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Brief article

Number bias for the discrimination of large visual sets in infancy

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Abstract

This brief report attempts to resolve the claim that infants preferentially attend to continuous variables over number [e.g. Psychol. Sci. 10 (1999) 408; Cognit. Psychol.44 (2002) 33] with the finding that when continuous variables are controlled, infants as young as 6-months of age discriminate large numerical values [e.g. Psychol. Sci. 14 (2003) 396; Cognition 89 (2003) B15; Cognition 74 (2000) B1]. In two parallel experiments, we compare 6-month-old infants' ability to discriminate number and ignore continuous variables with their ability to form a representation of a cumulative surface area and ignore number. We find that infants discriminate a 2-fold change in number but fail to discriminate a 2-fold change in cumulative surface area. The results point to a more complicated relationship between discrete and continuous dimensions than implied by previous literature.

Keywords: Numerosity; Number; Development; Infancy; Area; Numerical development

1. Introduction

A controversial question in developmental psychology is whether pre-verbal infants represent number. Number is an emergent property of a set of entities and is consequently an abstract and intangible concept. Two fish and two spoons look nothing alike and yet they share twoness. Over the past twenty years many reports have suggested that infants can discriminate small numerical values such as 2 versus 3 (e.g. Antell & Keating, 1983; Bijeljac-Babic, Bertoncini, & Mehler, 1991; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981). However these early findings have been criticized

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for failing to eliminate alternative stimulus cues such as cumulative surface area, density, or contour length (e.g. Clearfield & Mix, 1999; Feigenson, Spelke, & Carey, 2002) reopening the question of whether infants ever actually represent number.

Two recent findings inform this debate. On the one hand, there are studies showing that when surface area and other continuous dimensions are carefully controlled, infants fail to discriminate small numerosities (e.g. Feigenson et al., 2002; Xu, 2003) and that changes in continuous variables (e.g. surface area or contour length) are more salient to young infants than changes in number (Clearfield & Mix, 1999; Feigenson et al., 2002). For example, in the Clearfield and Mix study, 6-month-old infants were habituated to a series of stimuli that shared number and cumulative contour length and were then tested with number held constant and cumulative contour length changed or vice versa. Infants responded as if they only detected the change in contour length but not number (see also Feigenson et al., 2002 for a similar demonstration with cumulative area and number). Clearfield and Mix's (1999) results have been interpreted as evidence that young infants are not able to represent number and instead rely solely on continuous stimulus dimensions (e.g. Mix et al., 2002; Newcombe, 2002).

On the other hand there are studies showing that young infants can discriminate large numerosities when continuous dimensions are carefully controlled (Brannon, 2002; Lipton & Spelke, 2003; Xu, 2003; Xu & Spelke, 2000). For example, Xu and Spelke (2000) found that 6-month-old infants could discriminate 8 versus 16 but failed to discriminate 8 versus 12 when cumulative surface area, element size, and density were eliminated as potential cues.

There are two important distinctions between the Clearfield and Mix study and the Xu and Spelke study. First, Xu and Spelke neutralized continuous variables by varying cumulative surface area in habituation and holding number constant. In contrast, in the Clearfield and Mix study, infants were habituated to stimuli with both a constant area and a constant number and subsequently tested with stimuli with a new area and number held constant or with a new number and area held constant. Thus although Clearfield and Mix found that infants dishabitiated to changes in area and not number, this finding was not obtained in a situation that emphasized number as the relevant dimension (but see Feigenson et al., 2002). The second major difference between these two studies is that Clearfield and Mix tested infants' ability to represent small numerical values (2 and 3) whereas Xu and Spelke tested infants' ability to represent large numerical values (8 and 16). There is growing evidence that the conditions under which infants will attend to number differ dramatically for small and large numerosities (e.g. Xu, 2003; Feigenson, Dehaene, & Spelke, in press). One possibility then, is that when two small numerical arrays are contrasted, infants attend preferentially to area but when two large numerical arrays are contrasted infants attend preferentially to number. In agreement with this analysis, both Feigenson et al. (2002) and Xu (2003) found that infants also failed to dishabituate to numerical changes in small numerosities when surface area was controlled even when surface area and number were not pitted against each other.

