INFANCY, 5(3), 271–290
Copyright © 2004, Lawrence Erlbaum Associates, Inc.

Discrimination of Large and Small Numerosities by Human Infants

Jennifer S. Lipton and Elizabeth S. Spelke
Department of Psychology
Harvard University

Six experiments investigated infants' sensitivity to numerosity in auditory sequences. In prior studies (Lipton & Spelke, 2003), 6-month-old infants discriminated sequences of 8 versus 16 but not 8 versus 12 sounds, and 9-month-old infants discriminated 8 versus 12 but not 8 versus 10 sounds, when the continuous variables of rate, sound duration, and sequence duration were controlled. The current studies investigated whether infants' numerical discrimination is subject to the signature ratio limit of adults' numerosity discrimination. Four experiments at 6 and 9 months provided evidence for this signature limit, suggesting that common mechanisms underlie numerosity discrimination in infants and adults. In further experiments, infants failed to discriminate 2 versus 4 or 2 versus 3 sounds when tested under the same conditions as with large numbers. These findings accord with studies using visual-spatial arrays (e.g., Clearfield & Mix, 1999) and suggest that separate systems underlie infants' representation of small and large numerosities.

An important question in the study of cognition concerns the nature of the human capacity to represent number. Past research has demonstrated that humans and nonhuman animals represent and manipulate nonsymbolic numerical quantities. This research investigates the foundations of this ability by examining its roots in human infancy and how it changes over infant development.

Many studies provide evidence that human adults who are prevented from verbal counting nevertheless can discriminate between large numbers of dots or sounds, provided that the numbers differ by a ratio of 1.15 or higher (Barth, Kanwisher, & Spelke, 2003; Cordes, Gelman, Gallistel, & Whalen, 2001; Van Oeffelen & Vos, 1982). Adults can discriminate numerosities even when all continuous variables are controlled, and they can compare the numerosities of sets presented in different modalities and formats (dots vs. tones; Barth et al., 2003). The primary signature of adults' large number discrimination is the set size ratio limit, which accords with Weber's Law: For any numerical magnitude I, the minimum detectable difference (ΔI) obeys the equation $(\Delta I + I)/I = K$. Numerous studies have shown that adult number discrimination abilities follow Weber's Law, with a limit K of about 1.15 (see Brannon, 2004). That is, adults can reliably discriminate sets of 7 versus 8 and 14 versus 16 (both in a 1.15 ratio) but not sets of 14 versus 15.[1]

A second aspect of adults' numerical processing emerges when one compares discrimination of large versus small numbers of objects in visual arrays. In studies that require adults to enumerate exactly a set of objects flashed briefly, response times for enumerating one, two, and three objects are equally fast and accurate, but response times and errors increase in a linear fashion for numbers greater than 3 (Mandler & Shebo, 1982; Trick & Pylyshyn, 1994; for a review, see Dehaene, 1997). Studies using a multiple-object tracking paradigm (Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999) suggest that adults discriminate between arrays containing small numbers of objects (up to a limit that varies from two to six depending on the subject and the task) by virtue of a special mechanism for representing and processing distinct objects in parallel (Trick & Pylyshyn, 1994; see Scholl, 2001). The set size limit on subitizing and multiple-object tracking is a signature of adults' small number representations (see Carey, 1998).

These findings raise important questions about the origins and nature of number sense. Recent studies testing discrimination of large numerosities in visual-spatial arrays of dots provide evidence that 6-month-old infants discriminate 8-dot arrays from 16-dot arrays but not 12-dot arrays when the continuous variables of display size, item size, item density, and either summed filled area or total contour length are controlled (Xu, 2003; Xu & Spelke, 2000; Xu, Spelke, & Goddard, in press; see also Brannon, 2002). Moreover, infants discriminate numerosities in auditory sequences, and they show the same abilities and limits as with dot arrays: 6-month-old infants discriminate sequences of 8 versus 16 sounds but not 8 versus 12 sounds when the continuous variables of sequence duration, sequence rate, sound duration, and correlated quantities such as the amount of sound are controlled (Lipton & Spelke, 2003). Although precision is low at 6 months, it has improved by 9 months. Nine-month-old infants successfully discriminate sequences

Supplementary materials to this article are available on the World Wide Web at http://www.infancyarchives.com

Requests for reprints should be sent to Jennifer S. Lipton, Department of Psychology, Harvard University, 1120 William James Hall, 33 Kirkland Street, Cambridge, MA 02138. E-mail: lipton@wjh.harvard.edu

[1]Weber's Law is not unique to discrimination of number and also applies to discrimination of some continuous dimensions (for discussion, see Stevens, 1960; for recent evidence, see VanMarle & Wynn, 2002).

of 8 versus 12 sounds but not 8 versus 10 sounds, providing evidence that number discrimination becomes more precise over infancy, prior to the onset of language or symbolic counting (Lipton & Spelke, 2003).

This research attempts to extend these findings and to investigate whether infants' numerosity discrimination shows the Weber ratio signature limit found with adults. We tested for the Weber signature by investigating infants' numerical discrimination in the range of 4 to 8. In these studies, we presented infants with sound sequences rather than visual-spatial arrays because it is easier to control for continuous variables in sound sequences.[2] If the Weber ratio limits discrimination of sound sequences, 6-month-old infants should discriminate 4 versus 8 sounds (the same 2.0 ratio as 8 versus 16) but not 4 versus 6 sounds (the same 1.5 ratio as 8 versus 12). Moreover, 9-month-old infants, who discriminate sequences of 8 versus 12 but not 8 versus 10 sounds, should discriminate 4 versus 6 sounds (1.5 ratio) but not 4 versus 5 sounds (1.25 ratio). In contrast, if the absolute difference between two sound sequences limits their discriminability, 6-month-old infants should fail to discriminate 4 versus 8 sounds, and 9-month-old infants should fail to discriminate 4 versus 6 sounds, because these sequences differ by the same absolute amount as 8 versus 12 and 8 versus 10 sounds, respectively.

