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Brief article

Numerosity discrimination in infants: Evidence for two systems of representations

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Abstract

Two experiments investigated numerosity discrimination in 6-month-old infants, comparing their performance on both large numbers (4 vs. 8 elements) and small numbers (2 vs. 4 elements) with both total filled area and total contour length controlled for. These studies provide the first direct comparison between discrimination of small and large numbers in infants with the same methodology, the same type of stimuli, and the same continuous variable controls. Results showed that infants succeeded in discriminating 4 from 8 elements but failed to discriminate 2 from 4 elements, providing evidence for the existence of two systems of number representations in infancy.

Keywords: Numerosity discrimination; Infants

1. Introduction

The last few decades have witnessed a wealth of studies on number representations in infants, adults, and non-human animals (see Dehaene, 1997; Gallistel, 1990; Gallistel & Gelman, 2000; Wynn, 1998, for reviews). In recent years the debate on whether infants represent numerosity per se has inspired many new empirical investigations (e.g. Simons, Hespos, & Rochat, 1995; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Wynn, 1992). Early studies reported that infants can discriminate between small numbers of 2D visual forms or objects (e.g. Antell & Keating, 1983; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1983; Strauss & Curtis, 1981; Treiber & Wilcox, 1984). However, because these studies confounded number with other continuous variables (e.g. larger number

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arrays had larger amounts of stuff, whether in each display or over the average of the displays), the question of whether infants can discriminate arrays on the basis of number alone remains open. Recent studies by Clearfield and Mix (1999) and Feigenson, Carey, and Spelke (2002) have shown that when number is pitted against other continuous variables, or when other continuous variables are controlled for, no evidence for number discrimination is found for small numbers (1, 2, or 3) of two-dimensional displays or three-dimensional objects. Other studies have used non-objects or other visual displays as stimuli (e.g. Bijeljac-Babic, Bertoncini, & Mehler, 1991: syllables of a spoken word; Sharon & Wynn, 1998: jumps of a puppet; Wynn, Bloom, & Chiang, 2002: groups of visual forms undergoing rigid motion) within the small number range (1–4) and found positive evidence for number discrimination. However, in these studies number also correlated with other continuous variables such as the total amount of motion in the jump sequences, the total amount of sound in the words, and the variability of motion in the displays.

Inspired by research on representations of approximate numerosities in adults and non-human animals (e.g. Barth, Kanwisher, & Spelke, in press; Cordes, Gelman, Gallistel, & Whalen, 2001; Gallistel, 1990; Whalen, Gallistel, & Gelman, 1999), several investigators have found evidence for large number discrimination in infants, e.g. 8 vs. 16, when continuous variables such as total filled area, element size and element density as well as correlated perceptual variables such as average brightness and texture are controlled for (Brannon, 2002; Lipton & Spelke, in press; Xu & Spelke, 2000). One recent study found successful discrimination of even larger numbers (16 vs. 32) by 6-month-old infants when total filled area and total contour length were controlled for (Xu, Spelke, & Goddard, 2003). These studies also suggest that large number estimation in infants is highly imprecise, requiring a ratio between 2:3 and 1:2 (successes: 8 vs. 16, 16 vs. 32; failures: 8 vs. 12, 16 vs. 24). By 9 or 10 months, however, the precision improves and infants are able to discriminate between 8 and 12 elements (Lipton & Spelke, in press; Xu & Arriaga, 2003).

Given these two lines of investigations on number representations in infancy, some have suggested that there are two systems for representing number (e.g. Carey, 2001; Xu & Spelke, 2000). One is an object-tracking system (e.g. Scholl, 2001; Simon, 1997; Trick & Pylyshyn, 1994; Uller et al., 1999; Xu, 2003). This system operates on a small number of objects (3 or 4) for human infants, adults, and rhesus macaques monkeys (e.g. Feigenson, Carey, & Hauser, 2002; Feigenson & Halberda, 2002). It keeps track of individual objects but it does not represent groups of objects as sets. It is precise but it has a clear limit on set size. The other system is a number estimation system shared across species (e.g. Barth et al., in press; Cordes et al., 2001; Meck & Church, 1983; Xu & Spelke, 2000). This system represents approximate large numbers as sets, and it has no inherent set size limit. The representations, however, are imprecise, and discrimination accords with Weber's Law.

