Research Article

ORIGINS OF NUMBER SENSE: Large-Number Discrimination in Human Infants

Jennifer S. Lipton and Elizabeth S. Spelke

Massachusetts Institute of Technology

Abstract—*Four experiments investigated infants' sensitivity to large, approximate numerosities in auditory sequences. Prior studies provided evidence that 6-month-old infants discriminate large numerosities that differ by a ratio of 2.0, but not 1.5, when presented with arrays of visual forms in which many continuous variables are controlled. The present studies used a head-turn preference procedure to test for infants' numerosity discrimination with auditory sequences designed to control for element duration, sequence duration, interelement interval, and amount of acoustic energy. Six-month-old infants discriminated 16 from 8 sounds but failed to discriminate 12 from 8 sounds, providing evidence that the same 2.0 ratio limits numerosity discrimination in auditory-temporal sequences and visual-spatial arrays. Nine-month-old infants, in contrast, successfully discriminated 12 from 8 sounds, but not 10 from 8 sounds, providing evidence that numerosity discrimination increases in precision over development, prior to the emergence of language or symbolic counting.*

An important issue in human cognition concerns the origins and nature of the capacity to represent number. Is there an innate, core system of knowledge that underlies the number abilities seen in human children and adults? If so, how does this system emerge in infants, how is it transformed over development, and how does it compare to the numerical abilities of nonhuman animals?

A number of investigators have proposed that human adults' number representations and mathematical thinking depend, in part, on a sense of approximate numerical magnitudes, or "number sense" (Dehaene, 1997; Gallistel & Gelman, 1992). When adults are prevented from counting, they still are able to estimate large numerosities (Cordes, Gelman, Gallistel, & Whalen, 2001; see also Balakrishnan & Ashby, 1992), as do many nonhuman animals (Gallistel, 1990). Although the natural number concepts expressed by symbols such as "7" and "34" specify number exactly, these symbols also evoke a sense of approximate numerosity that adults use in reasoning about them (see Dehaene, 1997). Thus, adults are quicker to compare numbers the more distant they are from one another (e.g., subjects judge more rapidly that $9 > 5$ than that $6 > 5$; Dehaene, Dupoux, & Mehler, 1990; Moyer & Landauer, 1967), and quicker to reject false answers to arithmetic problems the more distant they are from the true answer (e.g., subjects are quicker to reject 19 than 13 as the sum of $7 + 5$; Ashcraft, 1992). In neuroimaging experiments, adults who perform mental arithmetic activate regions of parietal cortex that are implicated in the processing of approximate numerical magnitudes (Pinel, Dehaene, Riviere, & LeBihan, 2001). Most strikingly, neurological patients with normal verbal memory but impaired number sense have difficulty with many aspects of numerical reasoning, although they continue to be able to recite certain verbal arithmetic facts (Dehaene & Cohen, 1997). All these findings suggest that a sense of approximate numerical magnitudes plays a central role in human mathematical thinking (Dehaene, 1997). In the experiments reported here, we explored the developmental origins of number sense by investigating human infants' sensitivity to large, approximate numerosities in auditory sequences.

Although many experiments have explored human infants' sensitivity to number, the existing literature has some shortcomings. Most experiments have confounded differences in numerosity with differences in continuous variables such as the total length of contour or filled surface area within a display, or the amount or variability of motion. When continuous variables are decoupled from numerosity in experiments presenting small numbers of visible objects, infants have sometimes been found to respond to the continuous variables rather than number (Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002; although see also Wynn, Bloom, & Chiang, 2002). Furthermore, most experiments have presented infants with small numbers of entities: one, two, or three objects or events. Both studies of adults and studies of infants suggest, however, that discrimination of small numbers of objects can be accomplished by mechanisms for constructing and maintaining representations of individual objects, rather than by the mechanisms that underlie number sense (Carey, 1998; Simon, 1997; Trick & Pylyshyn, 1994; although see Cordes et al., 2001). Although an object-tracking mechanism would not account for infants' discrimination of small numbers of events (see Bijeljac-Babic, Bertoncini, & Mehler, 1991; Sharon & Wynn, 1998; Wynn, 1996), it is not clear whether this ability depends on a mechanism that is sensitive to larger numbers as well. Finally, most experiments have investigated numerosity discrimination with arrays presented in a single modality and format (most often, visual-spatial arrays), and those studies that have investigated transfer of numerical discrimination across modalities and formats have yielded inconsistent results (Mix, Huttenlocher, & Levine, 1996; although for new evidence for intermodal transfer with small numbers, see Feron, Streri, & Gentaz, 2002; Kobayashi, Hiraki, & Hasegawa, 2002; and Wynn, 1998). It is not clear, therefore, whether infants' numerosity discrimination depends on mechanisms specific to individual modalities or formats of numerical information or on a more general, abstract representation of number.