Here we test an implication of the idea that infants attend preferentially to area over number, by asking whether infants can summate a continuous variable across a changing number of discrete entities. In Experiment 1 we replicate Xu and Spelke's finding that 6-month-old infants discriminate 8 versus 16 dots when surface area and density are carefully controlled. In Experiment 2 we test whether infants of the same age can form representations of a cumulative surface area over large changes in number. The experimental designs are exactly parallel—infants are habituated to a constant number with area varying or to a constant area with number varying. Our results indicate that 6-month-old infants detect a 2-fold change in number after being habituated to stimuli that vary 5-fold in surface area but fail to detect a 2-fold change in area after being habituated to stimuli that vary 5-fold in number. These findings suggest that infants were able to ignore large changes in area to represent large numerical values, but that they were unable to ignore large changes in number to attend to cumulative surface area. This finding runs counter to the claim that continuous dimensions are unilaterally easier to represent than number and suggests a more complicated relationship between discrete and continuous dimensions.

2. Experiment 1

2.1. Method

2.1.1. Participants

Participants were 16 healthy full-term 6-month-old infants (mean age, 5 months 27 days; range 5 months 19 days–6 months 15 days). Ten of the infants were male. Data from an additional 6 infants were discarded because of fussiness resulting in failure to complete at least 4 test trials or parental interference.

2.1.2. Design

Half of the infants were habituated to 8-element arrays and half to 16- element arrays. All infants were then tested with 8- and 16- element arrays in alternation. The order of test trials was counterbalanced.

2.1.3. Stimuli

Stimulus parameters were modeled after Xu and Spelke (2000). Stimuli were 8- or 16-element arrays of black circles presented in a white stimulus background displayed in the center of a computer monitor (see Fig. 1 for example stimuli). Six habituation stimuli were used for each condition (8 and 16). Cumulative surface area varied 5-fold across the 6 habituation exemplars in each condition; however, the average element size in the 8-element arrays (mean area = 2.54 cm^2, range from 0.88 to 4.4 cm^2) was double that of the 16-element arrays (mean area = 1.27 cm^2, range from 0.44 to 2.2 cm^2) so that average brightness and cumulative surface area of the 8-element and 16-element arrays were equated. The stimulus background was constant in size (18×19 cm^2); consequently, density of the 16-element arrays (0.047 elements per cm^2) was double that of the 8-element arrays (0.023 elements per cm^2).

In test, infants saw 3 novel exemplars of each numerosity. Exemplars of a given numerosity differed only in the configuration of the elements. Element size was held constant at 1.77 cm^2 (diameter 1.5 cm). This element size was chosen so that the cumulative surface area of the 8-element and 16-element test stimuli differed from the average cumulative surface area of the habituation stimuli by the same ratio. In addition,

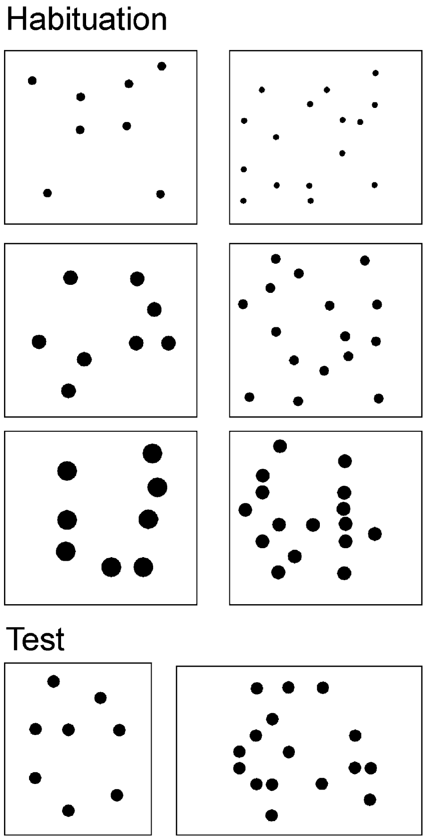

Fig. 1. Schematic representation of the visual stimuli used in Experiment 1.

element density of the test arrays was held constant at 0.037 elements/cm^2 by placing the 16-element test arrays within a stimulus background (18 × 24 cm^2) double the size of the 8-element test arrays (18 × 12 cm^2).