To date, however, small number and large number studies have often used different types of displays (e.g. objects vs. 2D visual forms), different methodologies (e.g. familiarization vs. habituation), and different continuous variable controls (e.g. total filled area vs. contour length), making it difficult to compare the results directly.

Two comparisons are critical for the claim of two systems of number representations:

4 vs. 8 and 2 vs. 4. They straddle the boundary between the small and large numbers, and they satisfy the required Weber fraction of 1:2.

The current experiments investigated 6-month-old infants' number discrimination using these two sets of numbers (Experiment 1: 4 vs. 8; Experiment 2: 2 vs. 4) with two types of continuous variables controlled for: total filled area and total contour length (i.e. circumference). We adopt the general methodology of Xu and Spelke (2000). Our goal is to explore whether infants process large and small numbers differently using the same type of stimuli, the same methodology, and with the same continuous variable controls.

2. Experiment 1

2.1. Method

2.1.1. Participants

The participants were 16 infants (eight males, eight females, age range: 5;17 [month;day] to 6;15, mean age: 6;5). All infants were recruited via public birth records in the greater Boston area. Three infants were excluded due to fussiness.

2.1.2. Apparatus and stimuli

Infants sat in an infant seat facing a well-illuminated puppet stage surrounded by black curtains. A camera was focused on the infant through a small hole below the stage center; it was connected to a TV monitor and a VCR in a corner of the room, on which an observer watched the infant and recorded his or her looking times by a button box connected to a computer. The observer was blind both to the infant's condition and to the displays. Interscorer reliability averaged 93%. A display camera was placed behind the infant to record the whole scene. A parent sat next to the infant and faced away from the displays. Parents were instructed to remain neutral.

A navy blue rectangular display board (74×30 cm) served as the background, about 60 cm from the infant. Displays consisting of black solid discs printed on white paper were glued onto smaller navy blue display boards measuring 52×21 cm, which were attached to the center of the background display board and removed between trials.

Habituation arrays consisted of 4 or 8 discs that varied in size and position within an array of a constant size (18×19 cm). The positions were chosen randomly from a matrix and varied for each display. Displays were discarded if the disc positions looked non-random or cluttered. The less numerous displays therefore had half the element density.

2.1.2.1. Total filled area control condition. Over the habituation trials, the average area occupied by an individual element was twice as large for the 4-element arrays (mean filled area = 5.28 cm^2, range from 1.76 to 8.82 cm^2) as for the 8-element arrays (mean filled area = 2.64 cm^2, range from 0.88 to 4.41 cm^2), and so the average size of all the discs in an array combined and the average brightness of those discs were equated. At the infant's viewing distance of about 60 cm, each array subtended visual angles of $34° \times 18°$. Six arrays of 4 discs and six arrays of 8 discs were presented. The less numerous displays had half the element density as the more numerous displays.

The test displays presented new arrays of 4 and 8 discs. The density of discs was equated and equidistant from the habituation densities. The 8-element arrays (38 × 24 cm) were twice as large as the 4-element arrays (24 × 19 cm). Moreover, the sizes of individual discs were equated (filled area = 3.96 cm^2), and therefore the total size and average brightness in the 8-element arrays were twice those of the 4-element arrays. At a viewing distance of about 60 cm, the 4-element array subtended $22.5° \times 18°$ and the 8-element array subtended $45° \times 18°$. The element density of the test arrays was also equated (see Fig. 1 for a schematic depiction of the displays). Thus, the continuous variables that varied across the two habituation groups were equated across the test displays, and vice versa.