The last two experiments investigate whether infants discriminate small numerosities in the auditory domain. Almost all research on small number discrimination in infants has used visual arrays of objects or two-dimensional forms. Infants successfully discriminate such arrays when continuous variables such as summed area, total contour length, or total amount of motion or sound are confounded with number (Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Wynn, 1996), but they fail to respond to numerical differences when small numbers of objects appear in displays in which these continuous variables are controlled (Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002; for a review, see Mix, Huttenlocher, & Levine, 2002). In contrast, infants do discriminate between large numbers of visual elements in displays that control for the same continuous variables of summed area and total contour length (Brannon, 2002; Xu, 2003; Xu & Spelke, 2000; Xu et al., in press). Infants, like adults, evidently show different performance for small and large number discrimination in the visual domain.

Such findings have led to two competing claims about infants' numerical representations. In one view, approximate representations are computed for all numbers, both large and small, but they are inhibited or overshadowed by representations of small numbers of objects (Feigenson, Carey, & Hauser, 2002). In a second view, the approximate number system fails to represent small numbers, because the computation of numerosity is based on estimates of density and area for visual-spatial displays (or estimates of rate and duration for sound sequences) that are undefined or unstable for arrays of one to three (Church & Broadbent, 1990; Spelke, 2000).

[2]In a two-dimensional visual array, it is impossible to control for both area and circumference simultaneously. In particular, total filled surface area is nonlinearly related to total contour length, so any given experiment can control for total surface area (e.g., Xu & Spelke, 2000) or total contour length (e.g., Xu et al., in press) but not both. Because sounds are one-dimensional through time, however, it is possible to control for all continuous variables (see Lipton & Spelke, 2003).

To distinguish between these proposals, we tested discrimination of small numbers of sounds (two vs. four and two vs. three) using the same method and stimulus controls as in our studies with larger numerosities. If approximate number representations are computed for small numbers but inhibited by object representations, infants should succeed at discriminating small numbers of events, because object representations are not engaged. If approximate number representations are not computed for small numbers, infants might fail to discriminate small numbers of events.[3]

EXPERIMENT 1

Experiment 1 investigated 6-month-old infants' discrimination of four- versus eight-element sound sequences. The experiment used the head-turn preference procedure developed for studies of speech perception (Kemler Nelson et al., 1995), as modified for studies of numerosity discrimination by Lipton and Spelke (2003). If the Weber ratio limits performance, infants should discriminate these sequences. If the absolute difference limits performance, infants should fail to discriminate these sequences.

Method

Participants. Seven male and 9 female full-term infants participated in the study (*M* age = 6 months 3 days; range = 5 months 17 days–6 months 17 days). Two additional infants were excluded because of fussiness.

[3]Two prior studies have found that infants are able to discriminate two versus three jumps of a puppet (Wynn, 1996) and two versus four tones (VanMarle & Wynn, 2002), suggesting that infants indeed represent small numbers of events. In each case, however, it is possible that discrimination depended on variables other than numerosity. In the jump experiment, the sequences of three jumps had 50% more motion than the sequences of two jumps, raising the possibility that infants responded to the amount of motion rather than the number of jumps (for another possible explanation, see Clearfield, 2003). In the tone sequences, each tone within a sequence was unique, and so the four-tone sequences were twice as variable as the two-tone sequences. The question therefore remains whether infants' numerosity discrimination extends to small numbers of events.

Apparatus. Infants sat on a caregiver's lap in the center of a 5 × 5 ft. (1.5 × 1.5 m) enclosure surrounded by black curtains. A green light was centered in front of the infant, and red lights were mounted about 70° to the infant's left and right at a distance of about 24 in. (61 cm). Speakers were hidden behind the curtain next to each red light. The experiment was conducted using Psyscope (version 1.2.5) software on a Macintosh G4 computer connected to the speakers and lights. The experimenter sat behind a curtain and controlled the start of each trial. A microcamera recorded the infant from the front so that coders in a separate room, blind to the infant's experimental condition, could record the length of time the infant turned to orient toward the speaker.

Auditory sequences. The sequences consisted of the same brief, complex, natural individual sounds used by Lipton and Spelke (2003). Each sound sequence presented a single sound played at a constant rate either 4 or 8 times, and was therefore about half the length of the sounds used in Lipton and Spelke's 8 versus 16 sound study (Lipton & Spelke, 2003, Experiment 1). Six sequences, each presenting a different sound and rate, were played twice during the familiarization trials, once on each side. The sequences of 4 sounds ranged in total duration from 1,245 to 2,715 msec, with a mean duration of 1,980 msec. The sequences of 8 sounds had the same rates, durations, sound–silence ratios, and qualities of individual sounds as the corresponding sequences of 4 sounds and therefore were about twice as long in total duration (range = 2,630–5,510 msec; $M = 4{,}070$ msec). The test trials consisted of three novel sounds, with each type of sound occurring in one four-element sequence and in one eight-element sequence. In total, therefore, six test sequences were presented, in an order that alternated between four- and eight-element sequences. Order of test sequences was counterbalanced across infants. The individual sounds in four-element test sequences were 550 msec in duration, with 150-msec interstimulus intervals (ISIs). The individual sounds in the eight-element test sequences, created by compressing by 50% the corresponding sounds in the four-element test sequence, were 275 msec, with 64.3-msec ISIs. All the test sequences therefore presented the same total duration and amount of sound (2,200 msec) and silence (450 msec) and the same sequence duration (2,650 msec). Figure 1 presents a schematic depiction of the sound sequences. The Appendix, which can be viewed at http://www.infancyarchives.com, presents a detailed description of each sound sequence used in Experiment 1.