In sum, the continuous variables that varied between the 8- and 16- element arrays in habituation (density and element size) were equated in the 8- and 16- element test displays, whereas cumulative surface area which was held constant across the 8- and 16- element habituation arrays varied between the 8- and 16- element test arrays. This design insured that if infants were to look longer at the novel compared with the familiar number test displays, this could not be attributed to the encoding of area, element size, or density.

2.1.4. Apparatus

Infants were seated in a high-chair 60-cm from a computer monitor resting on a stage surrounded by blue fabric. Parents were seated next to their infants and instructed to keep their eyes closed and refrain from talking to, touching, or otherwise interacting with their infant for the duration of the experiment. If an infant became fussy, the experimenter initiated a short break and then resumed the experiment. For an infant to remain in the final sample the break must have been less than 1 min in duration and could not occur between a pair of test trials.

A microcamera monitoring the infant's face and a feed directly from the stimulus presentation computer were multiplexed onto a TV monitor and VCR. One or two experienced experimenters blind to the experimental condition recorded the infants' looking behavior while viewing the live video with the display occluded. In the event that only one observer was available at the time of the experiment, data were coded from videotape at a later date. Looking behavior was recorded by holding a button down when the infant was looking at the computer monitor and letting go when the infant looked away. The button input was fed into a Visual Basic program, which signaled the Experimenter when to end a trial and when to move on to the test phase. The Visual Basic program recorded infants as looking or not looking for each 100 ms interval and calculated inter-observer reliability. Reliability between the 2 observers who coded the data live or from videotape (as conservatively computed based on agreement or disagreement at each 100 ms interval) was 93% on average.

2.1.5. Procedure

Informed consent was obtained from a parent of each participant before testing. Trials were initiated by the Experimenter when the infant looked in the direction of the computer monitor. Each trial continued until the infant looked for a minimum of 0.5 s and ended after the infant looked away for a continuous 2 s or a maximum of 15 s. The 6 different habituation stimuli were presented in a repeating random order until the infant met the habituation criterion (a 50% reduction in looking time over 3 consecutive trials, relative to the first 3 trials that summed to at least 12 s) or until 14 trials were completed. After habituation, the infants were tested with 6 test trials according to the same procedure and alternating between novel and familiar (counterbalanced for order).

3. Results and discussion

Fig. 2 shows the mean looking time for the first 3 and last 3 habituation trials, the 3 novel test trials and the 3 familiar test trials. In test, infants looked longer at the novel ($M = 7.3$) than the familiar test trials ($M = 5.6$). A $2 \times 2 \times 2$ mixed-factor analysis of variance (ANOVA) testing the between subject factors of habituation condition (8 or 16) and test trial order (novel or familiar first) and the within subject-factor of test trial type (novel or familiar) on infants' looking time revealed a main effect of test trial type ($F(1, 12) = 12.9$, $P < 0.01$) and no other significant main effects or interactions. Thirteen of the 16 babies looked longer at the novel compared to the familiar test trials (binomial test, $P = 0.5$, $P < 0.05$).

Infants looked significantly longer at the first 3 compared to the last 3 habituation trials ($t(15)3.0$, $P < 0.01$) and 10 out of 16 babies reached the habituation criterion before test. Although a t-test comparing the average looking time to the novel test trials with the last 3 habituation trials did not reach significance ($t(15) = -2.08$, $P = 0.05$), 12 out of 16 babies looked longer at the novel test trials compared to the last 3 habituation trials whereas only 7 out of 16 infants looked longer at the familiar test trials compared to the average of