2.1.2.2. Contour length (circumference) control condition. Over the habituation trials, the average total contour length for an individual element was twice as large for the 4-element arrays (mean circumference = 7.88 cm, range from 4.71 to 10.52 cm) as for the 8-element arrays (mean circumference = 3.94 cm, range from 2.35 to 5.26 cm).

The test displays presented new arrays of 4 and 8 discs. The sizes of individual discs were equated (circumference = 5.91 cm), and therefore the total contour length for the 8-element arrays was twice that of the 4-element arrays. Again, continuous variables that varied across the two habituation groups were equated across the test displays, and vice versa.

2.1.3. Design

Infants were randomly assigned to one of the two conditions. Half the infants were habituated to displays with 4 discs and half to displays with 8 discs. For each infant, the six habituation displays were presented in a random order. If the infant did not meet the habituation criterion after six trials, the displays were cycled in the same order until the end of habituation. Infants were then presented with six test trials in which displays with 4 discs and displays with 8 discs were shown alternately. The order of the test trials was counterbalanced across participants.

2.1.4. Procedure

At the beginning of the test session, the experimenter used a squeaky toy to draw the infant's attention to the display board. She squeaked the toy at the top, bottom, and the four far corners of the display to allow the observer to calibrate the infant's window of looking, and then the experiment began. On each trial, a curtain was raised to reveal a display, which remained visible until the infant looked for at least 0.5 s and then looked away for 2 s continuously (or for a maximum look of 120 s). Habituation trials continued until the infant either was given 14 trials or reached the habituation criterion of a 50% decline in looking time on three consecutive trials, relative to the total looking time on the first three trials that summed to at least 12 s. Ten of 16 infants reached the habituation criterion. Six test trials followed the habituation phase.

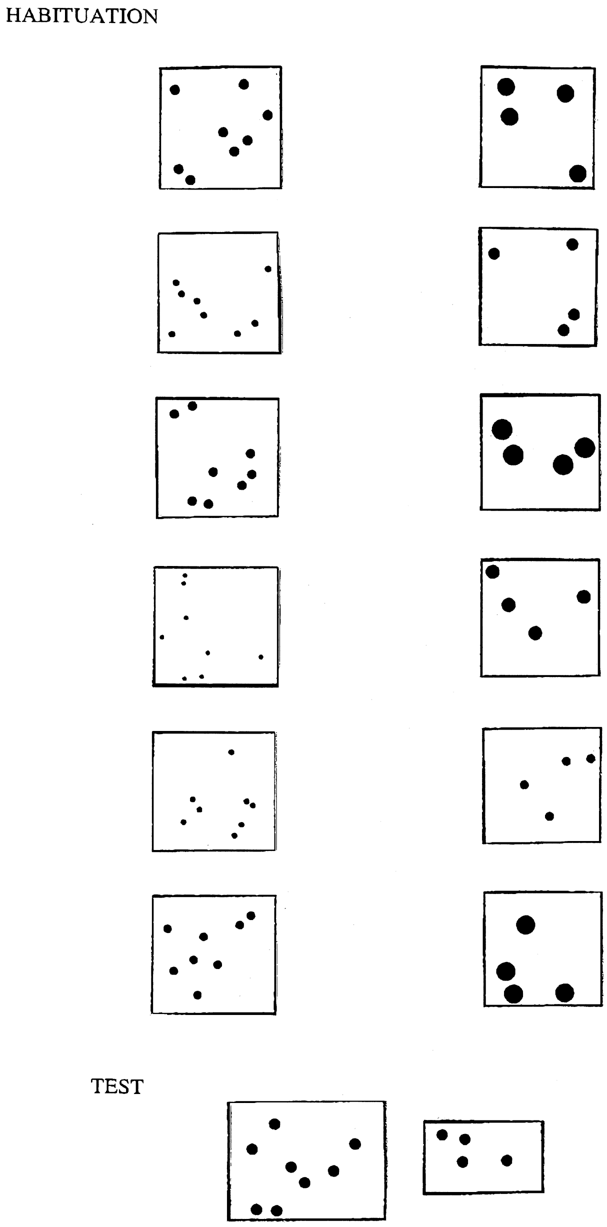

Fig. 1. Schematic representation of the habituation and test displays of Experiment 1 (total filled area control condition).

