Developmental Science 8:2 (2005), pp 173–181

REPORT

Infants' enumeration of actions: numerical discrimination and its signature limits

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Abstract

Are abstract representations of number – representations that are independent of the particular type of entities that are enumerated – a product of human language or culture, or do they trace back to human infancy? To address this question, four experiments investigated whether human infants discriminate between sequences of actions (jumps of a puppet) on the basis of numerosity. At 6 months, infants successfully discriminated four- versus eight-jump sequences, when the continuous variables of sequence duration, jump duration, jump rate, jump interval and duration, and extent of motion were controlled, and rhythm was eliminated. In contrast, infants failed to discriminate two- versus four-jump sequences, suggesting that infants fail to form cardinal number representations of small numbers of actions. Infants also failed to discriminate between sequences of four versus six jumps at 6 months, and succeeded at 9 months, suggesting that infants' number representations are imprecise and increase in precision with age. All of these findings agree with those of studies using visual–spatial arrays and auditory sequences, providing evidence that a single, abstract system of number representation is present and functional in infancy.

Recent research provides evidence that human infants discriminate between large sets of elements on the basis of numerosity when a variety of continuous quantitative variables are controlled. For example, 6-month-old infants discriminate visual arrays of eight versus 16 dots when array size and density, dot size, summed area and brightness, and summed contour length are equated either during habituation or during test (e.g. Brannon, 2002; Brannon, Abbott & Lutz, 2004; Xu & Spelke, 2000; Xu, 2003; Xu, Spelke & Goddard, 2005). Infants also discriminate auditory sequences of eight versus 16 sounds when sequence duration, rate, item duration, and duration and amount of sound are controlled and rhythm is eliminated (Lipton & Spelke, 2003, in press).

In these studies, infants' numerical discrimination shows four signature limits.[1] First, it is imprecise: for example, 6-month-old infants discriminate eight-dot arrays from 16-dot arrays but not from 12-dot arrays (Xu & Spelke, 2000). Second, discrimination depends on the ratio of the two numerosities: infants who discriminate eight dots or sounds from 16 but not from 12 also discriminate four dots or sounds from eight but not from six (Xu, 2003; Lipton & Spelke, in press). Third, discrimination increases in precision with development: from 6 to 9 months, the critical ratio decreases from 2.0 (e.g. four versus eight) to 1.5 (e.g. four versus six) (Xu & Arriaga, under review; Lipton & Spelke, 2003). Fourth, discrimination fails for the smallest numerosities when infants are tested with the same methods and controls: for example, 6-month-old infants show no evidence of discriminating one versus two or two versus four dots or sounds, and 9-month-old infants show no evidence of discriminating two versus three dots or sounds (Xu, 2003; Xu *et al.*, 2005; Lipton & Spelke, in press; see also Clearfield & Mix, 1999; Feigenson, Carey & Spelke, 2002). These four signature limits characterize a system of numerical representation that human infants appear

[1] The term 'signature limits' refers to a consistent pattern of positive and negative findings that are obtained in tasks that require a particular set of cognitive processes (e.g. processes for discriminating large numerosities), and that are observed across studies that vary in method (e.g. preferential looking versus head-turning), displays (e.g. visual arrays of dots versus sequences of sounds), and populations (e.g. infants versus adults, or human versus non-human primates). When such a pattern of findings is obtained, it can serve to test for the existence of those cognitive processes in further populations, for the situations that evoke them, and for the mechanisms that subserve them (e.g. Wood & Spelke, in press).

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to share both with human adults and with adult nonhuman primates tested with similar displays (Barth, Kanwisher & Spelke, 2003; Hauser, Tsao, Garcia & Spelke, 2003; see also van Oeffelen & Vos, 1982), suggesting continuity in numerical representations over primate phylogeny and human ontogeny.

Although the convergence among the above studies is striking, the extent of infants' numerical capacities and the abstractness of their numerical representations are still debated. Human adults enumerate diverse entities, including visual forms, sounds, parades, flocks of birds, home runs and arguments. Does the ability to enumerate varied types of entities depend on a later-developing mechanism that emerges as children gain skill at verbal counting or symbolic arithmetic, as some have suggested (Mix, 1999), or does this ability trace back to infancy?