Experiments by Xu and Spelke (2000; Xu, 2000) have overcome some of these limitations. In one study, 6-month-old infants were habituated to visual arrays containing 8 or 16 dots and then were tested with new, alternating dot arrays of the two numerosities. Because large numerosities were presented, successful discrimination could not depend on a system for tracking small numbers of objects. Moreover, Xu and Spelke controlled for the continuous variables of total array size, total filled surface area, element size, and element density by equating the first two variables in the two types of habituation displays and equating the last two variables in the two types of test displays. In-

Address correspondence to Jennifer S. Lipton, Department of Psychology, Harvard University, 1120 William James Hall, 33 Kirkland St., Cambridge, MA 02138; e-mail: lipton@wjh.harvard.edu.

fants looked longer at the test displays with the novel numerosity, providing evidence for discrimination of 16 from 8 dots on the basis of numerosity. In subsequent experiments, infants were found to discriminate visual arrays of 32 versus 16 dots but not 12 versus 8 dots or 24 versus 16 dots. These findings provide evidence that infants discriminate large numerosities, that their large-number discriminations are imprecise, and that discriminability depends on the ratio of the two set sizes, with the critical ratio lying between 1.5 and 2.0. The existence of a ratio limit on numerical discrimination suggests that the variability in infants' number representations is proportional to numerical magnitude (Weber's Law), as it is for adults and for other animals (Gallistel, 1990). All these findings suggest that a sense of approximate numerical magnitudes is present and functional by 6 months of age.

Nevertheless, the findings of Xu and Spelke raise three questions. First, because surface area and contour length are nonlinearly related, no study of numerosity discrimination using visual arrays of identical forms can equate for both of these variables: Equating for one variable introduces differences in the other.[1] Second, because Xu and Spelke's research focused only on visual-spatial arrays, it is not clear whether infants' discrimination depended on an abstract sense of numerosity or on processes that are specific to the treatment of visual information.[2] Third, Xu and Spelke's findings suggest that infants' numerosity discrimination depends on the ratio of the set sizes, as does number sense in adults, but they also reveal a striking difference between adults and infants. Adults who are presented with arrays containing large numbers of dots, under conditions that preclude verbal counting, reliably discriminate numerosities differing by a ratio as small as 1.15 (Van Oeffelen & Vos, 1982). In contrast, 6-month-old human infants appear to require a ratio difference as large as 2.0. This developmental difference raises the question whether adults' numerosity discrimination depends on an early-developing mechanism that gradually increases in precision, or on a later-developing mechanism that emerges as children gain skill at verbal counting or symbolic arithmetic (Ashcraft, 1992).

In the present studies, we attempted to overcome these limitations by investigating infants' sensitivity to numerosity in auditory sequences. In contrast to two-dimensional visual displays, one-dimensional auditory sequences allow for the control of all continuous temporal variables simultaneously. In particular, the present experiments controlled for item length, interstimulus interval (ISI), sequence length, and all other variables that depend on these quantities, such as the amount of acoustic energy and sequence rate. Sounds of equal amplitude were presented throughout the experiment, with the rate and durations of individual sounds equated across the two numerosities during familiarization, and with total sequence durations and amount of acoustic energy equated across the two numerosities during the test. Successful discrimination of these sequences therefore could not depend on any of these continuous variables and more likely would depend on number.

The first two experiments investigated 6-month-old infants' numerosity discrimination over two different ratios. If numerosity discrimination in visual arrays depends on an abstract sense of approximate numerical magnitudes whose precision depends on the ratio of the set sizes to be discriminated, then the same difference ratio might characterize 6-month-old infants' discrimination of auditory and visual arrays. Thus, we investigated 6-month-old infants' discrimination of sequences of 16 versus 8 sounds (a 2.0 ratio) in Experiment 1, and 12 versus 8 sounds (a 1.5 ratio) in Experiment 2. Finally, we began to explore the developmental progression of number representations by testing for 9-month-old infants' discrimination of 12 from 8 sounds (Experiment 3) and 10 from 8 sounds (Experiment 4). If the large difference in the precision of infants' and adults' number discriminations reflects differing mechanisms that emerge when children gain skill at verbal counting or symbolic arithmetic, then the same ratio limit of 2.0 might characterize numerosity discrimination throughout the infancy period. In contrast, if infants' and adults' numerosity discrimination depends on a common mechanism that increases in sensitivity over development, then evidence for an increase in precision might well be obtained during the infancy period itself, a time of rapid improvement in many perceptual capacities.

