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What Do Infants Know about Continuous Quantity?

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We investigated infants' sensitivity to amount of continuous quantity and to change in amount of continuous quantity. Using a habituation procedure, Experiment 1 examined whether 6-month-old infants can distinguish between different amounts of liquid in a container. Infants looked significantly longer at a novel quantity than at the familiar quantity. Using a violation-of-expectation paradigm, Experiment 2 examined whether 9-month-old infants expect a change in amount when liquid is added to a hidden container which is already one-fourth full of liquid. Infants looked significantly longer at the impossible event than at the possible event. These findings indicate that infants are sensitive to amount, calling into question claims that infants have a quantitative mechanism which is exclusive to number.

Key Words: infants' discrimination; quantity; number; calculation; mathematics.

There has been extensive research on infants' sensitivity to discrete number. Studies using the habituation method have shown that 4- to 5-month-old infants reliably distinguish between small numbers of objects (Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981; van Loosbroek & Smitsman, 1990). These experiments have shown that infants' looking times decreased after they were presented with several displays of the same small number of items (usually one to three) and their looking times increased when a display with a novel number of items was shown. The same result was found when the arrays were varied to control for differences in brightness, density, and homogeneity of items (Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981).

In a more recent study, Wynn (1992a) tested 5-month-old infants' sensitivity to change in number using a violation-of-expectation paradigm, in which infants' looking times at expected outcomes were compared to their looking times at unexpected outcomes (Baillargeon, Spelke, & Wasserman, 1985). In Wynn's study, infants were first presented with a Mickey Mouse doll sitting on a stage. A screen was rotated up to cover the doll. The experimenter's hand then appeared from one side of the stage, adding another identical doll behind the screen. The

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screen was then rotated down to reveal either one or two dolls. Wynn found that infants looked significantly longer at the impossible outcome (one doll) than at the possible outcome (two dolls). A similar pattern of longer looking time at the impossible outcome was found with a subtraction sequence as well. Wynn interpreted these findings as demonstrating that infants not only are able to enumerate small numbers of entities precisely, but also are able to carry out simple arithmetic computations precisely. Such findings led Wynn (1998) to propose that “there exists a mental mechanism, dedicated to representing and reasoning about number, that comprises part of the inherent structure of the human mind” (p. 297).

Whereas Wynn believes that infants form exact representations of the number of entities in a set and changes in set size after addition and subtraction, this view may be premature. First, the existing findings on infants’ early sensitivity could be explained by an approximate representation rather than an exact representation, as Huttenlocher, Jordan, and Levine (1994) have pointed out. Second, in contrast to numerous studies on infants’ sensitivity to number, few systematic studies have been done to investigate whether infants are sensitive to continuous quantity.

In one study that addressed this issue, Wynn (1993) reported that 9-month-olds did not appear to expect any change after seeing liquid added to a nonempty container. In Wynn’s experiment, infants were first shown a small cup with a little liquid in it. After hiding the cup behind a screen, the experimenter poured some liquid from a large pitcher into the hidden cup. The experimenter then removed the screen to reveal either a cup with the unchanged amount of liquid or a cup with more liquid. Wynn found that infants looked equally long at the impossible and possible outcomes. In Wynn’s experiment, however, two containers of different size and shape were used (a glass and a pitcher), which might have made it more difficult for infants to approximate the change in amount.

In the two experiments reported here, we investigated infants’ early sensitivity to continuous quantity using identical pouring and outcome containers. In the first, we used a habituation procedure to examine whether infants distinguish between different amounts of continuous substance. In the second, we used a violation-of-expectation paradigm to examine whether infants expect a change in continuous quantity when an additional amount is added to an initial amount.

EXPERIMENT 1

The habituation procedure used by previous researchers to investigate infants’ sensitivity to number of discrete entities (Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981; van Loosbroek & Smitsman, 1990) was used here to investigate infants’ sensitivity to continuous quantity. Specifically, we examined whether infants would detect a novel amount of liquid after being familiarized with a different amount. We expected that they would be able to do so given that studies on infant size constancy have shown that even 4-month-old infants dishabituate to a simple geometric object that differs in size, located at the same distance from the infant as the original object, as well as to an object of different size when the retinal sizes of the habituation and dishabituation objects are equalized by placing them at different distances from the infant (Granrud, 1986; Slater, Mattock, & Brown, 1990). Although these studies show that infants can discriminate simple objects of different size, it is not known whether they can discriminate different amounts of liquid in partially full containers of the same size. Experiment 1 addressed this question.

