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# Chronometric studies of numerical cognition in five-month-old infants

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**Abstract**

Developmental research suggests that some of the mechanisms that underlie numerical cognition are present and functional in human infancy. To investigate these mechanisms and their developmental course, psychologists have turned to behavioral and electrophysiological methods using briefly presented displays. These methods, however, depend on the assumption that young infants can extract numerical information rapidly. Here we test this assumption and begin to investigate the speed of numerical processing in five-month-old infants. Infants successfully discriminated between arrays of 4 vs. 8 dots on the basis of number when a new array appeared every 2 s, but not when a new array appeared every 1.0 or 1.5 s. These results suggest alternative interpretations of past findings, provide constraints on the design of future experiments, and introduce a new method for probing infants' enumeration process. Further experiments using this method provide initial evidence that infants' enumeration mechanism operates in parallel and yields increasingly accurate numerical representations over time, as does the enumeration mechanism used by adults in symbolic and non-symbolic tasks.


*Keywords:* Chronometric studies; Numerical cognition; Human infancy

Over the past two decades, a wealth of research has focused on the nature and origins of numerical knowledge. Although reports that infants represent small numbers of objects have been interpreted in multiple ways (Carey, 2001; Clearfield & Mix, 1999; Feigenson,

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Carey, & Spelke, 2002; Simon, 1997; Starkey & Cooper, 1980; Treiber & Wilcox, 1984; Wynn, 1992; Wynn, Bloom, & Chiang, 2002), recent research provides clear evidence that infants as young as 6 months represent the approximate cardinal values of large sets of entities. In studies using a looking time method, for example, six-month-old infants who were habituated to arrays of 8 or 16 dots looked longer at arrays with the novel numerosity (Xu & Spelke, 2000; see also Xu, 2003; Xu, Spelke, & Goddard, 2005). Further research revealed that infants also discriminate large numbers of jumps of a puppet (Wood & Spelke, in press), and research using a similar head-turn preference procedure revealed that they discriminate large numbers of sounds (Lipton & Spelke, 2003, 2004). In all these studies, continuous variables (including item size, summed area, summed contour length, image size, and image density for visual arrays, and including item duration, amount of motion or sound, sequence duration, rhythm, and sequence rate for visual and auditory sequences) were strictly equated either during habituation or during test, so that dishabituation was specific to the change in number.

Numerical discrimination in all of these studies shows four signature features. First, it is imprecise: for example, six-month old infants discriminate 8- vs. 16-dot arrays, but not 8- vs. 12-dot arrays (Xu & Spelke, 2000). Second, discrimination is subject to a set-size ratio limit: infants who discriminate 8 from 16, but not from 12, dots or sounds also discriminate 4 from 8, but not from 6, dots or sounds (Lipton & Spelke, 2004; Xu, 2003). Third, the critical ratio limit decreases with age, from 2.0 at 6 months to 1.5 at 9 months (Lipton & Spelke, 2003; Wood & Spelke, in press; Xu & Arriaga, in prep). Fourth, discrimination fails for the numerosities 1–3 in experiments using the same methods and continuous quantity controls (Lipton & Spelke, 2004; Wood & Spelke, in press; Xu, 2003; Xu et al., 2005), even though infants can track up to three objects when tested with other methods (Feigenson Carey, & Hauser, 2002) or with displays confounding number with continuous quantities such as summed volume, area, or contour length (Antell & Keating, 1983; Feigenson et al., 2002; Strauss & Curtis, 1981; Wynn, 1996). These common signatures suggest that infants have a single, abstract system for representing the approximate cardinal value of large numbers of entities. Because human adults and adult non-human primates also represent large approximate numerosities with a signature ratio limit (Barth, Kanwisher, & Spelke, 2003; Hauser, Tsao, Garcia, & Spelke, 2003; Van Oeffelen & Vos, 1982), a common system of numerical representation appears to operate over human ontogeny and primate phylogeny.

What are the properties of this system as it exists in infants? This question can be broken into more specific questions. First, what aspects of number do infants represent: Do their numerical representations capture information about ordinal relationships as well as cardinal values? To investigate infants' representation of ordinal relationships, Brannon (2002) tested 9- and 11-month-old infants' discrimination of sequences of rapidly occurring arrays with ascending or descending numerosity (e.g. 3-6-12 vs. 12-6-3). Infants discriminated the sequences over changes in the specific numerosities at 11, but not 9 months, suggesting that ordinal representations developed over that time period. Because each array was presented briefly, however, it is possible that the developmental change reflects an increase in the speed of cardinal number processing, rather than the emergence of a new capacity for numerical comparisons. Here we introduce a method for testing the speed of infants' numerical discrimination.

Second, what neural mechanisms underlie infants' number representation: Does a common set of mechanisms serve to represent number over human development and evolution? Investigators have begun to use event-related potentials (ERPs) to probe the neural mechanisms of enumeration in adults (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999) and children (Temple & Posner, 1998), and the method shows promise for studies of non-human primates and human infants. If common neural mechanisms underlie number representations across age and species, then all these studies may reveal common ERP signatures of number processing (Spelke, 2002). ERP methods, however, typically use rapid stimulus presentations. Such methods will only engage infants' numerical processing if infants are able to extract numerical information rapidly. To our knowledge, however, no study has investigated the speed of infants' numerical processing. The present studies begin this investigation.