In landmark research, Wynn (1996; Sharon & Wynn, 1998) addressed this question by investigating whether infants individuate and enumerate actions. Individuating actions is a complex task because each action consists of a structured series of motions (see Wynn, 1996). In these studies, 6-month-old infants were habituated to a puppet jumping either two or three times, and then were tested with both numerosities. Infants dishabituated to the sequences containing the novel number of puppet jumps. The convergence of these findings with those of earlier studies of infants' discrimination of arrays of two versus three visual forms (e.g. Starkey & Cooper, 1980; Strauss & Curtis, 1981; van Loosbroek & Smitsman, 1990) or sounds (e.g. Bijeljac-Babic, Bertoncini & Mehler, 1991) suggested that infants formed a fairly abstract concept of 'individual', encompassing diverse entities.

Nevertheless, recent findings suggest three alternative interpretations of Wynn's findings. First, infants may discriminate between sequences of two versus three jumps by attending to perceptual information such as the rate of movement in habituation versus test. In particular, Clearfield (2003) found that 6-month-old infants dishabituate equally to new and old numbers of actions when the rate of motion is not a reliable cue to numerosity. Second, infants may discriminate two- from three-jump sequences by forming a summary representation of one or more continuous variables. Because each jump in Wynn's study was identical in extent and duration, the number of jumps was positively correlated with the total duration and extent of motion in the sequence. Infants have been found to form summary representations of continuous extent or contour length when presented with small numbers of objects (Clearfield & Mix, 1999; Feigenson *et al.*, 2002b). These findings call earlier evidence for representations of small numerosities into question, and they raise the possibility that a summary representation of a continuous amount of motion underlies discrimination of small numbers of actions (Mix, Huttenlocher & Levine, 1996).[2]

According to a third proposal, the infants in Wynn's (1996) experiments represent each individual action with a unique symbol without representing or storing an explicit cardinal value (Carey, 2001). This account gains plausibility from evidence that infants' representations of small numbers of visible objects depend on mechanisms of parallel individuation, or 'object files' (see Simon, 1997; Scholl, 2001; Feigenson *et al.*, 2002b; Feigenson & Carey, 2003). A fourth proposal is Wynn's (1996, 1998, 2000): infants' discrimination of two- versus three-jump sequences depends on a dedicated numerical mechanism. In the latter case, however, note that Wynn's results fail to accord with two of the signature features of numerical discrimination, namely the ratio limit of 2.0 at 6 months and the failure of discrimination for small numerosities.

The present studies were undertaken both to disentangle these four proposals and to test Wynn's original hypotheses that infants individuate actions and form numerical representations of diverse types of entities. First, we investigated whether 6-month-old infants discriminate action sequences presenting large numerosities (four versus eight jumps of a puppet) on the basis of number when the continuous variables of sequence rate and duration, jump duration and extent, and motion duration and extent are controlled, and rhythm is eliminated (Experiment 1). Such a finding would suggest, following Wynn (1996), that infants can individuate and enumerate actions.

Next, we investigated whether infants' discrimination of action sequences shows the four signatures of infants' discrimination of visual–spatial arrays and auditory sequences: lack of precision, success at a 2.0 ratio at 6 months, success at a 1.5 ratio at 9 months, and failure for small numerosities. We investigated 6-month-old infants' discrimination between sequences of two versus four jumps (Experiment 2) and both 6- and 9-month-old infants' discrimination between sequences of four versus six jumps (Experiments 3 and 4). To preview our findings, infants' discrimination of jump sequences showed all the signatures found in past studies of discrimination of visual–spatial arrays and auditory–temporal sequences, contrary to the specifics of Wynn's (1996) findings but in support of her general claims for an abstract mechanism of enumeration.

[2] Other experiments provide evidence that infants discriminate small numbers (i.e. two versus four) with non-object stimuli such as collections of dots undergoing common motion (Wynn, Bloom & Chiang, 2002). In these studies, however, the number of individuals was correlated with the variability of motion, raising the possibility that discrimination depended on this correlated variable rather than on number.