Design. Separate groups of infants were familiarized to sequences containing four versus eight elements, for a total of 12 trials. Each of six different sound sequences was presented once on the left and once on the right in a quasi-random order such that no more than two consecutive sequences were presented on the same side. After familiarization, all infants were presented with the same six test sequences, with four- and eight-element sequences occurring in alternation, half

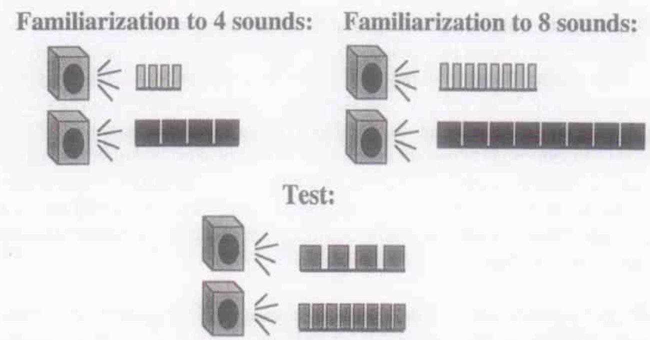

FIGURE 1 Schematic representation of the sound sequences used in Experiment 1.

on each side. The order of test trials (old or new number first) was counterbalanced within each familiarization condition.

Procedure. Infants sat in a dimly lit room on the lap of a caregiver, who wore headphones presenting music that masked the sound sequences and was instructed to face forward throughout the study. At the start of each familiarization and test trial, the central green light was illuminated until the baby looked at it and then it was replaced by a red light at one of the two lateral speakers, followed after 500 msec by the presentation of a sound sequence from that speaker. The red light remained illuminated for 10 sec after the end of the sequence and then was replaced by the central green light, beginning the next trial. Coders measured the length of time infants turned toward the speaker during the sound sequence and for the 10-sec period that followed.

Results

During familiarization, infants' head-turning times were equally long for the four- and eight-element sequences, and they decreased over the familiarization trials (see Figure 2), although variability across infants was high. A 2 (familiarization condition: four vs. eight) × 2 (trial block: first three vs. last three) analysis of variance (ANOVA) on the head-turning times during familiarization revealed no significant effects.

In the test, infants oriented longer to test sequences that presented a novel numerosity (Figure 2). A 2 × 2 × 3 ANOVA testing the effects of familiarization condition (four or eight), novelty (novel or familiar number), and test trial pair revealed a main effect of novelty, $F(1, 14) = 14.01$, $p < .01$. Thirteen of 16 infants

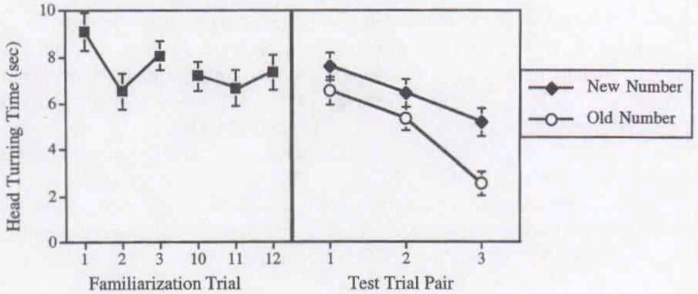

FIGURE 2 Mean head-turning times for the 6-month-old infants in Experiment 1 (four vs. eight sounds).

turned longer toward the novel numerosity, and 3 of 16 infants turned longer toward the familiar numerosity (binomial $p < .01$, one-tailed), providing evidence for successful discrimination of four from eight sounds.

Discussion

Experiment 1 provides evidence that 6-month-old infants discriminate four from eight sounds when the potentially confounding continuous variables of element duration, sequence duration, sequence rate, ISI, and amount of total acoustic energy are controlled. This finding suggests that 6-month-old infants discriminate numerosities in a 2.0 ratio, in accord with Weber's Law (Lipton & Spelke, 2003). Experiment 2 tested that suggestion further.

EXPERIMENT 2

Experiment 2 investigated whether 6-month-old infants discriminate between sound sequences containing 4 versus 6 elements. Because 6-month-old infants failed to discriminate 8 versus 12 sound sequences in past research (Lipton & Spelke, 2003), infants should fail to discriminate 4 versus 6, if their discrimination is subject to a ratio limit.

Method

The method was identical to Experiment 1 except as follows: Participants were 9 male and 7 female full-term infants (*M* age = 6 months 0 days; range = 5 months

16 days–6 months 15 days). The four-element sequences were the same as in Experiment 1. The six-element familiarization sequences had the same rates as the four-element familiarization sequences and therefore had total sequence durations ranging from 1,938 to 4,113 msec (*M* = 3,025 msec). The six-element test sequences had the same total amount of sound and silence and the same sequence durations as the four-element test sequences, with individual sound durations of 367 msec and ISIs of 90 msec. The Appendix (available online at www.infancyarchives.com) presents a detailed description of each sound sequence used in Experiment 2. Head-turning times during both familiarization trials and test trials were analyzed as in Experiment 1.