2.2. Results and discussion

Looking times were subjected to a $2 \times 2 \times 3 \times 2$ mixed-factor analysis of variance testing the between-subject factor of Test condition (area vs. contour length), Habituation condition (4 vs. 8) and the within-subject factors of Test trial pair (first, second, or third) and Test trial type (old vs. new number). There was a main effect of Test trial type ($F(1, 12) = 10.134$, $P < 0.01$). Infants looked longer at the new number ($M = 11.3$ s, SD = 11.2) than the old number ($M = 8.1$ s, SD = 6.7) in both the area control and the contour length conditions (Fig. 2a,b). No other main effects or interactions were

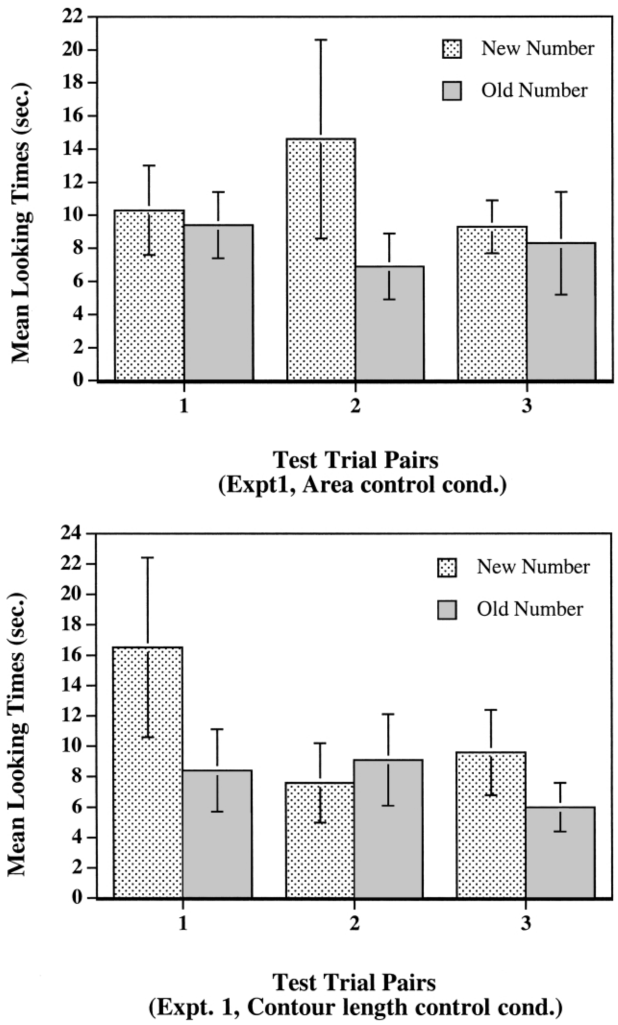

Fig. 2. (a,b) Mean looking times for Experiment 1.

statistically significant ($P > 0.1$). Fourteen of the 16 infants looked longer at the new number displays (Wilcoxon $z = -3.351$, $P < 0.001$). Infants who did or did not habituate showed the same pattern of looking on the test trials. Thus, infants succeeded in discriminating 4 from 8 elements. Next we used exactly the same methods and asked if 6-month-old infants discriminated between 2 and 4 elements.

3. Experiment 2

3.1. Method

3.1.1. Participants

The participants were 16 full-term infants (eight males, eight females, age range: 5;15 to 6;15, mean age: 6;1). All infants were recruited by the same methods as in Experiment 1. Two infants were excluded due to fussiness.