Experiment 1

Experiment 1 used a variant of the method of Wynn (1996) to investigate whether 6-month-old infants discriminate sequences of four versus eight jumps.

Method

Participants

Ten male and six female full-term infants (mean age: 5 months, 29 days; range: 5 months, 16 days to 6 months, 14 days) participated in the study. Three additional infants were excluded from the sample because of fussiness ($n = 2$) or parental interference ($n = 1$).

Apparatus

Infants sat on their mothers' laps and faced a stage in a dimly lit room. At the beginning of each trial, a curtain rose to reveal a 13 cm × 17 cm stuffed animal on a platform in front of a black cloth that hid an experimenter. To make this puppet jump, the experimenter lifted a black dowel attached to the puppet's back in time to a computer-generated pattern displayed on a concealed laptop. Video cameras directed at the infant and display were mixed on to a television monitor in a separate room.

Stimuli

The jump sequences controlled for the continuous quantitative variables that typically correlate with number as follows. During habituation, the rate, duration, interstimulus interval (ISI) and height of individual puppet jumps were equated across the two numerosities, yielding eight-jump sequences that were longer and contained more motion than the four-jump sequences (see Table 1). The rate, duration and height of individual jumps were constant within a sequence but varied across sequences. Sequences occurred in a quasi-random order such that the same sequence rate never occurred twice in succession. During the test, the total sequence duration, total extent and duration of motion, and total interval times were equated across the two numerosities: all test sequences therefore contained the same amount of total jumping time, total vertical extent and total ISI (again, see Table 1). These stimulus variations insured that a systematic preference for the novel numerosity could not be based on any of these variables. Because only one jump sequence was presented per trial, and the jumps on successive trials occurred at different rates, the jump sequences had no repeating rhythmic structure that could serve to differentiate between sequences of four versus eight actions. In this experiment, therefore, number was also not confounded with rhythm.

Design

Equal numbers of infants were habituated to a puppet that jumped four versus eight times per trial. In both habituation conditions, the puppet's jumps were constant in extent and duration within a sequence and varied across sequences, such that each infant was habituated to four different jump sequences (Table 1). Following habituation, infants were presented with six test trials in which four-jump and eight-jump sequences occurred in alternation. Half the infants in each

Table 1 *Parameters of habituation and test trials for Experiment 1*

	Jump duration	Interjump interval	Total jumping duration	Total interjump interval	Total duration of sequence	Jump height (cm)	Total jumping height (cm)
Test trials (ms)							
4	1000	700	4000	2100	6100	10	40
8	500	300	4000	2100	6100	5	40
Habituation trials (ms)							
4	375	600	1500	1800	3300	4	16
4	650	500	2600	1500	4100	8	32
4	850	500	3400	1500	4900	7	28
4	1125	400	4500	1200	5700	11	44
Mean	750	500	3000	1500	4500	7.5	30
8	375	600	3000	4200	7200	4	32
8	650	500	5200	3500	8700	8	64
8	850	500	6800	3500	10300	7	56
8	1125	400	9000	2800	11800	11	88
Mean	750	500	6000	3500	9500	7.5	60

habituation condition were presented first with the novel numerosity.

Procedure

During the habituation phase, the curtain rose to reveal a stationary puppet that began to jump after 1 s. Timing of the infant's looking began at the end of the jump sequence and continued until the infant looked away for 2 s consecutively or 30 s elapsed. When infants reached the habituation criterion (looking time on three consecutive trials less than half of the total looking time on the first three trials), or completed 12 habituation trials, they received a 30-s break. The six test trials were then presented following the same procedure. At the start of the study, parents were asked to interact with their child as little as possible. If the parent vocalized or pointed during any point in the test trial period, the infant was excluded from the study. Throughout the study, an observer recorded the infant's looking times from the video monitor in the separate coding room. During coding, the display portion of the screen was occluded to ensure that the coder 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 93% or greater).