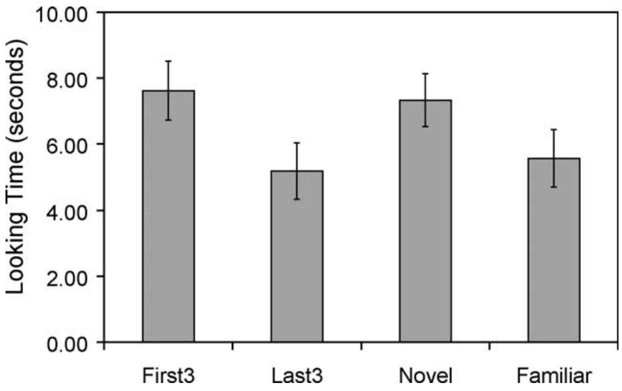

Fig. 2. Average looking time for infants in Experiment 1 for the first 3 and last 3 habituation trials and for the novel and familiar test trials.

the last 3 habituation trials. The main finding that infants looked longer at the novel compared with the familiar numerosity was true both for the 6 infants who did not habituate ($t(5) = 2.95$, $P < 0.04$) and the 10 infants ($t(9) = 2.6$, $P < 0.03$) who did habituate.

These findings replicate the results of Xu and Spelke (2000) and demonstrate that infants as young as 6 months of age discriminate 8 versus 16 when surface area and density are eliminated as potential cues.

4. Experiment 2

Experiment 1 demonstrated that when surface area varied, infants formed a numerical representation of 8 or 16. Experiment 2 tests the reverse question. If infants are habituated to stimuli with a constant area but variable in number will they form a representation based on area? To do this would require summating a continuous variable across a changing number of discrete entities. The design and stimulus parameters of Experiment 2 exactly mirrored the parameters of Experiment 1; however the roles of number and cumulative area were reversed.

4.1. Method

4.1.1. Participants

Participants were 16 healthy full-term 6-month-old infants (mean age, 5 months 26 days; range 5 months 14 days–6 months 12 days). Nine of the infants were male. Data from an additional 7 infants were discarded because of fussiness resulting in failure to complete at least 4 test trials or parental interference.

4.1.2. Design

The design of the experiment was exactly parallel to Experiment 1 except that area was held constant in habituation and number was varied rather than the reverse. Half of the infants were randomly assigned to the Small Area Condition and the other half to the Large Area Condition. All infants were then tested with small and large area arrays in alternation. The order of test trials was counterbalanced.

4.1.3. Stimuli

The stimuli were constructed according to the same logic as Experiment 1 except that number varied in habituation and cumulative surface area was held constant. Infants were habituated to small area arrays (cumulative surface area = 21.6 cm^2) or large area arrays (cumulative surface area = 43.2 cm^2). Habituation exemplars varied 5-fold in number (range 3–15; average 9) to match the 5-fold variation in cumulative surface area in Experiment 1. Six small area and 6 large area stimuli were used in habituation. Stimulus background was 18 × 19 for all stimuli so that density was variable across exemplars within a condition but on average exactly equal between the small and large area conditions.

In test, infants saw 3 novel exemplars of each area. Exemplars of a given area differed only in the configuration of the elements. Element size was held constant at 3.66 cm^2. The small area stimuli contained 6 elements and the large area stimuli contained 12 elements so that the 12-element stimuli had double the cumulative surface area compared

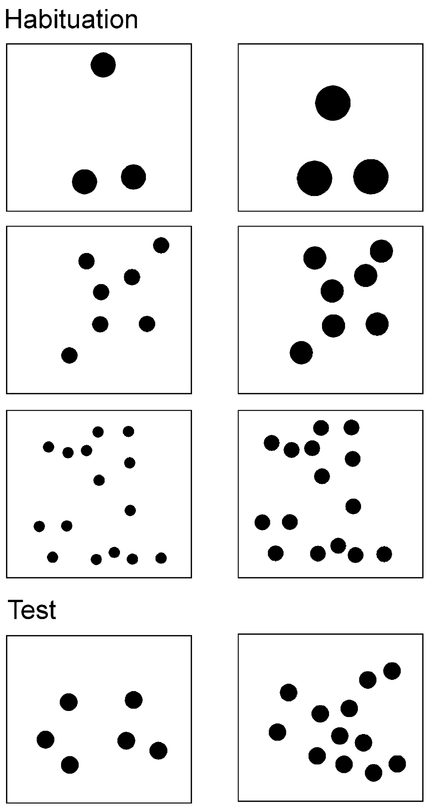

Fig. 3. Schematic representation of the visual stimuli used in Experiment 2.

to the 6-element stimuli. The numerical test values chosen (6 and 12) differed equally from the average number of elements in habituation (9). Fig. 3 shows example stimuli.