EXPERIMENT 1

Experiment 1 used a modified version of the head-turn preference procedure (Kemler Nelson et al., 1995) in order to investigate 6-month-old infants' discrimination of 8- versus 16-element sound sequences.

Method

Participants

Eight male and 8 female full-term infants participated in the study (mean age = 6 months 0 days; range: 5 months 18 days to 6 months 14 days). One additional infant was excluded because of fussiness.

Apparatus

Each infant sat on a caregiver's lap in the center of a 5-ft × 5-ft 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. Speakers were hidden behind the curtain next to each red light. The experiment was conducted using Psyscope 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 presenting the auditory sequence.

Auditory sequences

The sequences consisted of brief, complex, natural sounds such as bells, whistles, chirps, buzzes, drums, and horns, downloaded from

1. Clearfield and Mix (2001) described an experiment that equated for surface area and contour length simultaneously by varying element shapes in the test arrays. Because shape is a highly salient dimension of visual elements, however, infants' novelty responses in such an experiment may reflect dishabituation to new element shapes. Holding shape constant, surface area and contour length cannot both be controlled within a single experiment.

2. The most common specifically visual mechanisms that have been suggested to account for numerosity discrimination in visual-spatial arrays are mechanisms of texture perception (Durgin, 1995). Xu and Spelke (2000) controlled for texture differences by equating the test displays of 8 and 16 dots for element size and density, producing test displays that appear to adults to present the same surface texture. Nevertheless, it is possible that numerosity discrimination in these studies depends on detecting other properties specific to vision.

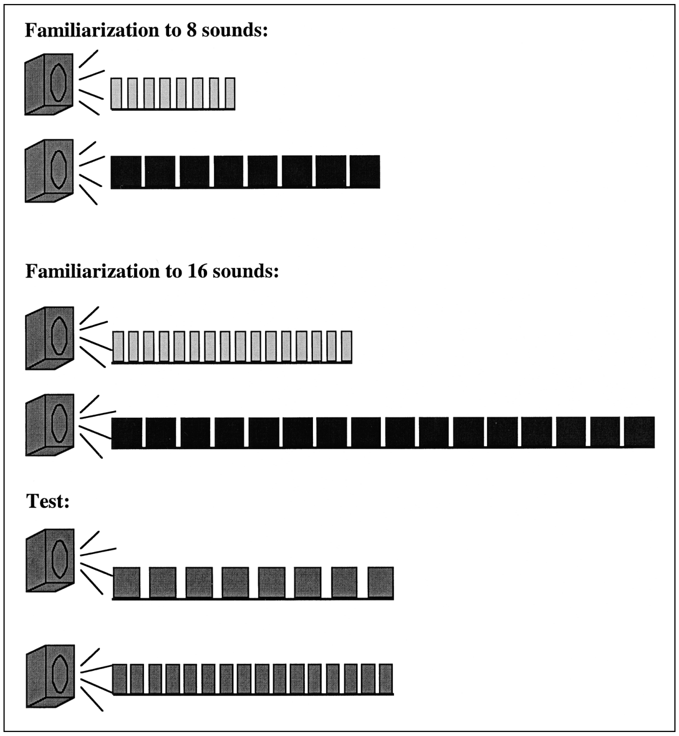

Fig. 1. Schematic representation of the auditory sequences used in Experiment 1.

free Web sites. Each sound sequence presented a single sound played at a constant rate either 8 or 16 times. Six sequences, each presenting a different sound and rate, were played twice during the familiarization trials, once on each side. The sequences of 8 sounds ranged in total duration from 2,630 to 5,510 ms, with a mean duration of 4,070 ms. The sequences of 16 sounds had the same rates, durations, and qualities of individual sounds as the corresponding sequences of 8 sounds and therefore were about twice as long in total duration (range: 5,400–11,100 ms, $M = 8{,}250$ ms).[3] For the test trials, three novel sounds were used. Each was presented once in a sequence of 8 and once in a sequence of 16. The individual sounds in 8-element test sequences were 550 ms in duration, with 150-ms ISIs. The individual sounds in the 16-element test sequences, created by compressing the corresponding sounds in the 8-element test sequences by 50%, were 275 ms, with 70-ms ISIs. All the test sequences therefore presented the same total duration and amount of sound (4,400 ms) and silence (1,050 ms) and the same sequence duration (5,450 ms) at one of two rates: 1.47 items/s (8-element sequences) or 2.94 items/s (16-element sequences). Figure 1 presents a schematic depiction of the sound sequences.

