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Brief article

Large number discrimination in 6-month-old infants

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Abstract

Six-month-old infants discriminate between large sets of objects on the basis of numerosity when other extraneous variables are controlled, provided that the sets to be discriminated differ by a large ratio (8 vs. 16 but not 8 vs. 12). The capacities to represent approximate numerosity found in adult animals and humans evidently develop in human infants prior to language and symbolic counting.

Keywords: Number discrimination; Infants

1. Introduction

Key questions in cognitive science concern the nature and origins of knowledge of number. Does a domain-specific mechanism – a core ''number sense'' (Dehaene, 1997) – account for our uniquely human talent for formal mathematics? If so, how does this mechanism emerge over phylogeny and human ontogeny? The present research focuses directly on the second question, and indirectly on the first, by investigating in human infants an ability that is much studied in other animals: the ability to represent large, approximate numerosities.

Many animals, including humans, represent the approximate numerosity of large sets of things or events (for reviews see Dehaene, 1997; Gallistel, 1990). Number discrimination depends on the ratio that distinguishes the two set sizes, in accord with Weber's Law, both for animals (e.g. Mechner, 1958) and for humans tested

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under conditions that discourage verbal counting (e.g. Whalen, Gallistel & Gelman, 1999). Even when mathematically sophisticated adults are given problems involving numbers presented in words or Arabic notation, their performance suggests the existence and use of a representation of approximate numerosity (for discussion see Dehaene, 1997). These findings suggest a common mechanism for representing approximate numerosity in animals and humans. How does this mechanism develop in humans?

Two lines of research provide evidence that children come to represent number well before the onset of verbal counting. First, infants discriminate between sets of 2 vs. 3 entities at many ages, including newborns, and with a variety of displays including visual dot displays, displays of objects with varying properties, positions, or motions, and sequences of actions or speech sounds (Antell & Keating, 1983; Bijeljac-Babic, Bertoncini & Mehler, 1993; Starkey & Cooper, 1980; Starkey, Spelke & Gelman, 1990; Strauss & Curtis, 1981; Treiber & Wilcox, 1984; van Loosbroek & Smitsman, 1990; Wynn, 1996). Second, infants represent that a single object added to a second occluded object results in two objects rather than one or three, and that a single object removed from an occluded two-object display leaves one object rather than two (Wynn, 1992b). Sensitivity to the effects of such additions and subtractions has been shown at various ages and with various objects in set sizes up to three (e.g. Baillargeon, Miller & Constantine, 1996; Koechlin, Dehaene & Mehler, 1998; Leslie, 1999; Simon, Hespos & Rochat, 1995; Uller, Carey, Huntley-Fenner & Klatt, 1999).

In contrast to the elegant studies of number representations in other animals, however, the above studies have been criticized for failing to control adequately for perceptual features of the displays that tend to covary with numerosity: differences in contour, coloring, brightness, amount of stuff, and either the element density or the total surface area of the display. The few studies that have controlled strictly for some of these variables have found no evidence that infants respond to the numerosities of small sets of objects (Clearfield & Mix, 1999; Feigenson, Spelke & Carey, 1998). Although such negative findings do not show that infants are incapable of forming numerical representations, they suggest that sensitivity to continuous variables contributed to infants' performance in many experiments designed to assess sensitivity to number.

In light of these findings, the best evidence for number discrimination comes from two sources. First, experiments using the addition paradigm have compared infants' abilities to add discrete numbers of objects to their ability to add continuous quantities such as piles of sand (Huntley-Fenner & Carey, 1998) or blocks (Wynn & Chiang, 1998). Although infants successfully added solid objects with the shape, color, and texture of sand piles or block constructions, they failed to add true piles, even though the objects and piles presented the same addition problem from the standpoint of continuous quantities and correlated perceptual variables. Second, experiments using the number-discrimination paradigm have compared infants' discrimination of two from three dots to their discrimination of four from six dots of constant size (Starkey & Cooper, 1980). Although infants successfully discriminated between the smaller set sizes, they failed to discriminate between the larger set sizes, even though both discrimination tasks presented the same correlated perceptual variables differing by the same ratio. Starkey and Cooper argued that these findings provided evidence for a ''subitizing'' mechanism limited to set sizes of three or less. This argument, however, raises new problems. Most investigators who grant numerical representations to infants have proposed that infants possess the same sense of approximate number as do other animals and human adults (Gallistel & Gelman, 1992; Wynn, 1995, 1996, 1998). In animals and adult humans, however, discriminability of numerosity is proportional to set size, in accord with Weber's Law: if sets of 2 vs. 3 elements are discriminable, therefore, sets of 4 vs. 6 elements should be discriminable as well.