Method

Participants

Twenty middle-class, healthy, full-term infants (10 males and 10 females) participated in the experiment, recruited by mailed advertisements. Included were 14 Caucasian and 6 African American infants ranging from 6 months 2 days to 7 months 6 days (mean = 6 months 22 days). Nine additional infants cried during the testing or failed to reach the habituation criteria and thus their data were excluded from the analyses.

Stimuli and Procedure

The visual displays included two identical clear plastic containers ($6 \times 5 \times 5$ in., in height, width, and depth, respectively) one one-fourth and the other three-fourths full of bright red liquid.

Infants were tested in a single session lasting approximately 15 min. Testing took place in an enclosed area consisting of a stage constructed of plywood painted black with a black drape opening. During the test session, the room was dark with the exception of one light mounted above the stage. The parent sat on a chair facing the stage, and held the infant on his/her lap. The infant was situated approximately 2.5 feet from the front panel of the stage. Parents wore a blindfold during the testing and were asked not to interact with their babies. Each session consisted of three phases.

Familiarization with screen movement. Each infant was first presented with six familiarization trials designed to acquaint the infant with the screen movement used on habituation and test trials to occlude and reveal a container of liquid. Since the room was kept dark, infants often spontaneously looked at the lighted stage. Once the infant fixated on the stage, the observer signaled the experimenter to start a trial. Each trial began with an empty stage, followed by a screen rotating up to cover the stage. A few seconds later, the experimenter rang a bell and rotated the screen down to reveal the empty stage again. The stage remained in view until the infant looked away for 2 consecutive seconds, after which the screen rotated up once again.

Habituation trials. Each habituation trial began with the screen covering the stage. Then the experimenter rang a bell and rotated the screen down to reveal the container and liquid on the center of the stage. The container was placed approximately at the infant's eye level, with one rectangular side (6×5 in.) face toward the infant. Although the parent was asked to try to hold the infant still, nearly all infants moved their bodies and heads during the experiment. Therefore, it was likely that infants had the opportunity to see the container as a three-dimensional cube-shaped object. Half of the infants were habituated to the one-fourth full container and the other half to the three-fourths full container. Infants were given unlimited time to look at the display, with looking time recorded by an observer viewing the infant through a peephole under the center of the stage. The observer, who had no knowledge of which container was on display, pressed the shift key on a computer keyboard whenever the infant looked at the display and released the key whenever the infant looked away. As soon as the infant had looked away for 2 consecutive seconds, the computer signaled the observer, who in turn signaled the experimenter to pull up the screen. This ended a habituation trial. The infant's looking during habituation and test trials was a summation of all fixations at the display during the course of the trial.

Trials continued until an infant's average fixation time on three consecutive trials was less than 50% of the average fixation time on the first three trials. All 20 infants included in this study reached this habituation criterion.

Test trials. The computer generated a beep when infants reached the habituation criteria, and four test trials were presented. Test trials alternated between novel and familiar quantities, distinguished only by the amount of liquid. For infants habituated to the one-fourth full container, the novel quantity was the three-fourths full container; for infants habituated to the three-fourths full container, the novel quantity was the one-fourth full container. The order of presentation of the familiar and novel quantities was counterbalanced across infants.

Test trials were conducted in the same manner as the habituation trials, so that trials were terminated after infants had looked away for 2 consecutive seconds. Each infant's looking time was the sum of his/her fixations at the display prior to the end of the trial. On 20% of the sessions, two observers independently recorded infants' looking time through two peepholes, with interobserver reliabilities ranging from .91 to .99.

Results and Discussion

A repeated measures analysis of variance on infants' looking times on the test trials was conducted with the following factors: sex, habituation quantity (one fourth or three fourths), order of testing (novel quantity or familiar quantity presented on the first test trials), test quantity (novel or familiar). The only significant effect was a main effect of test quantity, $F(1, 16) = 11.87$, $p = .003$, with shorter looking times on familiar- than on novel-quantity trials, means (*SD*s), respectively, 5.76 s (2.29 s) and 8.53 s (4.23 s). This effect indicates that after being habituated to a particular amount of continuous substance, infants regained interest when a different amount of substance was presented. As shown in Fig. 1, infants who viewed the novel quantity on the first test trial showed an increase in looking time, followed by a decrease in looking time when the familiar quantity was presented on the second trial. This pattern was followed by