Third, what is the process of enumeration: Do number representations depend on a serial, iterative process akin to counting (Gallistel, 1990; Gallistel & Gelman, 2000; Meck & Church, 1983) or on a parallel process akin to the representation of area or density (Church & Broadbent, 1990; Dehaene & Changeux, 1993)? This question has aroused considerable debate. When children and adults engage in verbal counting, they compute number through an iterative process: each item is attended in series and tagged with the next symbol in the count list; the cardinal value of the set is the final tag. Gallistel and Gelman (1992) have proposed that a similar iterative process underlies the imprecise estimation of approximate numerosities by animals, infants, and adults. One candidate iterative mechanism consists of a pulse generator, an accumulator, and a switch that links them and passes activation to the accumulator in series for each item to be enumerated (Meck & Church, 1983). In contrast, others have proposed that the non-verbal enumeration process operates in parallel. One candidate process involves simultaneous tagging of all of the items to be enumerated, normalizing of the activation from each item, and summing of the resulting activation (Dehaene & Changeux, 1993). A second parallel model involves operating on the global characteristics of the display, such as multiplying the duration and rate of a temporal sequence, or dividing the area by inter-element distance of a spatial array (Barth et al., 2003; Church & Broadbent, 1990).

Although serial and parallel mechanisms both can account for the imprecision of numerical estimation, parallel mechanisms can more easily explain two sets of findings. First, when adults discriminate numerosity in visual–spatial arrays, error rates rise in proportion to the numerical magnitudes. If error were introduced by an iterative mechanism, then one would expect it to rise as a binomial function of magnitude. Second, adults' reaction time depends on the ratio of the two numerosities, but not on their numerical magnitude: discriminating 30 from 35 is no faster than discriminating 60 from 70 (Barth et al., 2003). An iterative enumeration process, in contrast, would take longer for larger numerosities. These findings, however, are not fully decisive. Gallistel and Gelman (1992) have suggested that both the error and the processing time in numerical comparisons are introduced at a stage of memory comparison; thus, the error and speed of numerical estimations may not reflect the iterative enumeration process. Moreover, the adults in the experiment are mathematically sophisticated and highly practiced at enumeration. It is possible that practices leads to the development of fast, parallel recognition processes that obscure the basic iterative process of enumeration.

The present experiments attempt to overcome these problems. First, we test the enumeration process in five-month-old infants, who lack any knowledge of symbolic number and have had little opportunity to learn enumeration strategies. Second, we contrast serial and parallel enumeration processes not by focusing on errors or response times, but by varying the amount of time available for constructing a representation of the cardinal value of an enumerable set. If enumeration is a serial process, then longer presentation rates should be required for larger sets. If it is a parallel process, the sets of all sizes might be discriminated at the same presentation times.

This paper presents five experiments. The first three experiments tested whether five-month-old infants can discriminate numerosities in displays that appear every second (as in past ERP studies and in Brannon's studies addressing ordinal knowledge in older infants), every 1.5 s, and every 2 s. Infants successfully discriminated number only at the 2-s presentation rate, suggesting constraints on future behavioral and ERP studies. In the fourth experiment, we asked whether the minimum presentation time for discriminating 4 from 8 elements also suffices for discriminating 8 from 16 elements, as predicted by parallel enumeration mechanisms. Our findings provide initial support for a parallel enumeration mechanism. A fifth experiment tested for a further property of the enumeration mechanism that was supported by studies of number processing in adults: that numerical representations increase in precision over time (Gallistel & Gelman, 1992). We tested whether infants discriminate between arrays on the basis of number at a presentation rate of 1.5 s, when the ratio between the numerosities is increased from 2.0 (4 vs. 8, 8 vs. 16) to 4.0 (4 vs. 16). Infants succeeded at the latter discrimination, indicating that 2 s is not an absolute limit on their numerical processing. This finding supports Gallistel and Gelman's (1992) suggestion of a trade-off between the speed and accuracy of the enumeration process.

## 1. Experiment 1

In Experiment 1, we investigated infants' ability to discriminate numerosity in briefly presented visual arrays. Infants viewed a succession of dot arrays in which a new array appeared every 2 s. Infants were habituated to a sequence of visual displays with either four or eight elements and then were tested with new 4- vs. 8-element displays.

### *1.1. Method*

#### *1.1.1. Participants*

Seven male and nine female full-term infants (mean-age 5 months, 1 day: range 4 months, 16 days to 5 months, 15 days) participated in the study. Three additional infants were excluded from the sample because of fussiness ($n = 2$) or parental interference ($n = 1$).

#### *1.1.2. Apparatus*

Infants sat on a parent's lap and faced a screen surrounded by black surfaces and curtains in a dimly illuminated room. At the beginning of each trial, a black occluder rose to reveal a white 58 cm × 47 cm screen on which images were back-projected by a Toshiba

TDP-T1 projector. Video cameras directed at the display and the infant were mixed onto a TV monitor and a VCR a separate room, where an observer recorded the infant's looking times, with the display portion of the monitor occluded to ensure that the observer was blind to the habituation and test conditions. For each infant tested in the following experiments, the inter-coder reliability was above 90% (the mean reliability for each experiment was 92% or greater). The experimenter asked the parents to look away from the display during the experiment.