3.1.2. Apparatus and stimuli

The apparatus was identical to that of Experiment 1. The overall sizes of habituation and test arrays were the same as in Experiment 1, therefore individual elements were twice as large (measured by either total filled area or contour length) as the individual elements in Experiment 1.

3.1.3. Design and procedure

The design and procedure were identical to Experiment 1. Interscorer reliability averaged 92%. Eleven of 16 infants reached the habituation criterion.

3.2. Results and discussion

Looking times were subjected to a $2 \times 2 \times 3 \times 2$ mixed-factor analysis of variance with Test condition (area vs. contour length), Habituation condition (2 vs. 4), Test trial pair (first, second, or third) and Test trial type (old vs. new number) as factors. There was no main effect of Test trial type ($F(1, 12) = 1.044$, $P = 0.327$), and no other main effects or interactions. Infants did not look longer at the new number ($M = 5.3$ s, SD $= 4.5$) than the old number ($M = 5.9$ s, SD $= 4.1$) in either the total filled area condition or the contour length condition (Fig. 3a,b). Six of the 16 infants looked longer at the new number displays. Infants who did or did not habituate showed the same pattern of looking on the test trials. Thus, infants failed to discriminate between 2 and 4 elements when total filled area and contour length were controlled for.

4. General discussion

Two experiments investigated whether 6-month-old infants discriminate numerosities

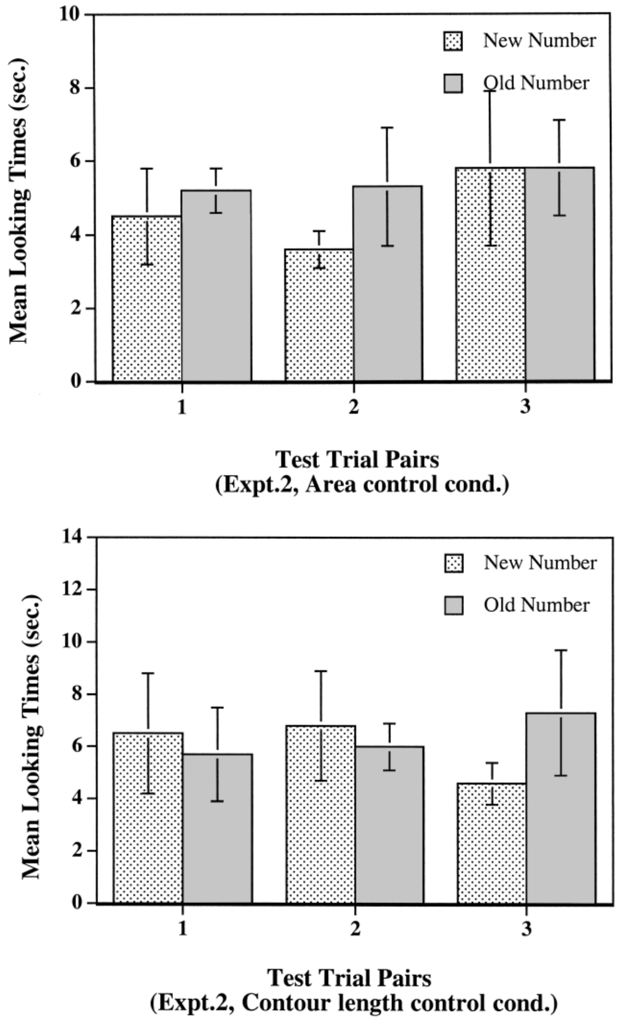

Fig. 3. (a,b) Mean looking times for Experiment 2.

that are either within or immediately outside the small number range (2 vs. 4 and 4 vs. 8), using the same ratio (1:2), the same type of stimuli (black discs on white background), the same procedure (habituation–dishabituation), and controlling for both total filled area and total contour length. Infants successfully discriminated between 4 and 8 elements but failed to discriminate between 2 and 4 elements. These results extend previous findings on number discrimination, suggesting that infants discriminate large numbers robustly, under conditions that control for total filled area, contour length, display size, element size, element density, and correlated perceptual variables such as surface brightness, contrast, and texture (Brannon, 2002; Lipton & Spelke, in press; Xu & Spelke, 2000; Xu et al., 2003).[1] In contrast, no evidence for small number discrimination was found, either with total filled area control or contour length control, consistent with earlier studies (e.g. Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002; Xu et al., 2003). These experiments provide the first direct comparison between infants' discrimination of large and small numerosities.