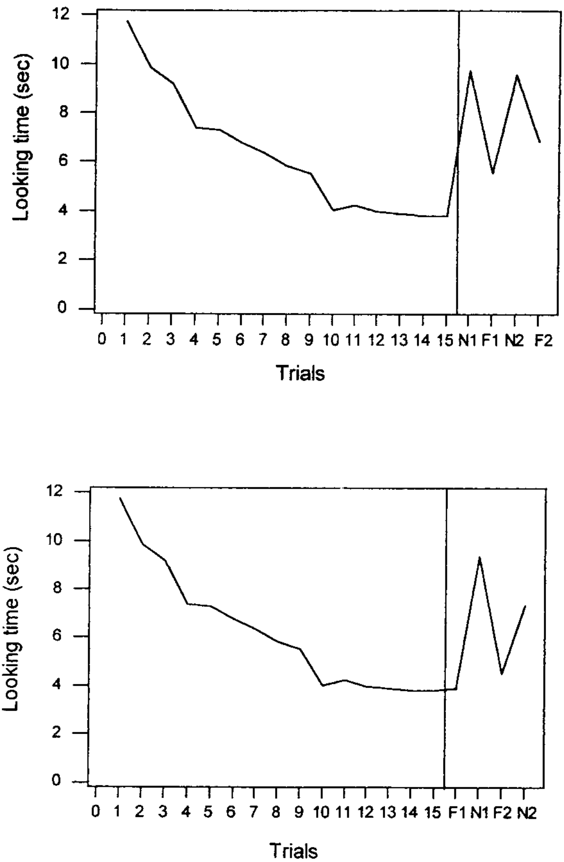

FIG. 1. Looking times in the habituation and test phases by orders: novel–familiar–novel–familiar or familiar–novel–familiar–novel.

an increase in looking time on the second presentation of the novel quantity and then a decrease with the second presentation of the familiar quantity. In contrast, infants who viewed the familiar quantity on the first test trial showed the same level of looking time as on the last habituation trial, then an increase in looking time with the first presentation of the novel quantity. The pattern was followed by a decrease in looking time with the second presentation of the familiar quantity, and an increase with the second presentation of the novel quantity.

On average, infants took 11.2 trials to reach the habituation criteria. The infants were grouped into "fast" and "slow" habituators by a median split of the number of trials needed to reach habituation (median = 12, mean for "fast" habituators = 9.8, mean for "slow" habituators = 13.6). Analysis of variance showed that "fast" versus "slow" habituators did not differ in their looking times during the test trials, $F(1, 19) = 0.04$.

The results show that 6-month-old infants can distinguish between familiar and novel amounts of continuous substance. This finding indicates that infants' sensitivity to quantitative information is not limited to discrete sets. Whereas earlier research on infant perception has shown that infants can distinguish sizes of simple objects (Granrud, 1986; Slater et al., 1990), the present experiment shows that they can also distinguish between different amount of liquid in containers of the same size.

EXPERIMENT 2

In this experiment, we used a violation-of-expectation paradigm to test whether 9-month-old infants expect a change in amount after seeing liquid being added to a nonempty container. Specifically, given that infants can distinguish between a one-fourth full and a three-fourths full container, as shown by Experiment 1, Experiment 2 investigated whether infants could anticipate a change after an addition of half a container of liquid.

Method

Participants

Twenty-four middle-class, healthy, full-term infants (12 males and 12 females) participated in the experiment, ranging in age from 8 months 11 days to 9 months 25 days (mean = 9 months 8 days). The sample included 18 Caucasian, 4 African American, and 2 Asian infants. The data of 8 additional infants who became fussy during the testing were dropped from the analysis. None of the infants in this study participated in Experiment 1.

Stimuli and Procedure

The visual displays were identical to those used in Experiment 1. Infants were tested in the same room with the same stage settings as in Experiment 1. Each three-phase session lasted approximately 15 min. The familiarization phase was identical to that of Experiment 1.

Baseline trials. Two baseline trials were given to examine whether infants had a preexperimental preference for the different quantities used in the experiment, each beginning with the screen covering the stage. Then the screen was rotated down to reveal one of the containers, either one-fourth or three-fourths full. Looking times and trial terminations followed the procedures used in Experiment 1. As before, the order of presentation of the two quantities was counterbalanced across infants.

Test trials. Six test trials were presented during the third phase. Infants were shown the red liquid being poured from one container to a hidden container. Test trials alternated between possible and impossible outcomes (three of each), with order of possible and impossible outcomes counterbalanced across subjects.