*1.1.3. Displays*

Fig. 1 presents a sample sequence of habituation and test displays. The habituation displays consisted of 46 cm by 34 cm pictures of 4 or 8 round purple dots created with Canvas software. The dot positions were chosen randomly for each picture, although displays that looked too cluttered were discarded. The eight-element-displays therefore had twice the density of the four-element displays (0.0051 vs. 0.0026 dots/cm$^2$). Three different dot sizes were used in each habituation condition: diameters 6.5, 7.5, and 8.5 cm for the four-element-displays and 4.6, 5.4, and 6.1 cm for the eight-element-displays. On average, the four-element-displays therefore contained individual dots that were twice the area of the individual dots in the eight-element-displays, and the summed area and brightness of displays at the two numerosities were equated. The test displays consisted of 6.2-cm diameter dots at a density of .0038 dots/cm$^2$, so the total surface area, average color, and image size of the eight-element-displays were greater than those in the four-element-displays. The continuous quantities that varied across the two habituation conditions therefore were equated in the test displays, and the continuous quantities that varied in the test were equated across the habituation conditions.

Throughout the experiment, infants viewed a different array of dots every 2 s, with each 1.7-s dot array followed by a 0.3-s blank display to make each array more distinct and to eliminate flicker. Fifteen dot arrays were created for each individual dot size, numerosity,

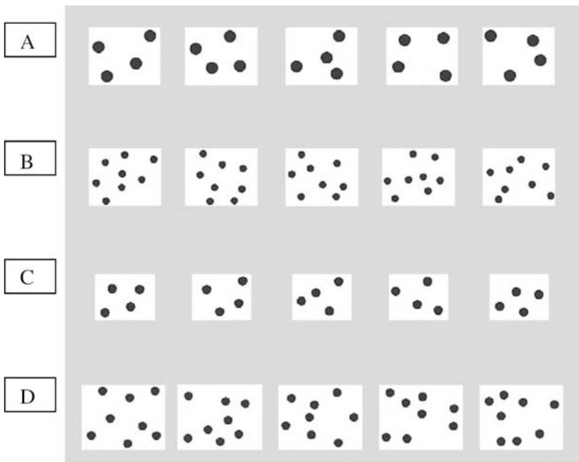



Fig. 1. Schematic representation of selected habituation (A and B) and test (C and D) displays of Experiments 1, 2, and 3.

and phase (habituation vs. test), for a total of 120 distinct images. Arrays were linked together into Quicktime movies with Director software.

*1.1.4. Design and procedure*

Equal numbers of infants were habituated to four-element vs. eight-element arrays. Each infant watched a repeating sequence of 15 displays on each trial, which began with the first 0.5-s look at the screen and ended when the infant looked away for 2 s continuously. During each trial, the infant watched repeating dot arrays of constant size (i.e. dot size varied across, but not within trials). Habituation trials continued until infants met the habituation criterion (50% decline in looking time over three consecutive trials, compared to the three trials) or received 14 trials. After habituation, infants viewed six test sequences with alternating arrays of 4 vs. 8 dots, following the same procedure as for habituation. Half of the infants in each habituation condition were tested first with each numerosity.

*1.2. Results*

Fig. 2 presents the mean looking times on the first three and the last three habituation trials and on the six test trials. Seven infants, three in the four-element habituation condition, failed to meet the habituation criterion; they showed the same pattern of test trial looking as the other infants in their condition. Initial, final, and total looking times during the habituation period did not differ for infants habituated to 4- vs. 8-item displays (all $P$s$>.05$). Test trial looking times were analyzed by a $2\times2\times3$ mixed factor analysis of variance, with the within-subjects factors of Test Trial Type (new number vs. old number) and Test Trial Pair (first, second, or third) and the between subject factor of Habituation condition (4 vs. 8). There was a main effect of Test Trial type, $F(1,15)=7.724$, $P<.02$. Infants looked longer at the new number ($M=17.01$ s,

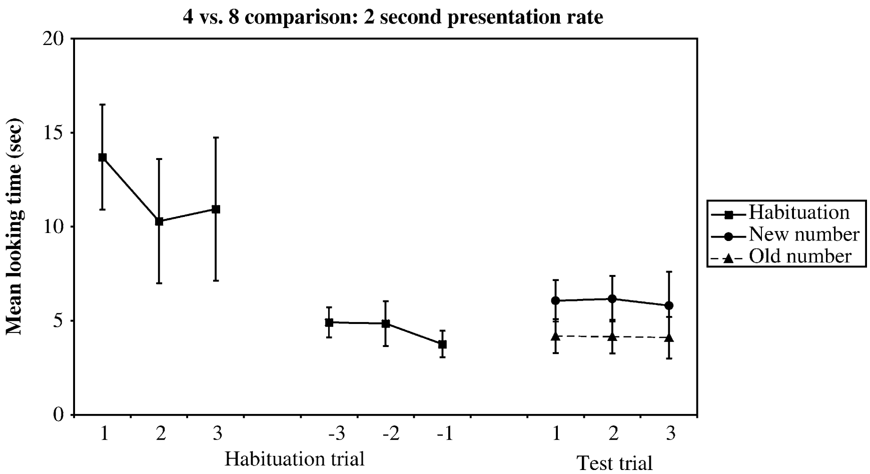



Fig. 2. Mean looking times for the first three habituation trials, the last three habituation trials, and the test trials of Experiment 1.