Results

Infants' head-turning times during the familiarization sequence did not differ for the four- versus six-element sequences but did decrease significantly from the first three to the last three familiarization trials, $F(1, 14) = 6.79$, $p < .05$. On the test trials, infants showed no head-turning response to the change in numerosity (Figure 3). The $2 \times 2 \times 3$ ANOVA revealed no main effect of novelty, $F(1, 14) = 1.08$, *ns*, and no other effects. Seven of 16 infants attended more to the novel numerosity, whereas 9 infants attended more to the familiar numerosity.

Discussion

Experiment 2 provides no evidence that 6-month-old infants discriminate between auditory sequences of 4 versus 6 elements. At 6 months of age, therefore, infants are able to discriminate 8 versus 16 sounds (Lipton & Spelke, 2003) and 4 versus 8 sounds (Experiment 1) but not 8 versus 12 sounds (Lipton & Spelke,

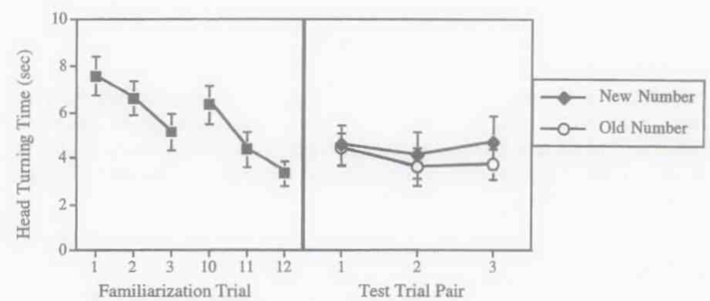

FIGURE 3 Mean head-turning times for the 6-month-old infants in Experiment 2 (four vs. six sounds).

2003) or 4 versus 6 sounds (Experiment 2). These findings provide evidence that infants' numerosity discrimination shows the Weber signature of discrimination in adults.

EXPERIMENT 3

Experiment 3 investigated whether 9-month-old infants discriminate sequences of 4 versus 6 sounds. Because such infants have been found to discriminate 8 versus 12 sounds, they should also succeed at 4 versus 6 sounds if the ratio limits discrimination.

Method

The method and analyses were identical to those of Experiment 2, except as follows: Seven male and 9 female full-term infants participated in the study (*M* age = 9 months 2 days; range = 8 months 21 days–9 months 16 days). One additional infant was excluded due to fussiness.

Results

Infants' head-turning times during the familiarization trials did not differ for the four- versus six-element sequences but did decrease significantly from the first three to the last three familiarization trials, $F(1, 14) = 18.28$, $p < .01$. In the test trials, infants oriented longer to test events presenting the novel numerosity, $F(1, 14) = 6.92$, $p < .05$ (Figure 4). Twelve of 16 infants oriented longer to the novel

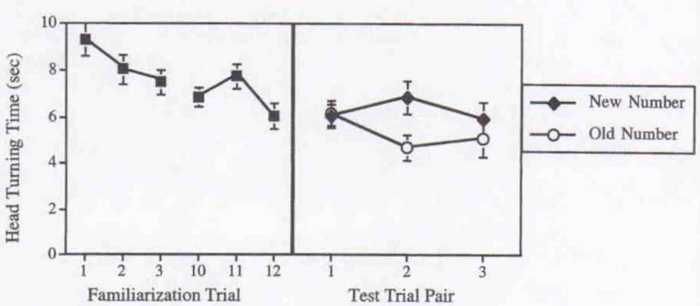

FIGURE 4 Mean head-turning times for the 9-month-old infants in Experiment 3 (four vs. six sounds).

numerosity, and 4 of 16 infants turned longer toward the familiar numerosity (binomial $p < .05$, one-tailed), providing evidence for successful discrimination of four from six sounds.

Discussion

Nine-month-old infants successfully discriminated 4 versus 6 sounds and 8 versus 12 sounds, consistent with a Weber signature limit. Accordingly, Experiment 4 tested for this limit further.

EXPERIMENT 4

Experiment 4 investigated 9-month-old infants' discrimination of 4 versus 5 sounds, the same ratio as 8- versus 10-sound sequences that they previously failed to discriminate (Lipton & Spelke, 2003).

Method

The method and analyses were the same as that of Experiment 3, except as follows: Seven male and 9 female full-term infants participated in the study (*M* age = 9 months 1 day; range = 8 months 16 days–9 months 15 days). The four-element sequences were the same as in Experiments 1 through 3. The five-element familiarization sequences had the same items and rates as the four-element familiarization sequences and therefore had total sequence durations ranging from 1,591 to 3,414 msec (*M* = 2,503 msec). The five-element test sequences had the same total duration of sound and silence and sequence durations as the four-element test sequences, with individual sound durations of 440 msec and ISIs of 113 msec. The Appendix (available online at www.infancyarchives.com) presents a detailed description of each sound sequence used in Experiment 4.

Results

Infants' head-turning time during the familiarization trials did not differ for the four- versus five-element sequences, but it did decrease significantly from the first three to the last three familiarization trials, $F(1, 14) = 21.88$, $p < .01$. In the test, infants showed no head-turning response to the change in numerosity, $F(1, 14) < 1$ (Figure 5). Seven of 16 infants attended more to the novel numerosity and nine attended more to the familiar numerosity (*ns*).

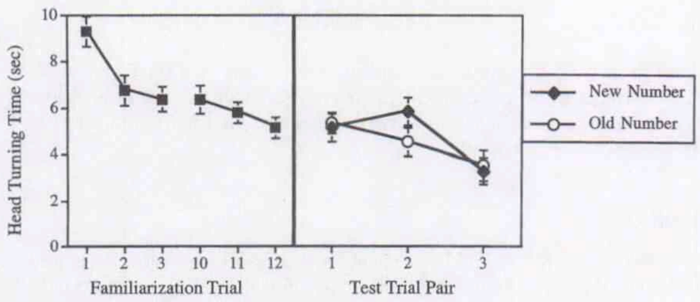

FIGURE 5 Mean head-turning times for the 9-month-old infants in Experiment 4 (four vs. five sounds).