Design

Separate groups of infants were familiarized to sequences containing 8 versus 16 elements. Each of the 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. Thus, each group heard a total of 12 familiarization trials. After familiarization, all infants were presented with the same six test sequences. The test trials alternated between 8- and 16-element sequences, and for each test numerosity, half the trials were presented on the left and half were presented on the right. 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; the green light was then replaced by a red light at one of the two lateral speakers, followed after 500 ms by presentation of a sound sequence from that speaker. The red light remained illuminated for 10 s 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 the infant turned toward the speaker presenting the auditory sequence during the sound sequence and the 10-s period that followed.

Results

The infants oriented longer to test sequences that presented a novel numerosity than to test sequences that presented a familiar numerosity (Fig. 2). A $2 \times 2 \times 3$ analysis of variance (ANOVA) testing the effects of familiarization condition (8 or 16), test numerosity (same or different), and test-trial pair (1, 2, or 3) revealed a main effect of test numerosity, $F(1, 15) = 7.022$, $p < .05$. Twelve of 16 infants turned longer toward the novel numerosity (binomial $p < .05$), providing evidence for successful discrimination of 8 from 16 sounds.

Discussion

Experiment 1 provides evidence that 6-month-old infants discriminate 8 from 16 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 accords with previous evidence that infants of this age discriminate numerosities in a 2.0 ratio in visual-spatial arrays (Xu & Spelke, 2000), and it raises the question whether numerosity discrimination has the same ratio limit for the two types of displays. Because 6-month-old infants failed to discriminate arrays of dots that differed in numerosity by a 1.5 ratio, we tested discrimination at this ratio in Experiment 2.

EXPERIMENT 2

Experiment 2 investigated whether 6-month-old infants discriminate between sound sequences containing 12 versus 8 elements.

Method

The method was identical to that of Experiment 1 except as follows. Participants were 8 male and 8 female full-term infants (mean age = 6 months 2 days; range: 5 months 19 days to 6 months 11 days). Five additional infants were excluded because of fussiness, parental interference, or experimenter error. The 8-element sequences were the same as in Experiment 1. The 12-element familiarization sequences

3. The durations of the 16-sound familiarization sequences were slightly more than twice those of the 8-sound familiarization sequences, because they contained more than twice as many intervals (15 vs. 7) .