Faced with this problem, a number of investigators have proposed that infants' discrimination between small sets of objects does not reflect the operation of a process for representing approximate numerosity, but rather a process for keeping track of visible objects. Under many conditions, adults can attend to three or four objects simultaneously (Kahneman, Treisman & Gibbs, 1992; Pylyshyn, 1990; Scholl & Pylyshyn, 1999; Trick & Pylyshyn, 1994), and the mechanisms by which they do so have been proposed to account for the findings of the above experiments with infants (Huttenlocher, Jordan & Levine, 1994; Leslie, Xu, Tremoulet & Scholl, 1998; Simon, 1997; Simon et al., 1995; Uller et al., 1999). On these views, infants represent objects but not sets with cardinal values. Their ability to discriminate displays of 1 vs. 2 objects therefore does not depend on representations of sets with specific numerosities but rather on representations of ''an object'' and ''an object and another object''. Such accounts provide a natural explanation for many findings: infants fail to discriminate four from six dots because these numerosities exceed the capacity of their object representations, and they fail to enumerate and add piles of stuff, because piles fail to meet the conditions on infants' object representations (Spelke & Van de Walle, 1993). On the other hand, object-based attention theories cannot easily explain infants' ability to discriminate two from three actions, tones, or speech syllables (Bijeljac-Babic et al., 1993; Wynn, 1996).

The present studies attempted to test directly whether infants represent approximate numerosities. To ensure that apparent responses to number could not depend on continuous perceptual variables, our experiments controlled for the latter variables as rigorously as in research with other animals. To ensure that such responses could not depend on mechanisms of object-based attention, our experiments tested for discrimination between numerosities that are too large to be handled by any mechanisms of object-based attention. Experiment 1 tested infants' discrimination of 8 vs. 16 elements, and Experiment 2 tested infants' discrimination of 8 vs. 12 elements.

2. Experiment 1

Experiment 1 investigated whether 6-month-old infants can discriminate between displays of 8 vs. 16 dots that varied in size and position, under conditions that controlled for average brightness, contour length, display density, element size, and display size.

2.1. Method

2.1.1. Participants

Eight male and eight female full-term infants participated in the study (mean age 6 months and 4 days; range 5 months and 20 days to 6 months and 15 days). Five additional infants were excluded from the sample because of fussiness or parental interference.

2.1.2. Apparatus

Infants sat in a reclining seat facing a puppet stage surrounded by black curtains and illuminated from above in an otherwise dark room. A curtain opened to reveal each display (described below), which appeared on a navy blue 74×30 cm rectangular display board that served as the background, 60 cm from the infant. A microcamera monitoring the infant and a second camera monitoring the display were mixed onto a TV monitor and VCR. An observer blind to the habituation condition and test order recorded the infant's looking times by viewing the monitor with the display occluded. Parents sat next to their infant facing away from the displays. They were instructed to remain neutral and not to elicit the infant's attention.

2.1.3. Design

Equal numbers of male and female infants were habituated to displays with 8 vs. 16 elements. Following habituation, infants were presented with six test trials in which displays with eight elements and displays with 16 elements were shown alternately, in an orthogonally counterbalanced order.

2.1.4. Stimuli

Displays consisted of solid round black dots printed on white paper (Fig. 1). Each set of six habituation displays consisted of 8 or 16 dots that varied in size and position across trials within an 18×19 cm display. The less numerous displays therefore had half the element density (0.023 vs. 0.046 element/cm^2). The dot positions varied across displays and were chosen randomly from a matrix; displays that looked too cluttered were discarded. Over the habituation trials, the average surface area of an individual element was twice as large for the 8-element displays (mean dot diameter 1.83 cm, range 1.06–2.37 cm) as for the 16-element displays (mean 1.30 cm, range 0.75–1.67 cm), and so the average size of all the elements in a display combined, the average brightness of those elements, and the average contour length of those elements were equated.