SD = 12.21 s) than the old number ($M$ = 11.65 s, SD = 8.24). No other main effects or interactions were significant. Twelve of the 16 infants looked longer at the displays with the new number (binomial $P < .05$), providing evidence that the infants discriminated the two numerosities.

### 1.3. Discussion

Experiment 1 provides evidence that infants discriminate between four-element displays and eight-element-displays when a new display is presented every 2 s. This finding suggests that infants can enumerate a visual array of items relatively quickly. Additionally, to our knowledge, the infants in this study are the youngest in the existing literature to discriminate between large, approximate numerosities when the continuous quantities of summed surface area, item size, image size, and density are controlled. In light of these findings, Experiment 2 investigated whether infants would continue to make this numerical discrimination when the duration of each display was reduced.

## 2. Experiment 2

Infants were presented with the same displays as in Experiment 1, but with the presentation time of each array reduced from 2 to 1 s. A 1-s display duration was chosen because it is commonly used in ERP studies, and because it has been used to investigate older infants' ordinal processing (Brannon, 2002).

### 2.1. Method

The method was the same as in Experiment 1, except as follows. Participants were 16 infants (mean age, 5 months, 2 days; range, 4 months, 18 days to 5 months, 15 days), with two additional infants excluded because of fussiness. The dot arrays and display sizes of Experiment 1 were presented, with each array displayed for 0.7 s and followed by a 0.3-s blank display. A new array therefore appeared every second.

### 2.2. Results

Fig. 3 presents the mean looking times during habituation and test. Looking times to the 4- vs. 8-item displays did not differ during the habituation period (all $P$s > .05). Six infants, two in the four-element habituation condition, failed to meet the habituation criterion; they showed the same pattern of test trial looking as the other infants in their condition. Test trial looking times to the familiar and novel numerosities also did not differ: the $2 \times 2 \times 3$ ANOVA revealed no main effect of Test Trial type ($F < 1$) and no other main effects or interactions. The infants did not look longer at the new number ($M$ = 18.0 s, SD = 12.52) than the old number ($M$ = 20.05 s, SD = 14.24). Seven of the 16 infants looked longer at the displays that contained the novel number of elements (n.s.).

A further 2 (Experiment: 1 vs. 2) by 2 (Test Trial type: new number vs. old number) ANOVA compared infants' looking times in Experiments 1 and 2. This analysis revealed

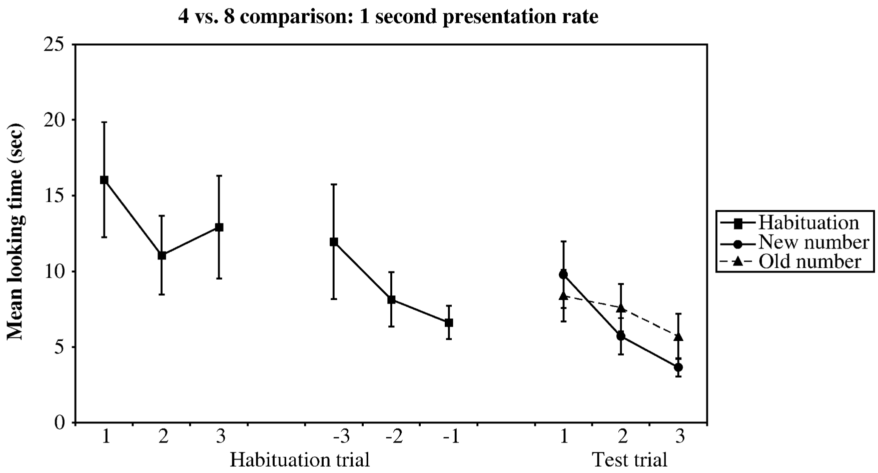



Fig. 3. Mean looking times for the first three habituation trials, the last three habituation trials, and the test trials of Experiment 2.

a significant interaction between Test Trial Type and Experiment, $F(1, 31)=4.234$, $P<.05$. Infants showed a greater preference for the novel numerosity in Experiment 1 than in Experiment 2.

### 2.3. Discussion

Experiments 1 and 2 provide evidence for a temporal constraint on infants' extraction of numerical information from visual displays. Although five-month-old infants discriminated between four- and eight-item displays when a new display appeared every 2 s, they failed to do so when a new display appeared every second. Because performance in the two experiments differed reliably, and because the only difference between the two experiments concerned the presentation rate of the two displays, we suggest that infants show a striking temporal limit for extracting numerical information in these arrays.

The present results suggest constraints on future studies investigating the neural signatures of infants' numerical processing using ERP methods. ERP experiments typically present a new display every second. The present results suggest, however, that such presentations are too brief to allow young infants to extract full numerical information. Effective ERP experiments, therefore, may require longer presentation rates to give infants more time to form representations of numerosity.

The finding that five-month-old infants require more than 1 s to extract numerical information from a visual array also suggests an alternative interpretation of Brannon's (2002) studies of ordinal knowledge. As Brannon (2002) noted, discrimination of ascending from descending numerical arrays might have emerged between 9 and 11 months either because infants have begun to represent numerical order, or because they have become more efficient processors of briefly presented information. Our findings lend plausibility to the latter interpretation, although it is still an open question how quickly nine-month-old infants process numerical information in Brannon's displays.