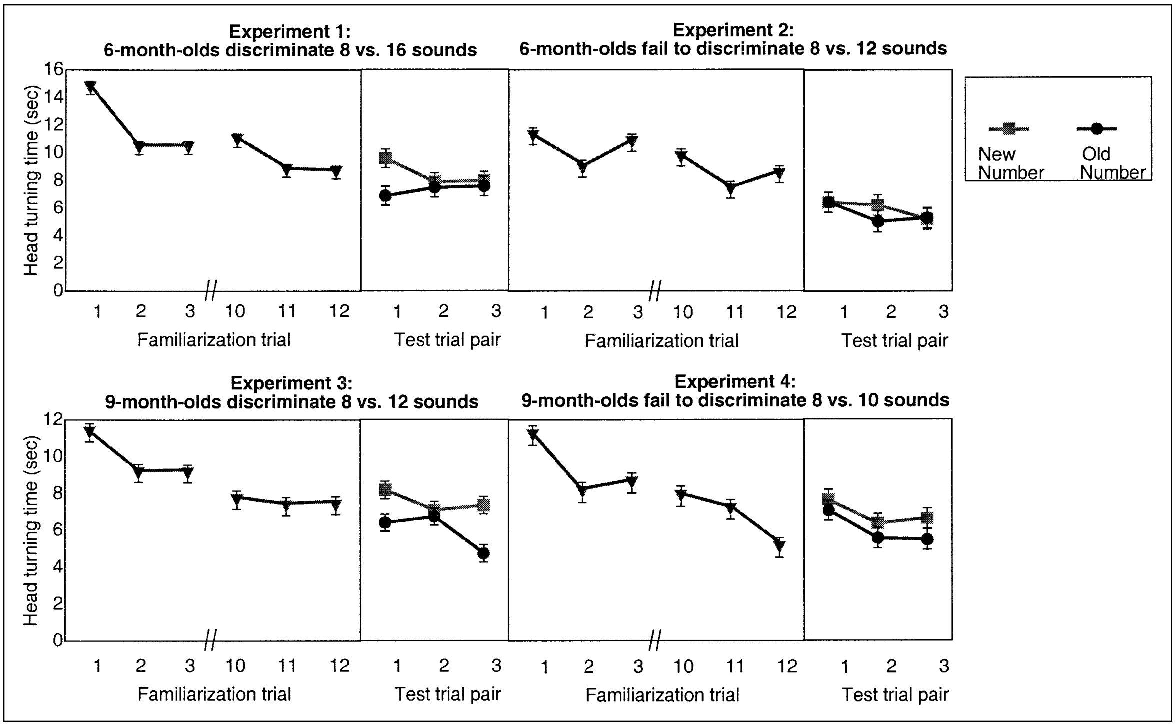

Fig. 2. Mean head-turning times for the first three and last three familiarization trials and the six test trials for the 6-month-old infants in Experiments 1 and 2 and the 9-month-old infants in Experiments 3 and 4.

had the same rates as the 8-element familiarization sequences, and therefore had total sequence durations ranging from 4,015 to 8,305 ms (M = 6,160 ms). The 12-element test sequences had the same total amount of sound and silence and the same sequence durations as the 8-element test sequences, with individual sound durations of 367 ms, ISIs of 95 ms, and a rate of 2.20 items/s.

Results

The infants showed no orienting response to the change in numerosity (Fig. 2). The 2 × 2 × 3 ANOVA testing the effects of familiarization condition (8- vs. 12-element sequences), test numerosity, and test-trial pair revealed no main effect of test numerosity, $F(1, 15) < 1$, and no other effects. Eight of 16 infants attended more to the novel than to the familiar numerosity. A 2 (experiment) × 2 (test numerosity) ANOVA comparing the test-trial orienting times obtained in Experiments 1 and 2 revealed a significant interaction of experiment and test numerosity, $F(1, 30) = 5.95$, $p < .05$. Infants showed greater orientation to the novel numerosity when the numerosities differed by a 2.0 ratio than when they differed by a 1.5 ratio.

Discussion

Experiment 2 provides no evidence that 6-month-old infants discriminate between auditory sequences of 8 versus 12 elements. Performance reliably differed from that in Experiment 1, providing evidence that 6-month-old infants' numerosity discrimination is affected by the ratio of the set sizes. The same critical ratio between 1.5 and 2.0 therefore appears to limit 6-month-old infants' discrimination of large sets in both auditory-temporal sequences and visual-spatial arrays (Xu & Spelke, 2000). In light of these findings, in Experiment 3 we investigated whether developmental changes occur in this critical discrimination ratio, by testing older infants with the same task used in Experiment 2.

EXPERIMENT 3

Experiment 3 investigated whether 9-month-old infants discriminate sequences of 8 versus 12 sounds.

Method

The method was identical to that of Experiment 2 except as follows. Nine male and 7 female full-term infants participated in the study (mean age = 8 months 27 days; range: 8 months 13 days to 9 months 13 days). Two additional infants were excluded because of fussiness. During pilot testing, we found that 9-month-old infants were distracted by the caregiver's headphones. Accordingly, headphones were not used, and caregivers were monitored by coders for compliance with our instructions to face forward throughout the study.

Results

The infants oriented longer to test events presenting the novel numerosity than to test events presenting the familiar numerosity (Fig. 2). The 2 × 2 × 3 ANOVA testing the effects of familiarization condition, test numerosity, and test-trial pair revealed only a main effect of test numerosity, $F(1, 15) = 10.26$, $p < .01$. Thirteen of 16 infants oriented longer to the novel numerosity (binomial $p < .01$), providing evidence for successful discrimination of 8 from 12 sounds. A 2 (age) ×

2 (test-trial type) ANOVA comparing Experiment 2 and Experiment 3 revealed a significant interaction of age and test numerosity, $F(1, 30) = 7.12$, $p < .05$. The tendency to orient toward the novel numerosity increased from 6 to 9 months of age.