Results

Figure 1 presents the mean looking times during habituation and test. Initial, final and total looking times

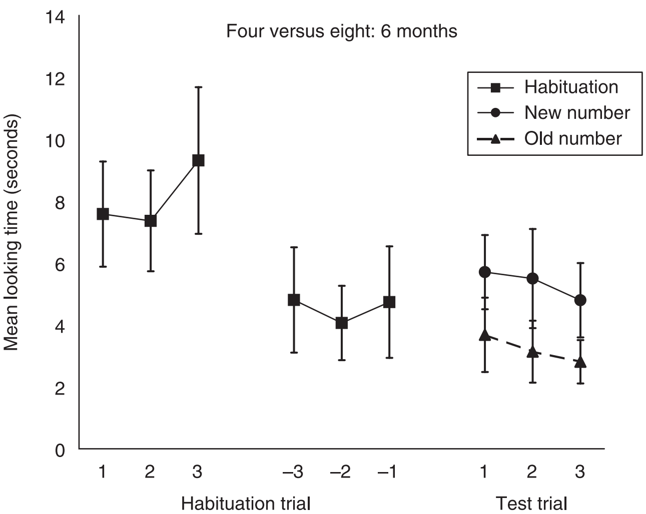

Figure 1 *Mean looking times for the first three habituation trials, the last three habituation trials and the test trials of Experiment 1. Error bars represent the standard error.*

during the habituation period did not differ for the infants habituated to the four- versus eight-jump sequences (all *t*s < 1). Four infants, two in the four-jump 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 were analyzed with a $2 \times 2 \times 3$ ANOVA, with the within-subject factors of Test Numerosity (new number versus old number) and Test Trial Pair (first, second, or third) and the between-subject factor of Habituation Condition (four versus eight). The analysis revealed only a main effect of Test Numerosity, $F(1, 15) = 10.56$, $p < .01$: Infants looked longer at the new number ($M = 13.3$ s, SD = 11.5 s) than the old number ($M = 8.3$ s, SD = 7.9 s). Twelve of the 16 infants looked longer at the jump sequences with the new number (binomial $p < .05$).[3]

Discussion

Experiment 1 provides evidence that 6-month-old infants discriminated sequences of four jumps from sequences of eight jumps. The study is the first to show that infants individuate and enumerate large numbers of actions, and it is the first showing numerical discrimination of actions with controls for the continuous variables of rate, rhythm, extent and duration of motion. In particular, infants' success in Experiment 1 cannot be explained by responses to rate information rather than number (e.g. Clearfield, 2003) or by construction of a summary representation of continuous extent (analogous to the explanation in Feigenson, Carey & Hauser, 2002a) because the design of the experiment controlled for both of these possibilities. Infants' success also cannot be explained by any response to rhythm (Clearfield, 2003) because the habituation series of jump sequences presented variable rates and sequence intervals and therefore was aperiodic. Infants' success in Experiment 1 also could not depend on parallel individuation of actions

[3] Although it is common to analyze infants' degree of dishabituation to each test display by comparing looking at that display with looking time to the final habituation display, such an analysis is not appropriate for experiments using the present design because of the nature of its controls for continuous quantitative variables. During habituation, the rate, duration, interstimulus interval and height of individual puppet jumps were equated across the two numerosities, whereas during test, the total sequence duration, total extent and duration of motion and the total interval times were equated across the two numerosities. Because all these variables changed from habituation to test, any increase in looking from the habituation trials to the test trials could stem either from detection of a change in number or from detection of the changes in continuous variables. With the present design, therefore, the only comparison that provides evidence for discrimination on the basis of number is the comparison between looking times at the old number versus the new number test displays.

(analogous to explanations in terms of object files, e.g. Simon, 1997) because the number of actions tested well exceeds the representational capacities of known systems of parallel individuation (see Feigenson & Carey, 2003). The results are most consistent with Wynn's (1996) thesis that infants represent cardinal numbers.