## 3. Experiment 3

Infants were presented with the same displays as in Experiments 1 and 2, but with the presentation time of each array increased to 1.5 s. A 1.5-s presentation rate was chosen, because testing the performance at 1.5 s should specify more precisely the minimum presentation time under which five-month-old infants successfully show numerical discrimination.

### 3.1. Method

The method was the same as in Experiment 1, except as follows. Participants were 16 infants (mean age, 5 months, 1 days; range, 4 months, 18 days to 5 months, 17 days), with two additional infants excluded because of fussiness. The dot arrays and display sizes of Experiment 1 were presented, with each array displayed for 1.2 s and followed by a 0.3-s blank display. A new array therefore appeared every 1.5 s.

### 3.2. Results

Fig. 4 presents the mean looking times during habituation and test. Looking times to the 4- vs. 8-item displays did not differ during the habituation period (all $Ps > .05$). One infant in the eight-element habituation condition failed to meet the habituation criterion. Test trial looking times to the familiar and novel numerosities also did not differ: the $2 \times 2 \times 3$ ANOVA revealed no main effect of Test Trial type ($F < 1$) and no other main effects

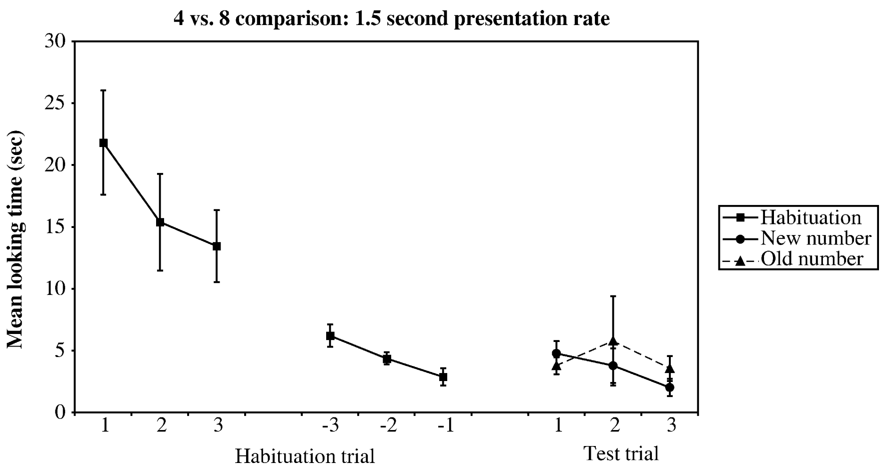



Fig. 4. Mean looking times for the first three habituation trials, the last three habituation trials, and the test trials of Experiment 3.

or interactions. The infants did not look longer at the new number ($M = 9.43$ s, SD = 7.34) than the old number ($M = 11.06$ s, SD = 14.98). Nine of the 16 infants looked longer at the displays that contained the novel number of elements (n.s.).

A further 2 (Experiment: 1 vs. 3)×2 (Test Trial Type: new number vs. old number) ANOVA compared infants' looking times in Experiments 1 and 3. This analysis revealed a marginally significant interaction between Test Trial Type and Experiment, $F(1, 31) = 4.024$, $P = 0.054$. Infants showed a more reliable preference for the test sequence presenting the novel numerosity when a new array appeared every 2 s than when a new array appeared every 1.5 s.

### 3.3. Discussion

In contrast to Experiment 1, the infants in Experiment 3 did not discriminate between four- and eight-element displays. Together with the previous findings, this experiment provides evidence that at 5 months, the critical presentation time for constructing numerical representations that are sufficient to discriminate these numerosities lies between 1.5 and 2 s.

Experiments 1-3 suggest a new method for investigating the mechanisms of infants' numerical processing. Serial, iterative mechanisms and parallel, non-iterative mechanisms would explain the present findings in different ways. If infants' enumeration mechanism is non-iterative, then the infants in Experiments 1–3 might have succeeded with a 2-s presentation rate, but not with a shorter presentation rate, because they required more than 1.5 s to sample and process the global characteristics of the displays. In contrast, if infants' enumeration mechanism is iterative, then infants may have failed to discriminate numerosities with 1 or 1.5-s presentation rates, because they required more time to enumerate all the elements serially. Although either kind of mechanism could account for the present findings, iterative and non-iterative theories make contrasting predictions about infants' processing of larger sets. Most non-iterative models would predict that infants will require as brief a presentation time to discriminate arrays of 8 from 16 or 16 from 32 dots as they require to discriminate 4 from 8 dots. The same patterns of success and failure obtained in the present experiments therefore should be obtained with larger numerosities. In contrast, most iterative models would predict that infants tested with large numerosities will require longer presentation rates. In Experiment 4, we test these contrasting predictions.

## 4. Experiment 4

Experiment 4 investigated five-month-old infants' discrimination of arrays of 8 vs. 16 dots, when a new array appeared every 2 s. The method was the same as in Experiment 1 except for the numerosities tested, which were twice as large. Because a 2-s presentation rate is close to the limit of infants' discrimination for sets of 4 vs. 8 elements, serial iterative models of enumeration should predict that longer times would be necessary for the larger numerosities.