For the test displays, element density was equated and equidistant from the habituation densities (0.035 dots/cm^2), display height was equated (19 cm), and therefore the 16-element displays were twice as wide as the 8-element displays (24 vs. 12 cm). Moreover, the sizes of individual elements were equated (1.5 cm in diameter), and therefore the total size, average brightness, and average amount of

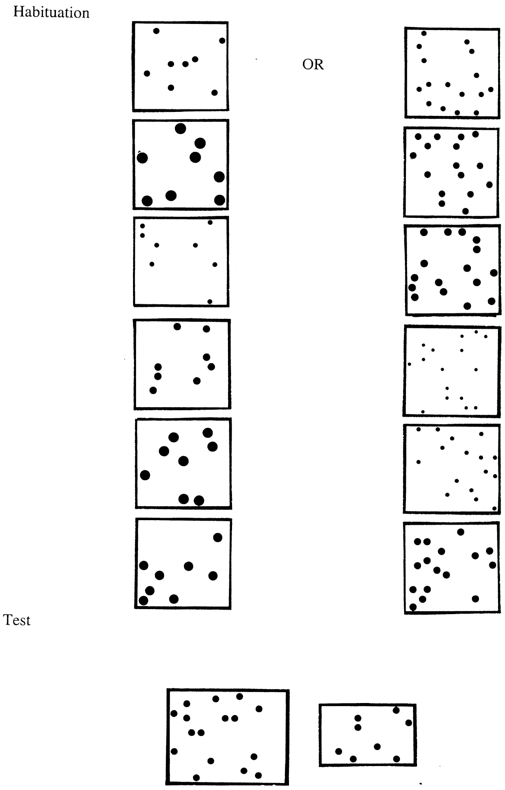

Fig. 1. Schematic representation of the habituation and test displays of Experiment 1.

contour in the 16-element displays were twice those of the 8-element displays. Thus, the continuous variables that varied across the two habituation conditions were equated across the test displays, and vice versa.

2.1.5. Procedure

Each infant viewed one habituation display on each trial, which began with the first 0.5-s look at the display and ended with the first 2-s look away. Over trials, the infant viewed all the habituation displays depicting one numerosity in a random repeating order until she met the habituation criterion (a 50% decline in looking time over three consecutive trials, relative to the first three trials that summed to at least 12 s) or until 14 trials were given. After habituation, infants were shown the six test displays following the same procedure and alternating between the two numerosities.

2.2. Results

Fig. 2 presents the mean looking times during the six test trials. Infants looked

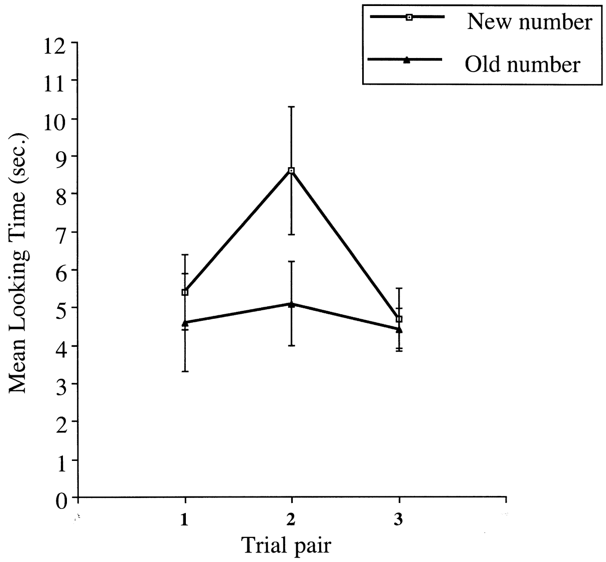

Fig. 2. Mean looking times for the test trials of Experiment 1.

longer at the novel numerosity than at the familiar numerosity. A $2 \times 2 \times 3$ analysis of variance examining the effects of habituation condition (8 or 16), test trial type (old or new number), and test trial pair on looking times revealed a main effect of test trial type, $F(1, 15) = 4.722$, $P < 0.05$, two-tailed. That is, infants (12 of the 16) looked longer at the displays with the new number of dots ($M = 6.2$ s, SD 5.1) than those with the old number ($M = 4.7$ s, SD 4.2). There was also a marginal main effect of trial pair ($P = 0.051$) because overall infants looked longer on the second pair of test trials than the other two. There was no other main effects or interactions.