Discussion

Experiment 4 provides no evidence that 9-month-old infants discriminate between auditory sequences of four versus five elements. Together with Experiment 3 and with the findings of Lipton and Spelke (2003), this suggests that the critical discrimination ratio at 9 months might fall between 1.50 and 1.25.

DISCUSSION OF EXPERIMENTS 1 THROUGH 4

Experiments 1 through 4 tested whether discrimination of auditory sequences depends on the ratio or the absolute difference between the two numbers. Our findings provide evidence that a Weber ratio limit characterizes infants' discrimination of auditory sequences at both 6 and 9 months of age. In every case, when infants were tested at ratios that yielded successful performance in the range of 8 to 16, they showed successful discrimination in the range of 4 to 8. In every case in which infants were tested at ratios that showed no discrimination in the larger range, they showed no discrimination in the smaller range. These converging findings provide support for a ratio limit on infants' numerical discrimination.

These findings replicate the finding of Lipton and Spelke (2003) that numerical discrimination abilities increase in precision with age. Six-month-old infants are able to discriminate sequences of four versus eight but not four versus six sounds, and 9-month-old infants are able to discriminate sequences of four versus six but not four versus five sounds. Nevertheless, the discrimination performance of 9-month-old infants still falls below that of adults. We return to this issue in the General Discussion section.

EXPERIMENT 5

The final two experiments focus on infants' discrimination of small numerosities. Experiment 5 investigated whether 6-month-old infants discriminate between sound sequences containing two versus four elements, the same ratio at which they succeed with large numbers.

Method

The method was identical to Experiment 1 except as follows. Participants were 8 male and 8 female full-term infants (*M* age = 5 months 29 days; range = 5 months 17 days–6 months 14 days).

We ran the experiment in two ways. In one version, we had the same individual sounds as in Experiments 1 through 4. Therefore, the sequences of two and four sounds were about half the total duration of the sequences in Experiments 1 through 4. Because these sequences were so brief, however, we were concerned that infants might fail to attend to them. To address this possibility, we also created another set of two-element and four-element sequences that had the same total sequence durations as in Experiments 1 through 4, so the individual sounds were twice as long as in the prior experiments.[4] Figure 6 illustrates the two types of sound sequences used in Experiment 5. The Appendix (available online at www.infancyarchives.com) presents a detailed description of the short and long sets of sequences used in Experiment 5.

Short sequences. Both the two- and four-element familiarization sequences had the same rates as the familiarization sequences in Experiment 1. The two-element familiarization sequences had total sequence durations ranging from 552 to 1,318 msec (*M* = 935 msec), and the four-element sequences had total sequence durations ranging from 1,245 to 2,715 msec (*M* = 1,980 msec). The two types of test sequences had identical total amounts of sound and silence and the same sequence durations. The two-element test sequences had individual sound durations of 550 msec and ISIs of 150 msec. The four-element test sequences had individual sound durations of 275 msec and ISIs of 50 msec. Therefore, the total sound, total silence, sound–silence ratio, and total duration for the two- and four-element test sequences were identical (see the online Appendix).

Long sequences. Both the two- and four-element familiarization sequences had the same total durations as the familiarization sequences in Experiment 1. The two-element familiarization sequences had total sequence durations ranging from

[4]Three of the sounds had to be replaced because, when their durations were increased to create the long sounds, they sounded cyclical and so each could be interpreted as a countable entity.

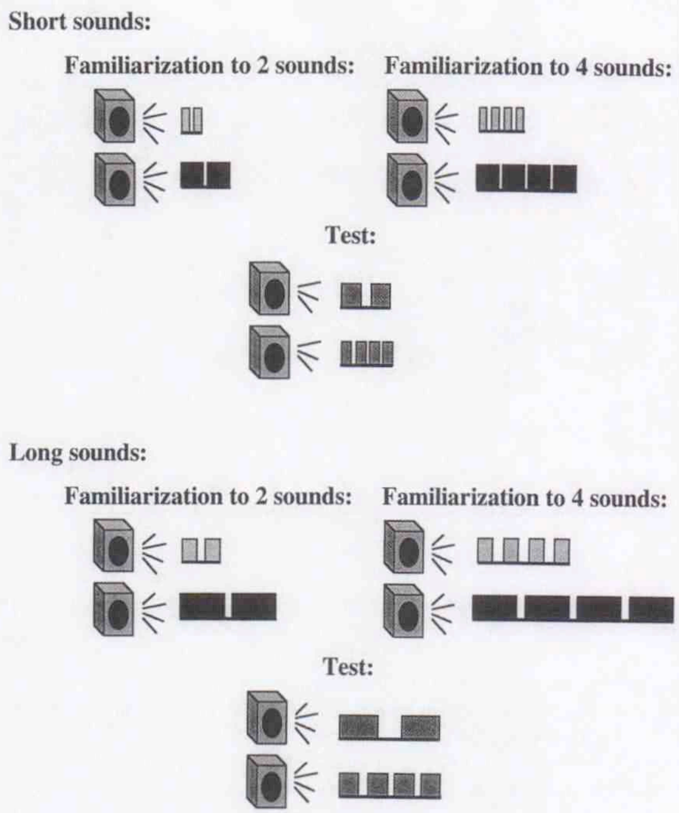

FIGURE 6 Schematic representation of the sound sequences used in Experiment 5.