### 4.1. Method

The method was the same as in Experiment 1, except as follows. Participants were 16 infants (mean age, 4 months, 30 days; range, 4 months, 16 days to 5 months, 15 days), with one additional infant excluded because of fussiness. We presented new dot arrays to the infants, with the total surface area of the elements in each array equal to the corresponding array in Experiments 1–3. Therefore, on average each individual dot in the present experiment was one-half of the size as the individual dots in the four- and eight-dot arrays in Experiments 1–3 (Fig. 5).

### 4.2. Results

Fig. 6 presents the mean looking times on the first three and the last three habituation trials and on the six test trials. Two infants, both in the eight-element habituation condition, failed to meet the habituation criterion. Initial, final, and total looking times during the habituation period did not differ for infants habituated to 8- vs. 16-item displays (all $P$s $>$ .05). Test trial looking times, analyzed as in the previous studies, revealed a main effect of Test Trial type, $F(1,15) = 6.759$, $P < .03$. Infants looked longer at the new number ($M = 19.98$ s, SD = 15.35 s) than the old number ($M = 14.44$ s, SD = 9.73). No other main effects or interactions were significant. Twelve of the 16 infants looked longer at the displays with the new number (binomial $P < .05$), providing evidence that the infants discriminated the two numerosities.

### 4.3. Discussion

Infants successfully discriminated 8- vs. 16-dot arrays on the basis of number when a new array appeared every 2 s. Importantly, the infants in the present experiment discriminated large sets at the same presentation rate as the infants in Experiment 1 with

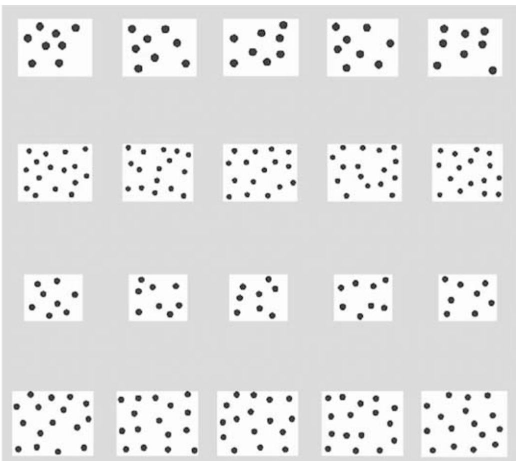
A
B
C
D


Fig. 5. Schematic representation of selected habituation (A and B) and test (C and D) displays of Experiment 4.

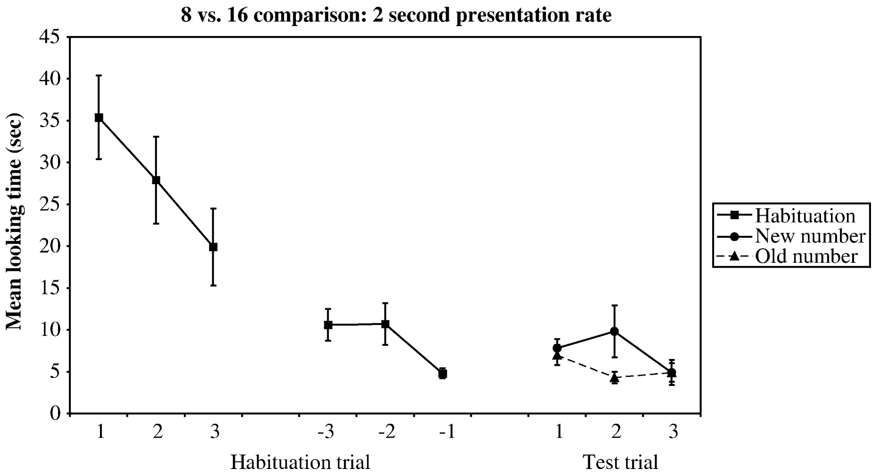



Fig. 6. Mean looking times for the first three habituation trials, the last three habituation trials, and the test trials of Experiment 4.

smaller sets. These results provide initial evidence for a parallel enumeration mechanism in infancy.

There are, however, alternative interpretations for these findings. First, infants' performance in all of the above experiments may be limited by cognitive or motivational factors extrinsic to the enumeration mechanism. In particular, infants may fail to attend to arrays that appear for less than 2 s, regardless of the information to be processed. Under this proposal, infants in Experiments 2 and 3 failed to enumerate the four- and eight-dot displays not because they did not have enough time to complete the enumeration processes, but because the arrays were presented too quickly for infants to extract information in general. Second, infants' performance in Experiments 1–3 may depend on a serial mechanism of enumeration, but the enumeration process may be very rapid: too rapid to reveal an effect of numerosity on discrimination at the presentation rates tested here.

Our final experiment was undertaken to test these alternatives and to explore a further property of the enumeration process suggested by Gallistel and Gelman (1992) and by Dehaene (1997). Reviewing the literature on symbolic numerical comparison and computation, Gallistel and Gelman noted that the performance of human adults suggests a trade-off between the speed and the precision of numerical representation. For example, adults take longer to judge that a number, presented in Arabic notation, is larger or smaller than 65 if the number is close to 65, and their response time declines monotonically with increasing numerical distance (Dehaene, 1997). Gallistel and Gelman (1992) proposed that symbolic numerical operations are supported by non-symbolic number representations that become increasingly accurate over time.