We ask now whether the same mechanism supports numerical representations of actions, objects and sounds. If performance is supported by a single abstract system of numerical information, then infants' performance should show the same signature limits with all three types of entities. Wynn's results (1996), however, appear to provide evidence against such an account, for the infants in her studies discriminated two- from three-jump sequences, contrary both to the small number limit and to the 2.0 ratio limit. Because Wynn (1996) did not control for all continuous quantitative variables, however, it is possible that infants' success in her studies depended on one or more of those variables. In Experiment 2, we investigate whether infants discriminate small numbers of puppet jumps (two versus four) in sequences using the same methods and continuous quantity controls as in Experiment 1.

Experiment 2

Method

The method was the same as in Experiment 1 except as follows. Participants were nine male and seven female full-term infants (mean age: 5 months, 27 days; range: 5 months, 19 days to 6 months, 17 days). Three additional infants were excluded from the sample because of fussiness ($n = 2$) or parental interference ($n = 1$).

Table 2 presents the temporal properties of the jump sequences. The two-jump and the four-jump habituation sequences contained the same total jumping time as the four-jump and the eight-jump sequences in Experiment 1, respectively, with individual inter-stimulus interval approximately equal to those used in Experiment 1. The sequences were constructed to achieve the same continuous quantity controls as in Experiment 1.

Results

Figure 2 presents the mean looking times during habituation and test. Looking times to the two- versus

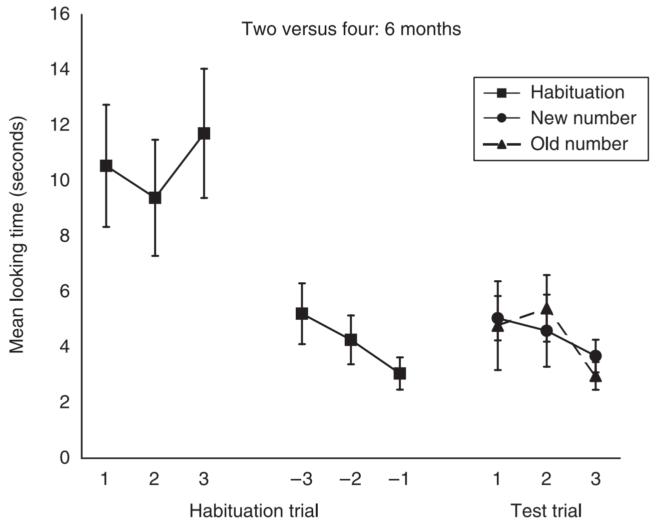

Figure 2 *Mean looking times for the first three habituation trials, the last three habituation trials and the test trials of Experiment 2. Error bars represent the standard error.*

Table 2 *Parameters of habituation and test trials for Experiment 2*

	Jump duration	Interjump interval	Total jumping duration	Total interjump interval	Total duration of sequence	Jump height (cm)	Total jumping height (cm)
Test trials (ms)							
2	2000	900	4000	900	4900	10	20
4	1000	300	4000	900	4900	5	20
Habituation trials (ms)							
2	750	600	1500	600	2100	4	8
2	1300	500	2600	500	3100	8	16
2	1700	500	3400	500	3900	7	14
2	2250	400	4500	400	4900	11	22
Mean	1500	500	3000	500	3500	7.5	15
4	750	600	3000	1800	4800	4	16
4	1300	500	5200	1500	6700	8	32
4	1700	500	6800	1500	8300	7	28
4	2250	400	9000	1200	10200	11	44
Mean	1500	500	6000	1500	7500	7.5	30

four-jump sequences did not differ during the habituation period (all *t*s < 1). Four infants, one in the two-jump habituation condition, failed to meet the habituation criterion; they showed the same pattern of test-trial looking as the other infants. The 2 × 2 × 3 ANOVA revealed no main effect of Test Numerosity, ($F < 1$), and no other effects. The infants did not look longer at the new number (M = 12.6 s, SD = 9.4) than the old number (M = 12.5 s, SD = 13.6 s). Nine of the 16 infants looked longer at the displays with the novel number (n.s.).