1,245 to 2,715 msec (M = 1,970 msec), and the four-element sequences had total sequence durations ranging from 2,650 to 5,670 msec (M = 4,260 msec). The two-element test sequences had individual sound durations of 1,100 msec and ISIs of 450 msec. The four-element test sequences had individual sound durations of 550 msec and ISIs of 150 msec. Therefore, the total sound, total silence, sound–silence ratio, and total duration for the two- and four-element test sequences were identical and the total sequence durations were the same as in Experiment 1 (see the online Appendix).

TABLE 1
Mean Head-Turning Times for the 6-Month-Old Infants in Experiment 5 (2 Versus 4 Short Sounds and 2 Versus 4 Long Sounds)

Head Turning Times (in Sec)	*Short*	*Long*	*Difference*
Familiarization trial			
1	8.8	9.3	–0.4
2	6.1	5.3	0.8
3	8.7	7.4	1.4
10	8.0	7.6	0.5
11	7.7	6.6	1.1
12	5.6	6.0	–0.4
Test trial pair			
1			
New number	5.9	5.1	0.8
Old number	5.7	5.1	0.6
2			
New number	5.0	4.6	0.4
Old number	5.5	4.8	0.7
3			
New number	5.0	4.6	0.4
Old number	4.6	3.8	0.8

Results

Head-turning times for infants in the short-sound and long-sound conditions were compared separately for the familiarization trials and for the test trials. Table 1 presents the head-turning times for the two sets of sounds. Because there was no difference in head-turning times for infants in the two types of sound sequences either for the familiarization or for the test trials, both $Fs(1, 12) < 1$, *ns*, the data from the two sequence conditions were combined.

On the familiarization trials, infants' head-turning time did not differ for the two numerosities and decreased only nonsignificantly over the familiarization trials, $F(1, 12) = 2.64$, $p = .13$ (see Figure 7), but this decline was not significant. In the test, infants showed no differential head turning to the change in numerosity (Figure 7): The 2 × 2 × 3 ANOVA revealed no significant effects, all $Fs < 1$. Ten of 16 infants attended more to the novel numerosity, and 6 attended more to the familiar numerosity (binomial $p > .05$).[5]

[5]Because Experiment 5 was conducted after Experiment 1, participants were not assigned randomly to the two experiments. Nevertheless, we conducted a further analysis to test whether head-turn preferences differed reliably for small versus large numerosities. This 2 (experiment: 1 vs. 5) × 2 (novelty) ANOVA comparing performance with larger (four vs. eight) and smaller (two vs. four) numerosities revealed a significant effect of novelty, $F(1, 30) = 9.18$, $p < .01$, and a significant Novelty × Set Size interaction, $F(1, 30) = 6.58$, $p < .02$. The interaction indicates that infants showed a greater preference for the novel numerosity when tested with four versus eight than when tested with two versus four.

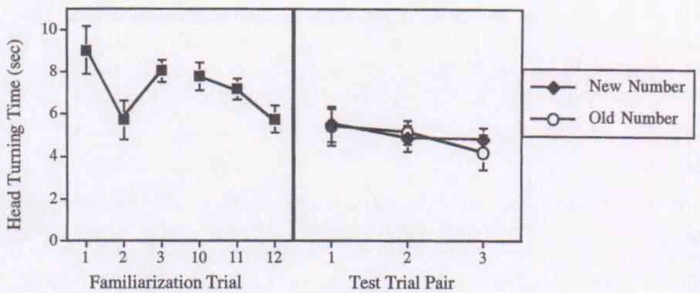

FIGURE 7 Mean head-turning times for the 6-month-old infants in Experiment 5 (two vs. four sounds).

Discussion

Experiment 5 provides no evidence that 6-month-old infants discriminate between auditory sequences of 2 versus 4 elements. At 6 months of age, therefore, infants are able to discriminate numerosities that differ by a 2.0 ratio when they are presented with large numbers (4 vs. 8 and 8 vs. 16) but not with small numbers (2 vs. 4). Because it is unlikely that object files serve to track auditory events, our findings cast doubt on the thesis that object tracking systems inhibit approximate number representations in the small number range. Instead, the system for representing large, approximate numerical magnitudes might fail to compute the cardinal values of small sets of entities (see also Feigenson, Carey, & Hauser, 2002).

Infants' failure in Experiment 5 is particularly interesting in light of infants' success with four versus eight sounds. This success suggests that 6-month-olds infants are able to discriminate the approximate cardinal value 4 from larger but not smaller numbers. However, an alternative explanation for the failure to discriminate two versus four sounds is that the number 4 lies outside the bounds of small number representations. Most studies of subitizing and object tracking suggest that the division in adult small and large number representation occurs between about 3 and 4 (Mandler & Shebo, 1982; Trick & Pylyshyn, 1994). Experiment 6 overcomes this possible problem by testing 9-month-old infants' discrimination of two versus three sounds.

EXPERIMENT 6

Experiment 6 investigated whether 9-month-old infants discriminate between sound sequences containing two versus three elements. Because such infants can

discriminate large numbers that differ by a 1.5 ratio, infants should succeed at discriminating two versus three sounds if the ratio governs discrimination of small numerosities. In contrast, if infants' numerosity discrimination does not extend to small numbers, infants might fail to discriminate two versus three sounds.

Method

The method and analyses were identical to Experiment 5 except as follows: Participants were 7 male and 9 female full-term infants (M age = 9 months 0 days; range = 8 months 15 days–9 months 15 days). As in Experiment 5, we ran two versions of the experiment with long- and short-sound sequences. The Appendix (available online at www.infancyarchives.com) presents a detailed description of the short and long sets of sequences used in Experiment 6.