In Experiment 5, we investigated this proposal by testing infants' discrimination of numerosities that appeared every 1.5 s and differed by a larger ratio than 2.0: arrays of 4 vs. 16 elements. If infants failed to discriminate 4- vs. 8-dot arrays in Experiment

3 because they do not process information from any arrays that appear for less than 2 s, then the infants in Experiment 5 also should fail to discriminate numerosities at a 1.5-s presentation rate. In contrast, if infants failed at 1.5 s to discriminate 4 vs. 8 dots because they did not have enough time to complete the parallel enumeration process, and if Gallistel and Gelman's (1992) suggestion of a speed-accuracy trade-off is correct, then infants may discriminate 4- vs. 16-element arrays at this presentation rate.

## 5. Experiment 5

Experiment 5 investigated whether five-month-old infants process numerical information at a 1.5 s presentation rate when the ratio difference between the numerosities is increased. The method was the same as in Experiment 3, except for the numerosities tested: 4 vs. 16.

### 5.1. Method

Participants were 16 infants (mean age, 5 months, 2 days; range, 4 months, 15 days to 5 months, 14 days), with one additional infant excluded because of fussiness. We presented new dot arrays to the infants, with the total surface area of the elements in each array equal to the corresponding array in Experiments 1–3. The habituation displays consisted of 43 cm by 32 cm pictures of 4 or 16 purple dots. The 16-element displays therefore had four times the density of the four-element displays (.0116 vs. .0029 dots/cm$^2$). Three different dot sizes were used in each habituation condition: diameters of 6.5, 7.5, and 8.5 cm for the 4-element displays, and 3.25, 3.8, and 4.3 cm for the 16-element displays. On average, the four-element displays therefore contained individual dots that were four times the area of the individual dots in the 16-element displays, and the summed area and brightness of displays at the two numerosities were equated. The test displays consisted of 5.4 cm diameter dots at a density of .0072 dots/cm$^2$, so the total surface area, average color, and image size of the 16-element displays were greater than those in the four-element displays. As in Experiments 1–4, the continuous quantities that varied across the two habituation conditions therefore were equated in the test displays, and the continuous quantities that varied in the test were equated across the habituation conditions.

### 5.2. Results

Fig. 7 presents the mean looking times on the first three and the last three habituation trials and on the six test trials. All infants met the habituation criterion. Initial, final, and total looking times during the habituation period did not differ for infants habituated to 4- vs. 16-item displays (all $P$s > .05). Test trial looking times, analyzed as in the previous studies, revealed a main effect of Test Trial type, $F(1,15) = 13.685$, $P < .005$. Infants looked longer at the test displays presenting the new number ($M = 20.28$ s, SD = 14.28 s) than the old number ($M = 11.01$ s, SD = 5.75 s). No other main effects or interactions were significant. Twelve of the 16 infants looked longer at the displays with the new number (binomial $P < .05$), providing evidence that the infants discriminated the two numerosities.

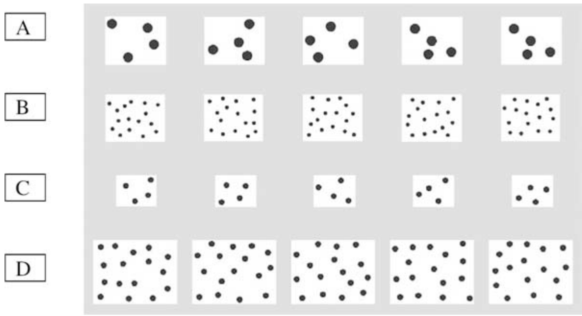



Fig. 7. Schematic representation of selected habituation (A and B) and test (C and D) displays of Experiment 5.

A further 2 (Experiment: 3 vs. 5) by 2 (Test Trial Type: new number vs. old number) ANOVA revealed both a main effect of Trial Type, $F(1,31)=8.429$, $P<.01$, and an interaction of Experiment and Trial Type, $F(1, 31)=4.257$, $P<.05$. At a presentation rate of 1.5 s, infants showed a greater preference for the new number test displays when the ratio between the numerosities differed by a 4.0 ratio than when the numerosities differed by a 2.0 ratio (Fig. 8).

### 5.3. Discussion

Infants successfully discriminated 4- vs. 16-dot arrays on the basis of number when a new array appeared every 1.5 s. This finding provides evidence that infants in Experiments 2–3 did not fail to discriminate number because of general processing constraints, such as a failure to attend to arrays presented at a rate faster than 2 s. This finding strengthens the evidence for a parallel enumeration mechanism by suggesting that the temporal limit on

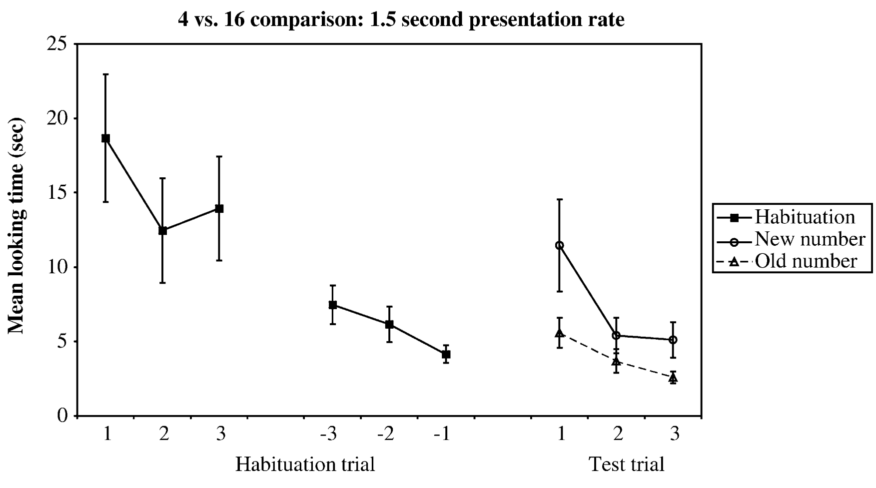



Fig. 8. Mean looking times for the first three habituation trials, the last three habituation trials, and the test trials of Experiment 5.

infants' numerical processing stems from factors intrinsic to numerical processing itself. Infants' speed of numerical processing is directly affected by the ratio difference, rather than the magnitude, of the numerosities, consistent with parallel enumeration mechanisms.