A further 2 (Experiment) × 2 (Habituation Condition: larger versus smaller number) × 2 (Test Numerosity) × 3 (Test Trial Pair) ANOVA compared the test trial looking patterns of infants in Experiments 1 and 2. This analysis revealed a main effect of Test Numerosity, $F(1, 30) = 4.902$, $p < .05$, qualified by an interaction of Experiment and Test Numerosity, $F(1, 30) = 7.124$, $p < .05$. Infants looked longer at the test sequence presenting the novel numerosity, and this effect was greater for those in the first experiment who were presented with larger set sizes.

Discussion

Experiment 2 provided no evidence that infants discriminated between two- and four-jump sequences on the basis of numerosity when correlated continuous variables were controlled. Number discrimination was reliably lower in this experiment than in Experiment 1, which used the same method and stimulus controls but larger set sizes.[4] These results accord with previous research in which infants were presented with dots or sounds (Xu, 2003; Lipton & Spelke, 2003), suggesting that number discrimination shows a common signature limit for diverse types of entities.

The next experiments investigated whether infants' performance also shows a second signature feature of approximate number representation. Experiment 3 tested the precision of large number discrimination by examining whether 6-month-old infants discriminate sequences of four versus six actions. If the same system supports enumeration of objects, sounds and actions, then such infants should fail to discriminate four versus six actions, just as they have failed to discriminate four versus six dots or sounds (Xu, 2003; Lipton & Spelke, 2003).

[4] One possibility is that infants failed to discriminate two versus four jumps because the duration of each individual jump was too long. To address this possibility, we tested an additional eight infants in a two-versus four-jump condition with individual jump durations equal to those in Experiment 1. Thus, the total sequence durations were approximately one half of those in Experiment 1. A 2 × 2 × 3 ANOVA revealed no main effect of test numerosity ($F < 1$). Four of the eight infants looked longer at the novel numerosity (n.s.). Infants did not look longer at the jump sequences with the novel number (M = 13.0 s, SD = 5.17 s) than the familiar number (M = 12.9 s, SD = 6.20 s).

Experiment 3

Experiment 3 investigated whether 6-month-old infants discriminate between sequences of four versus six actions on the basis of number.

Method

The method was the same as in Experiment 1 except as follows. Participants were 16 infants (mean age: 6 months, 1 day; range: 5 months, 14 days to 6 months, 16 days). Four additional infants were excluded due to fussiness. The four-jump sequences were the same as in Experiment 1, whereas the six-jump sequences were constructed so as to achieve the same continuous-quantity controls as in Experiment 1 (see Table 3).

Results

Figure 3 presents the mean looking times during habituation and test. Looking times to the four- versus six-jump sequences did not differ during the habituation period (all *t*s < 1). Two infants, both in the four-jump habituation condition, failed to meet the habituation criterion; they showed the same pattern of test-trial looking as the other infants. Test trial looking times to the familiar and novel numerosities also did not differ: the 2 × 2 × 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 = 7.3 s, SD = 4.5 s) than the old number (M = 7.6 s, SD = 7.3 s). Eight of the 16 infants looked longer at the displays that contained the novel number of elements (n.s.).

A 2 (Ratio: 8.4 versus 6.4) × 2 (Habituation Condition: smaller versus larger number) × 2 (Test Numerosity) × 3 (Test Trial Pair) ANOVA compared infants' looking patterns in Experiments 1 and 3. This analysis revealed a significant interaction of Ratio and Test Numerosity, $F(1, 30)$ 4.346 = $p < .05$, and no other significant effects. Infants showed a greater preference for the novel numerosity when the sets differed by a 2.0 ratio than when they differed by a 1.5 ratio.