2.3. Discussion

Infants distinguished between 8- and 16-element displays when continuous variables such as density of the elements and brightness of the displays were controlled. These results suggest that the ''limit of 3'' is not a true limit on infant's numerical competence, provided that the ratio difference between two numerosities is sufficiently large.

3. Experiment 2

Experiment 2 investigated whether 6-month-old infants discriminate between large numerosities when the discrimination ratio is reduced to 1:3: a ratio that often yields success when infants are presented with small numbers (2 vs. 3) but that once led to failure with larger numbers (4 vs. 6: Starkey & Cooper, 1980).

Infants were presented with displays of 8 and 12 elements, using the procedure and stimulus controls of Experiment 1.

3.1. Method

The method was the same as in Experiment 1, except as follows.

3.1.1. Participants

Sixteen infants participated in the study (mean age 6 months and 0 days; range 5 months and 17 days to 6 months and 15 days). Six additional infants were excluded due to fussiness, or interference.

3.1.2. Stimuli

Each habituation display measured 20×19 cm. The mean dot size was 2.24 cm in diameter (range 1.41–2.82 cm) for the 8-dot displays and 1.82 cm (range 1.14–2.44 cm) for the 12-dot displays. Element densities in the 8- and 12-dot displays were 0.021 and 0.031 element/cm^2, respectively. The test displays had the same dimensions as in Experiment 1 except for width (16 and 24 cm, respectively, for the 8- and 12-dot displays). The dots were 2 cm in diameter and their density was 0.026 element/cm^2 for all test displays. These values differed equally from those of the 8-dot and 12-dot habituation displays, as in Experiment 1.

3.2. Results

After habituating to 8- or 12-element displays, infants looked about equally at displays with the familiar vs. novel numerosity (Fig. 3). There were no significant effects in the analysis, including no main effect of test numerosity, $F(1, 15) < 1$.

3.3. Discussion

Experiment 2 provided no evidence that infants discriminated between large numerosities when the difference between the two numerosities was reduced. This finding is consistent with those of Starkey and Cooper (1980), in which infants failed to discriminate four from six elements: sets that differ by the same ratio as in the present study. Together with Experiment 1, it suggests that infants can discriminate between large sets of differing numerosity only when the ratio of difference between the sets is large.

4. General discussion

The present experiments provide evidence that a sense of number exists in human infants by 6 months of age, at least in crude form. Infants discriminated between displays that differed in numerosity, under conditions in which discrimination could not be based on the detection of perceptual variables such as the amount of contour, average brightness, element density, or display size. Moreover, infants discriminated between sets that were too large to be represented by object-based attentional

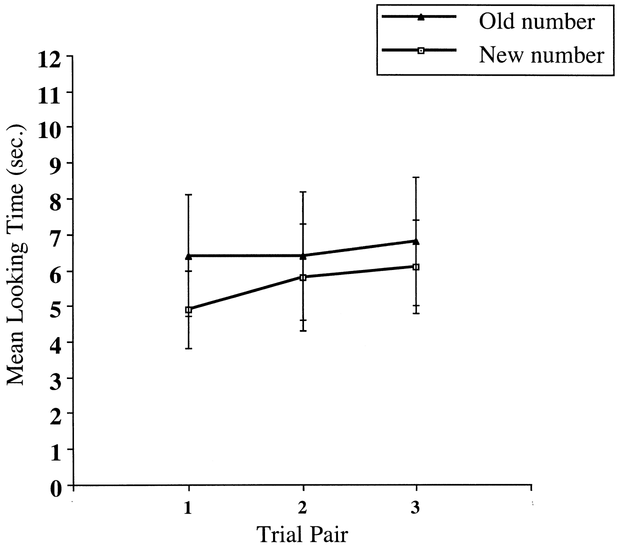

Fig. 3. Mean looking times for the test trials of Experiment 2.

mechanisms. We conclude that true representations of number, rather than representations of continuous quantities or capacity-limited mechanisms of object-based attention, underlie infants' responses.