Collectively, current and previous studies provide evidence that 6-month-old infants fail to discriminate between small numerosities, 1 vs. 2 and 2 vs. 4, but they succeed in discriminating large numerosities, 4 vs. 8, 8 vs. 16, and 16 vs. 32, when the ratio between the two numbers is held constant. These results are consistent with the hypothesis that two systems of representations are present early in infancy. One is an object-tracking system, and its signature property is the set size limit of 3 or 4 in adults and infants; the other is a number estimation system, and its signature property is the Weber fraction, i.e. the system accords with Weber's Law – successful discrimination is determined by the ratio between two numbers, not the absolute difference.

What exactly is the set size limit for the object-tracking system? Why is it the case that 4 is discriminated successfully when paired with 8 but not when paired with 2? One possibility is that the set size limit is 3, therefore 4 lies outside of it. The 2 vs. 4 experiment therefore engages both systems, the object-tracking system for 2 elements and the number estimation system for 4 elements. The object-tracking system keeps track of 2 individual elements but it fails to register the constant cardinal value of the set, namely 2, across displays. The number estimation system correctly estimates the larger array as a set of about 4 elements. These two representations, however, are difficult to compare with each other. Another possibility is that 4 can be processed by either system. The object-tracking system represents each array as either "one object, another object" or "one object, another object, another object, and yet another object", but it fails to register the cardinal value of either set, resulting in a failure to discriminate 2 from 4 elements. The approximate number system represents the arrays of 4 discs as a set with approximately 4 elements and those of 8 discs as a set with approximately 8 elements, resulting in a success in discriminating 4 from 8 elements.

Why are small numbers processed differently from large numbers? We raise two possibilities. The first possibility is that the number estimation system may fail to operate on small numbers because its computations are unstable or undefined for small values. It has been suggested that the number estimation system in human adults and non-human animals works as follows: it estimates numerosities by assessing the area covered by an array of elements and the average inter-item distance of those elements and then dividing

[1] Clearfield and Mix (1999) and Feigenson, Carey, and Spelke (2002) found that when numerosity is pitted against contour length or total spatial extent, infants discriminated the test displays on the basis of contour length or spatial extent. In the current experiments, when total filled area was controlled for, contour length co-varied with numerosity, and vice versa. Then why didn't we find evidence of dishabituation to contour length or area? One possibility is that successful discrimination of contour length or area also requires a fairly large ratio. The Clearfield and Mix (1999) study contrasted a 2:3 ratio in contour length, and Arriaga (personal communication) reanalyzed their and Feigenson et al.'s data to show that success depended on a 1:2 ratio in area. The current experiments did not provide a consistent ratio in these continuous variables. Under these circumstances, numerosity discrimination turned out to be robust with 4 vs. 8 elements but not 2 vs. 4 elements.

the first value by the second (e.g. Church & Broadbent, 1990). However, it is not possible to estimate the inter-item distance for 1 element, and it is difficult to compute area for arrays with less than 3 elements. The number estimation system therefore may be used only for large numbers. The second possibility is that perhaps the output of the object-tracking system inhibits the output of the number estimation system. On this view, both the number estimation system and the object-tracking system operate on small numbers, but the object-tracking system wins out; thus, when presented with small numbers of items, infants keep track of individual objects and fail to register the cardinal value of the set. Further research is needed to decide between these possibilities.

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