Discussion

In contrast to Experiment 1, infants failed to discriminate four versus six actions. These findings accord with previous research testing numerosity discrimination with objects (Xu, 2003) and sounds (Lipton & Spelke, 2003),

Table 3 *Parameters of habituation and test trials for Experiments 3 and 4*

	Jump duration	Interjump interval	Total jumping duration	Total interjump interval	Total duration of sequence	Jump height (cm)	Total jumping height (cm)
Test trials (ms)							
4	1000	700	4000	2100	6100	10	40
6	667	420	4002	2100	6102	6.67	40
Habituation Trials (ms)							
4	375	600	1500	1800	3300	4	16
4	650	500	2600	1500	4100	8	32
4	850	500	3400	1500	4900	7	28
4	1125	400	4500	1200	5700	11	44
Mean	750	500	3000	1500	4500	7.5	30
6	375	600	2250	3000	5250	4	24
6	650	500	3900	2500	6400	8	48
6	850	500	5100	2500	7600	7	42
6	1125	400	6750	2000	8750	11	66
Mean	750	500	4500	2500	7000	7.5	45

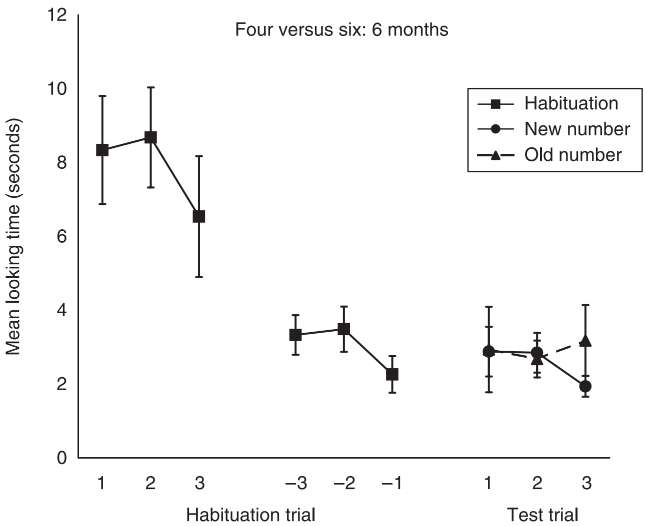

Figure 3 *Mean looking times for the first three habituation trials, the last three habituation trials and the test trials of Experiment 3. Error bars represent the standard error.*

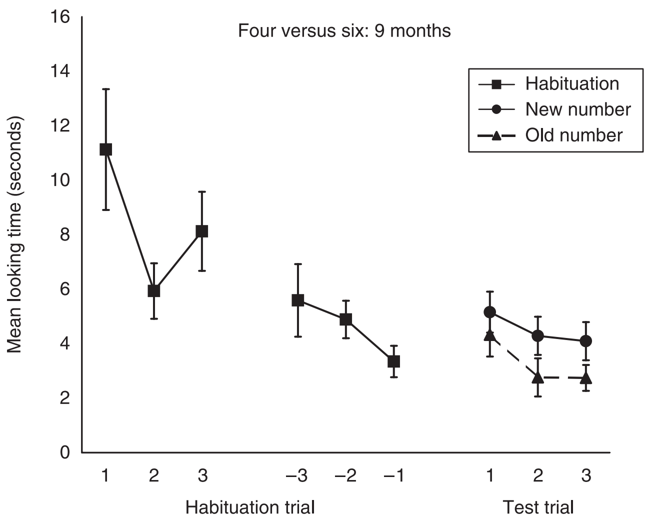

Figure 4 *Mean looking times for the first three habituation trials, the last three habituation trials and the test trials of Experiment 4. Error bars represent the standard error.*

providing evidence for a common 2.0 ratio limit at 6 months of age. The last experiment accordingly tested whether infants' enumeration of actions shows the final signature limit found in studies with objects and sounds: an increase in precision from a 2.0 ratio at 6 months to a 1.5 ratio at 9 months.

Experiment 4

Experiment 4 investigated whether 9-month-old infants discriminate between sequences of four versus six actions on the basis of number.

Method

The method was the same as in Experiment 3. The participants were 16 infants (mean age: 8 months, 30 days; range: 8 months, 15 days to 9 months, 17 days). Two additional infants were excluded due to fussiness.