Our findings complement those of a recent experiment by Wynn and Bloom (1999) on infants' enumeration of collections. In their research, infants were presented with multiple, commonly moving groups of separated elements. Infants were habituated either to two groups of three elements or to four groups of three elements, and then all the infants were tested with two groups of four elements and with four groups of two elements. Because the two test displays presented the same total number of objects (eight), this experiment controlled for a variety of correlated perceptual variables; because all the displays presented groups of spatially separated objects rather than single cohesive bodies, moreover, the experiment tested for number discrimination under conditions that may not be appropriate for the operation of mechanisms of object representation. As in our research, infants successfully discriminated the two-group displays from the four-group displays. This experiment, like the present studies, provides evidence for true sensitivity to numerical differences in a 1:2 ratio. Infants evidently are sensitive to numerical differences in this ratio with small set sizes as well as large ones.

Because 6-month-old infants lack experience with verbal counting or formal arithmetic, our findings are consistent with the thesis that the number sense develops spontaneously in humans, as it does in other animals. Because large number discrimination is achieved only when the difference between the sets to be discriminated is large, our findings also are consistent with the thesis that the number representations found in human infants depend on a mechanism for representing approximate but not exact numerosity, as do the mechanisms found in other animals and one of the mechanisms found in human adults (e.g. Dehaene, 1997; Meck & Church, 1983; Whalen et al., 1999). Nevertheless, the evidence for a common mechanism in human infants, human adults, and non-human vertebrates continues to be indirect and needs to be studied further, perhaps through experiments using the newer methods of cognitive neuroscience.

Our findings raise two questions. First, why did infants respond to number in the present study, with its controls for correlated continuous variables, when they failed to respond to number in past experiments controlling for a subset of those variables (Clearfield & Mix, 1999; Feigenson et al., 1998)? Second, why did number discrimination require a 1:2 difference ratio in the present studies, when previous research with small numbers of objects has shown successful discrimination of 2 vs. 3 objects (Strauss & Curtis, 1981; Starkey et al., 1990), dots (Antell & Keating, 1983; Starkey & Cooper, 1980), syllables (Bijeljac-Babic et al., 1993), and jumps (Wynn, 1996)? It is unlikely that the different discriminability ratio observed in tests with small vs. large numerosities stems from differences in the displays or methods, because Starkey and Cooper (1980) found the same difference when they tested infants with small and larger sets under very similar conditions.

Although the answers to both questions await further research, we close with a speculation. When infants are presented with small numbers of objects, events, or sounds, they may attempt to keep track of each individual through mechanisms of object-based attention or other, similar devices. In these cases, infants represent each display as a collection of individual entities with distinct properties rather than as a set with a distinctive cardinality. Infants' predisposition to represent small numbers of objects or events as individuals rather than as a set may account for their preferential response to continuous perceptual variables in studies of small number discrimination: such variables characterize individual objects whereas numerosity characterizes the set but not its individual members.

When infants are presented with large numbers of objects, in contrast, their mechanisms for keeping track of distinct individuals are overwhelmed. Under these conditions, infants may focus attention not on the individuals but on the collection, apprehending properties such as its global spatial distribution, density, and numerosity. Infants' predisposition to represent large numbers of elements as a set rather than as individuals may account for their successful response to number under conditions in which continuous perceptual variables are controlled. If sensitivity to numerosity requires a 1:2 difference ratio, whereas abilities to track individual objects and events can operate on as many as three entities simultaneously, then the existence of these two mechanisms would account for the departure of infants' discrimination performance from Weber's Law.

Our account makes two predictions. First, infants who are trained to respond to numerical relationships with large sets should transfer their discrimination to other large sets but not to sets that are small enough for their members to be tracked as individuals. Second, when children first begin counting, they should relate number words either to representations of individual objects (those involved in object-based attention) or to representations of large sets (those involved in approximate number discrimination), but not both. As children learn the meanings of the number words and the purpose of the counting routine, they may come to bring together these two types of representation to form a unitary, distinctly human, and language-dependent notion of discrete number. We believe this prediction receives some initial support from studies of children developing understanding of counting and quantifiers (Bloom & Wynn, 1997; Wynn, 1990, 1992a). If it is correct, it could explain why uniquely human number representations, centering on the property of discrete infinity, are tied to language (Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999).

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