employed in these two paradigms invoke different cognitive systems. For example, three-dimensional objects may be more likely to invoke an object-file system. In addition, successive presentation of the elements in Feigenson et al. (in press) appears to be the main reason for infants' failure given that they succeeded when tested with sets of 3 vs. 6 visible food items. More work is needed to resolve these issues and map out the conditions that elicit different numerical strategies in the first year of life.

In summary, the present results suggest that by 11 months of age infants represent the greater than and less than relations between large numerical values. This result provides further support for the idea that a primitive system for representing and comparing numerical values is in place early in both phylogeny and ontogeny. More tenuous is the implication of the results that ordinal numerical abilities develop between 9 and 11 months of age. If true, this developmental time course raises many interesting issues for future research such as what brain systems support ordinal numerical knowledge and how these brain systems change between 9 and 11 months of age and the role of infants' specific experiences in the development of ordinal numerical knowledge.

Acknowledgements

The experimental design benefited from discussions with Susan Hespos who was conducting similar experiments in collaboration with Elizabeth Spelke. Thanks also to Susan Carey, Lisa Feigenson, Amy Needham, and Gretchen Van de Walle for helpful advice on experimental design and procedures and to Susan Carey, Amy Needham, Michael Platt, Gretchen Van de Walle, and two anonymous reviewers for their comments on the paper. Finally, thanks to Stan Dehaene for suggesting the stimulus controls used in Experiment 2 and for other helpful comments on an earlier draft of this paper. This research would not have been possible without the help of a team of undergraduate research assistants, especially Lauren Wolfe, Yuko Hansbrough, Jen Hurtgen, Komal Nandwani, Joanna Bradley, Lindsay Bunk, Davie Yoon, and Eliza Bobek. The research was supported by a B/START NIMH award MH63075-01 and The Arts and Science Research Council at Duke University.

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