Results

Figure 4 presents the mean looking times during habituation and test. Initial, final and total looking times during the habituation period did not differ for the infants habituated to the four- versus six- jump sequences (all *t*s < 1). Four infants, two in the four-jump habituation condition, failed to meet the habituation criterion; they showed the same pattern of test-trial looking as the other infants in their condition. A 2 × 2 × 3 ANOVA revealed a main effect of Test Trial Type, $F(1, 15) = 7.59$, $p < .05$. Infants looked longer at the new number ($M = 11.5$ s, SD = 8.2 s) than the old number ($M = 8.9$ s, SD = 7.4 s). No other main effects or interactions were significant. Twelve of the 16 infants looked longer at the jump sequences with the new number (binomial $p < .05$), providing evidence that the infants discriminated four versus six jumps.

A 2 (Age: 6 versus 9 months) × 2 (Habituation Condition: four versus six) × 2 (Test Numerosity) × 3 (Test Trial Pair) ANOVA compared looking patterns in Experiments 3 and 4, which used the same method at two different ages. The analysis revealed a significant interaction between Age and Test Numerosity, $F(1, 30) = 4.61$, $p < .05$. Preference for the novel numerosity increased from 6 to 9 months of age.

Discussion

In contrast with Experiment 3, 9-month-old infants successfully discriminated between the sequences presenting four versus six actions. These findings provide evidence that 9-month-old infants discriminated the sequences on the basis of numerosity. Moreover, numerical discrimination is more precise at 9 months than at 6 months, and it shows the same ratio limit found in studies presenting visual arrays of dots (Xu & Arriaga, under review) and sequences of sounds (Lipton & Spelke, 2003).

General discussion

To reconcile conflicting accounts of numerical processing in infants, four experiments investigated infants' discrimination of sequences of actions. Six-month-old infants successfully discriminated large (four versus eight) but not small (two versus four) numbers of jumps. Moreover, the ratio limit on discrimination narrowed with age from 2.0 at 6 months to 1.5 at 9 months. These findings accord with previous research testing numerosity discrimination with arrays of dots and sequences of sounds (Xu & Spelke, 2000; Lipton & Spelke, 2003; Xu, 2003; Lipton & Spelke, in press). The convergence across these studies provides evidence in support of Wynn's (1996) thesis that humans possess a single, abstract system of numerical representation long before they learn verbal counting or symbolic arithmetic.

Although the present method provided no evidence for discrimination of small sets, it remains an open question whether infants can establish parallel representations of small numbers of actions, analogous to object-file representations of small numbers of objects (Feigenson *et al.*, 2002a). It is possible that the infants in Wynn's (1996) study and those in Experiment 2 represented each action in parallel and computed the total extent of motion in each sequence, just as infants presented with small numbers of visible objects compute the continuous spatial extent of those objects (Feigenson *et al.*, 2002b). Current research is testing that possibility.

Why was the mechanism of large number discrimination not engaged by the sequences presenting small numbers of actions? Recent studies of the mechanisms of numerical processing suggest two possible answers. First, studies of adults (e.g. Scholl & Pylyshyn, 1999) and infants (e.g. Carey & Xu, 2001) provide evidence for a parallel, pre-attentive system that represents small numbers of individuals. Infants' system for representing large, approximate numerosities may extend to small numbers of actions, but these representations may be inhibited by the output of this pre-attentive system (Xu, 2003). Second, studies of adults (Barth *et al.*, 2003) and infants (Wood & Spelke, in press) suggest that the mechanism underlying non-symbolic processing of large numerosities operates non-iteratively and in parallel. This mechanism may not operate stably for small numerical values. For example, one non-iterative model of enumeration invokes an intermediate process of computing the average interval duration between two successive events (Church & Broadbent, 1990), and another model invokes a process of computing the average size of elements (Dehaene & Changeux, 1993). These statistical estimates become increasingly stable as the number of elements grows.

Whatever the reason for these signature limits, their existence supports two conclusions. First, a common mechanism underlies numerical discrimination in infants and adults. Second, the mechanism operates on diverse inputs long before children learn verbal counting or symbolic arithmetic. Both findings suggest that abstract number representations are part of human core knowledge.

Acknowledgments

This research was supported by N.I.H. Grant HD23103 to Elizabeth S. Spelke. We thank Jennifer Lipton for important contributions to the research.

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Received: 20 November 2003
Accepted: 21 May 2004