Short sequences. Both the two- and three-element familiarization sequences had the same rates as the familiarization sequences in Experiments 2 and 3. The two-element familiarization sequences were identical to those in Experiment 5, and the three-element sequences had total sequence durations ranging from 899 to 2,016 msec (M = 1,458 msec). The two types of test sequences had identical total amounts of sound and silence and the same sequence durations. The two-element test sequences were identical to those in Experiment 5. The three-element test sequences had individual sound durations of 367 msec and ISIs of 75 msec. Therefore, the total sound, total silence, sound–silence ratio, and total duration for the two- and three-element test sequences were identical (see the online Appendix).

Long sequences. Both the two- and three-element familiarization sequences had about the same total durations as the familiarization sequences in Experiments 2 and 3. The two-element familiarization sequences were identical to those used in Experiment 5, and the three-element sequences had total sequence durations ranging from 1,950 to 4,200 msec (M = 3,115 msec). The two-element test sequences were identical to those used in Experiment 5. The three-element test sequences had individual sound durations of 733 msec and ISIs of 225 msec. Therefore, the total sound, total silence, sound–silence ratio, and total duration for the two- and three-element test sequences were identical and the total sequence durations were the same as in Experiments 2 and 3 (see the online Appendix).

Results

Table 2 presents the head-turning times for the short-sound and long-sound conditions. There was no difference in head-turning times, either during familiarization or during test, for infants presented with short and long sequences, both

TABLE 2
Mean Head-Turning Times for the 9-Month-Old Infants
in Experiment 6 (2 Versus 3 Short Sounds and 2 Versus 3 Long Sounds)

Head Turning Times (in Sec)	*Short*	*Long*	*Difference*
Familiarization trial			
1	6.8	9.9	−3.1
2	6.4	6.8	−0.4
3	6.9	6.7	0.2
10	6.0	7.7	−1.7
11	4.5	5.8	−1.3
12	4.0	4.8	−0.8
Test trial pair			
1			
New number	4.4	5.4	−0.9
Old number	6.3	4.6	1.7
2			
New number	4.8	5.2	−0.4
Old number	4.3	5.7	−1.4
3			
New number	6.1	5.6	0.5
Old number	4.4	5.3	−0.9

Fs(1, 12) < 1, and so the data for the two sequence conditions were combined. Infants' head-turning time during the familiarization trials did not differ for the two-sound versus three-sound sequences but did decrease significantly from the first three to the last three familiarization trials, $F(1, 12) = 7.52$, $p < .05$. Infants showed no head-turning response to the change in numerosity during test trials, and no other effects, all *Fs*(1, 12) < 1 (Figure 8). Seven of 16 infants attended more to the novel numerosity, and 9 infants attended more to the familiar numerosity (binomial $p > .05$).[6]

Discussion

Experiment 6 provides no evidence that 9-month-old infants discriminate between auditory sequences of 2 versus 3 elements. At 9 months of age, infants discriminate 8 versus 12 and 4 versus 6 sounds, but not 2 versus 3 sounds, when they are tested under these conditions.

[6]Although assignment to Experiments 3 and 6 was not random, a further 2 × 2 ANOVA testing the effects of experiment (3 vs. 6) and novelty compared 9-month-old infants' performance with larger (four vs. six) and smaller (two vs. three) numerosities. This analysis revealed a significant effect of novelty, $F(1, 30) = 5.63$, $p < .05$, and a marginally significant Novelty × Set Size interaction, $F(1, 30) = 2.91$, $p = .097$.

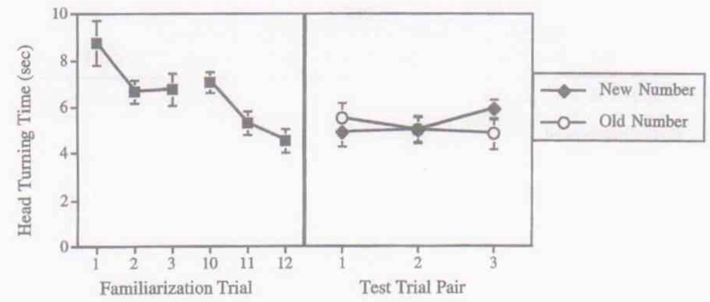

FIGURE 8 Mean head-turning times for the 9-month-old infants in Experiment 6 (two vs. three sounds).

GENERAL DISCUSSION

These experiments shed light on the origins and nature of numerical representations. Early in human development, numerical discrimination is approximate in nature and shows a ratio signature limit. Moreover, infants' numerical representations increase in precision over the infancy period, prior to the onset of language or symbolic counting. Whereas 6-month-old infants successfully discriminate auditory sequences in a 2.0 ratio (8 vs. 16 and 4 vs. 8) but not a 1.5 ratio (8 vs. 12 and 4 vs. 6), 9-month-old infants successfully discriminate auditory sequences in a 1.5 ratio (8 vs. 12 and 4 vs. 6) but not a 1.25 ratio (8 vs. 10 and 4 vs. 5).

Our findings provide an important link to studies of numerosity discrimination in human adults, who compare numerosities both within and across modalities with a ratio limit on performance (Barth et al., 2003; Cordes et al., 2001; Van Oeffelen & Vos, 1982; Whalen, Gallistel, & Gelman, 1999). Recent studies have found that tamarin monkeys also discriminate sound sequences in studies similar to our studies of infants, and they show the same ratio signature of 1.5 as 9-month-old infants (Hauser, Tsao, Garcia, & Spelke, in press). This common signature limit suggests that a common system for representing numerosity exists in human infants, human adults, and nonhuman animals. Representations of large, approximate numerosities may be continuous both over ontogeny and over phylogeny (Hauser & Spelke, in press).