Discussion

When presented with sequences of sounds, 9-month-old infants discriminate large numerosities that differ by a 1.5 ratio. The findings contrast with those obtained with 6-month-old infants, providing evidence that numerosity discrimination increases in precision between 6 and 9 months of age, well before the onset of verbal counting and arithmetic skills. A final experiment investigated the limits on the precision of 9-month-old infants' numerical representations, by testing discrimination at a still more difficult ratio.

EXPERIMENT 4

Experiment 4 investigated 9-month-old infants' discrimination of 8 versus 10 sounds.

Method

The method was the same as that of Experiment 3 except as follows. Six male and 10 female full-term infants participated in the study (mean age = 8 months 26 days; range: 8 months 14 days to 9 months 16 days). The 8-element sequences were the same as in Experiments 1 through 3. The 10-element familiarization sequences had the same items and rates as the 8-element familiarization sequences and therefore had total sequence durations ranging from 3,323 to 6,908 ms ($M = 5{,}115$ ms). The 10-element test sequences had the same total duration of sound and silence and sequence durations as the 8-element test sequences, with individual sound durations of 440 ms, ISIs of 117 ms, and a rate of 1.83 items/s.

Results

The infants showed a weak tendency to orient toward the novel numerosity (Fig. 2), but this tendency was not reliable. The $2 \times 2 \times 3$ ANOVA revealed no main effect of test numerosity, $F(1, 15) = 2.72$, $p > .05$, and no other effects. Ten of 16 infants attended more to the novel than to the familiar numerosity (n.s.). A 2 (experiment) $\times$ 2 (test-trial type) ANOVA comparing the test-trial orienting times obtained in Experiments 3 and 4 revealed a significant main effect of test numerosity, $F(1, 30) = 10.50$, $p < .01$, and no other effects.

Discussion

Experiment 4 provides no evidence that 9-month-old infants discriminate between auditory sequences of 8 versus 10 elements. Together with Experiment 3, this experiment suggests that the critical discrimination ratio at 9 months falls between 1.5 and 1.25. Performance at these two ratios did not differ reliably, however, raising the possibility that some 9-month-old infants are sensitive to numerical differences at the smaller ratio.

GENERAL DISCUSSION

The findings of these experiments provide evidence that infants are sensitive to approximate numerical magnitudes, as are adults. Infants' numerical discriminations cannot be explained wholly by mechanisms for representing small numbers of objects or events (e.g., object files), because the numerosities used in the present studies far exceed the capacities of the object-file system in infants (e.g., Carey & Xu, 2001) or adults (e.g., Trick & Pylyshyn, 1994). Moreover, infants' discrimination cannot be explained by sensitivity to changes in continuous variables that are correlated with changes in numerosity, because the present studies used sound sequences for which such variables were controlled. We conclude that 6-month-old infants represent large numerosities in auditory-temporal sequences.

The present findings support two further conclusions about infants' numerical discrimination. First, discrimination is imprecise: Six-month-old infants discriminated 8 sounds from 16 sounds but not from 12 sounds. Second, the precision of numerical discrimination increases over the infancy period: Nine-month-old infants succeeded at the same 8-versus-12 discrimination task that 6-month-old infants failed. These conclusions are consistent with the thesis that a common mechanism underlies numerical discrimination in infants and adults, and that the precision of the mechanism gradually increases over infancy, long before children learn verbal counting or symbolic arithmetic.

Finally, the present findings suggest that a single, abstract sense of numerical magnitudes guides infants' discrimination of diverse perceptual arrays. The common 2.0 ratio limit obtained when 6-month-old infants are presented with auditory-temporal sequences and with visual-spatial arrays is consistent with this thesis, which leads to a number of further predictions. First, sensitivity to number should undergo the same developmental change from 6 to 9 months for visual-spatial arrays as for sound sequences: Discrimination of visual arrays of 8 versus 12 elements should emerge between 6 and 9 months. Second, numerical discrimination should transfer from one modality or format to another. Finally and most strongly, if visual-spatial and auditory-temporal number discrimination depend on the same, abstract mechanisms in infants and adults, then both discrimination tasks should activate in infants the brain systems in parietal cortex whose activation is associated with number sense in neuroimaging studies of adults (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Pinel et al., 2001). Experiments with infants now can test all these predictions.

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