In sum, element size varied between the small and large area arrays in habituation but was equated in the test displays, whereas density and number were equated for small and large habituation displays but varied in the test displays. This design insured that if infants were to look longer at the novel compared with the familiar area test displays this could not be attributed to the encoding of number, element size, or density.

4.1.4. Apparatus and procedure

The apparatus and procedure were identical to Experiment 1.

5. Results and discussion

Fig. 4 shows the mean looking time for the first 3 and last 3 habituation trials, the 3 novel test trials and the 3 familiar test trials. Infants did not look differentially at novel ($M = 5.4$ s) and familiar test trials ($M = 5.1$ s). A $2 \times 2 \times 2$ mixed-factor ANOVA testing the between subject factors of habituation condition (small or large) and test trial order (novel or familiar first) and the within subject-factor of test trial type (novel or familiar) on infants' looking time revealed no significant main effects or interactions. Nine of the 16 babies looked longer at the novel compared to the familiar test trials (binomial test, $P = 0.5$, $P > 0.10$).

Infants looked significantly longer at the first 3 compared to the last 3 habituation trials ($t(15)4.3$, $P < 0.01$) and 10 out of 16 babies reached the habituation criterion before test. There was no dishabituation effect for novel or familiar test trials. *T*-tests comparing the average looking time to the last 3 habituation trials with looking time to the novel and familiar test trials revealed no significant effects ($P > 0.05$). The main finding that infants did not look longer at the novel compared with the familiar area was true both for the 6

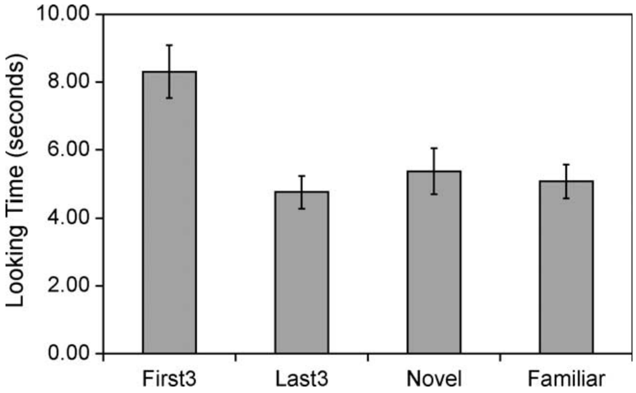

Fig. 4. Average looking time for infants in Experiment 2 for the first 3 and last 3 habituation trials and for the novel and familiar test trials.

infants who did not habituate ($t(5) = 1.48$, $P > 0.2$) and the 10 infants ($t(9) = -0.62$, $P > 0.5$) who did habituate.

These findings suggest that 6-month-old infants do not form a representation of a given surface area when it requires summating area over variable numbers of discrete elements and ignoring large changes in number.

6. General discussion

The results described above juxtapose the finding that 6-month-old infants can discriminate 8 versus 16 elements but fail to discriminate a similar 2-fold change in surface area. In a follow-up study not presented here we have replicated this failure to detect a 2-fold change in area in a group of sixteen 8-month-old infants. One explanation for why both 6- and 8-month-old infants failed to detect the 2-fold change in area is that they were unable to sum area across discrete entities. A second possibility is that continuous variables are not salient to infants when number varies widely (e.g. 3–15). Either way, these findings suggest that whereas infants are adept at ignoring variations in continuous variables and attending to consistencies in number, they do not as easily attend to consistencies in cumulative surface area over large changes in number. Although results by Clearfield and Mix (1999) and Feigenson et al. (2002) present a clear case that infants are sensitive to the continuous dimensions of small arrays, the present results temper their conclusions. This report demonstrates that with large arrays, infants have difficulty attending to continuous variables that require summating across discrete entities. Thus the assumption that continuous variables are primary for the human infant is not as unshakeable as it may have previously appeared.

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