Our findings provide suggestive evidence that numerical representations fail to encompass small numbers. Although prior studies provide no clear evidence that infants discriminate small numbers of visual objects when continuous properties are controlled (Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002; Xu, 2003; Xu et al., in press), those studies all used visual displays, raising the possibility that object file representations were engaged by the displays and inhibited or overshadowed representations of numerosity. The failure of infants to discriminate between small sets on the basis of numerosity in these studies cannot, however, be explained by the inhibiting effect of object representations, because these studies presented auditory sequences. Our findings therefore strengthen the hypothesis that approximate number representations are not computed for small numbers. Definitive tests of this hypothesis, however, will require further and more direct studies of the mechanisms of numerosity perception and discrimination.

ACKNOWLEDGMENTS

This research was supported by National Institutes of Health Grant R37 HD23103 to Elizabeth S. Spelke and by a Harvard University Fellowship to Jennifer S. Lipton.

REFERENCES

Barth, H., Kanwisher, N., & Spelke, E. (2003). The construction of large number representation in adults. *Cognition, 86,* 201–221.

Brannon, E. (2002). The development of ordinal numerical knowledge in infancy. *Cognition, 83,* 223–240.

Brannon, E. (2004). Number knows no bounds. *Trends in Cognitive Sciences, 7,* 279–281.

Carey, S. (1998). Knowledge of number: Its evolution and ontology. *Science, 282,* 641–642.

Church, R. M., & Broadbent, H. A. (1990). Alternative representations of time, number, and rate. *Cognition, 37,* 55–81.

Clearfield, M. W. (2003, April). *Infants' sensitivity to rhythm in enumerating actions.* Poster presented at the 70th Biennial Conference of the Society for Research in Child Development, Tampa, FL.

Clearfield, M. W., & Mix, K. S. (1999). Number versus contour length in infants' discrimination of small visual sets. *Psychological Science, 10,* 408–411.

Cordes, S., Gelman, R., Gallistel, C. R., & Whalen, J. (2001). Variability signatures distinguish verbal from nonverbal counting for both large and small numbers. *Psychonomic Bulletin and Review, 8,* 698–707.

Dehaene, S. (1997). *The number sense.* New York: Oxford University Press.

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object files versus analog magnitudes. *Psychological Science, 13,* 150–156.

Feigenson, L., Carey, S., & Spelke, E. S. (2002). Infants' discrimination of number vs. continuous extent. *Cognitive Psychology, 44,* 33–66.

Hauser, M. D., & Spelke, E. S. (in press). Evolutionary and developmental foundations of human knowledge: A case study of mathematics. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (3rd ed.). Cambridge, MA: MIT Press.

Hauser, M. D., Tsao, F., Garcia, P., & Spelke, E. (in press). Evolutionary foundations of number: Spontaneous representation of numerical magnitudes by cotton-top tamarins. *Proceedings of the Royal Society, London, B.*

Kemler Nelson, D. G., Jusczyk, P. W., Mandel, D. R., Myers, J., Turk, A., & Gerken, L. A. (1995). The head-turn preference procedure for testing auditory perception. *Infant Behavior and Development, 18,* 111–116.

Lipton, J. S., & Spelke, E. S. (2003). Origins of number sense: Large number discrimination in human infants. *Psychological Science, 14,* 396–401.

Mandler, G., & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General, 111,* 1–21.

Mix, K. S., Huttenlocher, J., & Levine, S. C. (2002). Multiple cues for quantification in infancy: Is number one of them? *Psychological Bulletin, 128,* 278–294.

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking system. *Spatial Vision, 3,* 179–197.

Scholl, B. J. (2001). Objects and attention: The state of the art. *Cognition, 80,* 1–46.

Scholl, B. J., & Pylyshyn, Z. W. (1999). Tracking multiple items through occlusion: Clues to visual objecthood. *Cognitive Psychology, 38,* 259–290.

Spelke, E. S. (2000). Core knowledge. *American Psychologist, 55,* 1233–1243.

Starkey, P., & Cooper, R. G. (1980). Perception of numbers by human infants. *Science, 210,* 1033–1035.

Starkey, P., Spelke, E. S., & Gelman, R. (1990). Numerical abstraction by human infants. *Cognition, 6,* 97–128.

Stevens, S. S. (1960). Psychophysics of sensory function. *American Scientist, 48,* 226–252.

Trick, L., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited capacity preattentive stage in vision. *Psychological Review, 101,* 80–102.

VanMarle, K., & Wynn, K. (2002, April). *Seven-month-old infants' sensitivity to number in the auditory domain.* Poster presented at the 13th Biennial International Conference on Infant Studies, Toronto, Ontario, Canada.

Van Oeffelen, M. P., & Vos, P. G. (1982). A probabilistic model for the discrimination of visual number. *Perception & Psychophysics, 32,* 163–170.

Whalen, J., Gallistel, C. R., & Gelman, R. (1999). Nonverbal counting in humans: The psychophysics of number representation. *Psychological Science, 10,* 130–137.

Wynn, K. (1996). Infants' individuation and enumeration of actions. *Psychological Science, 7,* 164–169.

Xu, F. (2003). Numerosity discrimination in infants: Evidence for two systems of representations. *Cognition, 89,* B15–B25.

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition, 74,* B1–B11.

Xu, F., Spelke, E. S., & Goddard, S. (in press). Number sense in human infants. *Developmental Science.*