The findings of Experiment 5 also provide initial support for Gallistel and Gelman's (1992) thesis of a tradeoff between the speed and accuracy of numerical representations. At a 1.5-s presentation rate, infants failed to discriminate four from eight dots, but successfully discriminated four from 16 dots. Infants therefore appear to construct numerical representations gradually, from an initial, highly imprecise representation to a representation that increases in precision. These findings suggests striking convergence between chronometric studies of non-symbolic numerical cognition in infants and symbolic numerical cognition in adults.

## 6. General discussion

Five experiments investigated the speed of numerical processing in five-month-old infants. In Experiments 1–3, we presented infants with 4- vs. 8-element displays, with presentation rates of 2, 1.5, and 1.0 s. Infants successfully discriminated arrays of 4 vs. 8 elements when a new array appeared every 2 s, but they failed to discriminate those arrays with a 1.0- or 1.5-s presentation rate. In Experiment 4, we investigated the functional processes by which infants construct numerical representations by testing infants with sets of 8 vs. 16 elements at the minimum 2-s presentation rate at which infants succeeded with sets of 4 vs. 8 elements. At this presentation rate, infants successfully discriminated the larger numerosities. In Experiment 5, we investigated infants' processing time with numerosities that differed by a larger ratio. Unlike the infants in Experiment 3, who failed to discriminate arrays of dots that appeared for 1.5 s and that differed by a 2.0 ratio, infants in Experiment 5 successfully discriminated on the basis of number when the ratio between the numerosities was increased to 4.0 (4 vs. 16). These findings provide initial evidence that infants' enumeration mechanism operates in parallel (Church & Broadbent, 1990; Dehaene & Changeux, 1993) and builds increasingly precise numerical representations over time (Gallistel & Gelman, 1992).

The present experiments contribute two further findings to the study of numerical cognition. First, they provide alternative interpretations of past findings and methodological constraints on the design of future studies. Studies of young infants using event-related potentials, for example, typically present arrays with presentation rates of 1 s or less. Although it is possible that functional neuroimaging constitutes a more sensitive test than behavioral studies, our studies suggest caution in drawing negative conclusions from these studies, because they may not allow infants enough time to extract information from an array. Second, these studies provide a new chronometric method for assessing numerical processing in infants. This method provides a tool for investigating developmental changes in cognitive processes throughout the lifespan and for probing the nature of the mechanisms that subserve those processes.

Our findings suggest that the mechanism of infants' enumeration operates in parallel, but what kind of parallel enumeration mechanism could underlie infants' numerical representations? Dehaene and Changeux (1993) proposed that enumeration proceeds by simultaneously tagging all of the items in an array, normalizing the activation of each item, and summing the activation. This model is similar to the serial models of Meck and Church (1983), except that activation for all of the items is summed simultaneously instead of successively. In contrast, Barth et al. (2003) and Church and Broadbent (1990) proposed that enumeration proceeds by estimating the global characteristics of a display. For visual arrays, number could be constructed by estimating the area covered by an array and the average inter-element distance of the items within the array, and by dividing the first value by the second. How can one evaluate such models?

Recent studies suggest limits to infants' abilities to form representations of small numbers (2 vs. 4), when the methodology, displays, and set-size ratio are the same as for the larger sets that infants successfully discriminate. Although both the existence and the interpretation of this limit is currently under debate, infants have failed to discriminate between set sizes of 1–4 when tested with visual–spatial arrays of objects (Feigenson et al., 2002), two-dimensional patterns (Xu, 2003; Xu et al., 2005), auditory sequences (Lipton & Spelke, 2004), and visual sequences (Wood & Spelke, in press), as long as continuous quantities are controlled. Neither the Meck and Church (1983) or the Dehaene and Changeux model (1993) predict these findings; indeed, such models predict that small numbers will be at least as easy to enumerate as larger numbers, because the processing cost and activation should only increase with the number of items to be enumerated. Church and Broadbent's model (1990), however, could explain infants' difficulty in discriminating small numbers. Infants may fail to form an accurate representation of the area or the average inter-element distance of a small array, because these global characteristics are more variable for small set sizes and are undefined for the smallest sets.

This last suggestion is speculative, because it depends on negative findings that can be questioned, but it supports testable predictions. If number representations depend on processing of continuous variables such as area and average inter-element distance, then factors influencing perceptual area or density should have a greater influence on representations of numerosity. In contrast, if number representations depend instead on a normalization and summation process, then factors that influence the ease of normalization should influence the ease of numerical discrimination. The present method may be useful for testing these predictions.

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