Each test trial started with the screen rotated down to reveal a one-fourth full container on the stage. The experimenter waited until the infant looked away for 2 consecutive seconds. Then the screen rotated up, hiding the container from the infant's view. The movement of the screen drew the infant's attention back to the stage. The experimenter's hand then emerged holding an identical one-half full container, held steadily and in an upright position so the liquid level could be seen clearly. After the infant had fixated on the container held by the experimenter for 2 s, the experimenter began pouring the liquid in the one-half full container into the occluded container behind the screen (one-fourth full). The action of pouring was in clear and full view of the infant throughout, although the outcome container was occluded by the screen. After adding in all the liquid, the experimenter held the container upright to show that the container was now empty and then withdrew the container from the stage. The screen was rotated down, revealing either a possible (three-fourths full) or an impossible (one-fourth full) outcome. All infants looked at the containers immediately after the screen rotated down. Looking times were recorded as in Experiment 1. The experimenter achieved the impossible outcome by secretly switching the resultant container after pouring with a prearranged one-fourth full container. To avoid confounding factors, such as noise, movement, or duration, on the possible outcome trials, the experimenter also secretly switched the resultant container, but with a prearranged three-fourths full container. On 21% of the sessions, two observers independently recorded infants' looking time, with interobserver reliabilities ranging from .92 to .98.

Results and Discussion

A repeated measures analysis of variance on infants' mean looking times was conducted with the following factors: sex, order of testing (possible outcome presented first or impossible outcome presented first in test trials), outcome event (possible or impossible). The analysis yielded a significant main effect of outcome event, $F(1, 19) = 5.79$, $p = .02$, with shorter looking times for possible than for impossible outcomes, with means (*SD*s) of 6.05 s (3.73 s) versus 7.38 s (3.67 s), respectively. There were no other significant main effects or interactions. Figure 2 shows the looking time on each trial averaged across infants. It can be seen that the difference in looking time between the impossible and possible events was most apparent for the first two pairs of trials. The difference in looking time decreased to some degree for the third pair of trials, most likely due to increasing familiarity with both outcomes over trials.

To investigate whether infants showed a preexisting preference for either of the two quantities, a repeated measures analysis of variance also was conducted on infants' baseline looking time, with sex, order (one fourth or three fourths presented on the first trial), and quantity (one fourth or three fourths) as factors. There was no pretesting preference in looking time at the two outcome quantities (one fourth vs three fourths), $F(1, 19) = 0.10$, with means (*SD*s), respectively, 6.85 s (5.20 s) and 7.09 s (5.51 s), suggesting that the significant effect of impossible versus possible outcome was not due to a preference for one of the quantities. To test the possibility that a preference for one quantity could have developed during the course of the experiment, we examined data in Experiment

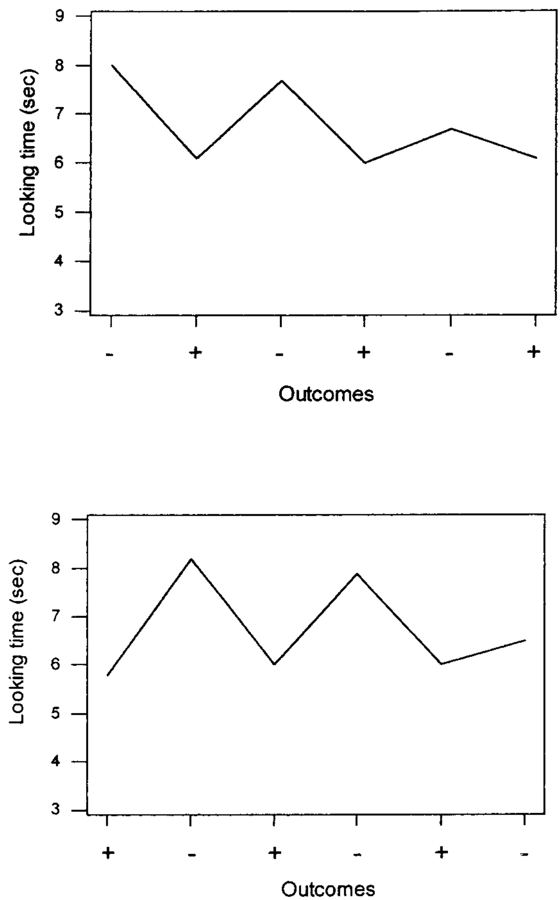

FIG. 2. Looking time at possible and impossible outcomes by orders: possible outcome (+) first or impossible outcome (−) first.

1, in which half of the infants had been habituated to the one-fourth full and half to the three-fourths full container. An analysis of variance using quantity as a factor was carried out on infants' mean looking times on the last three trials in the habituation phase. We did not find a difference in looking times by quantity, $F(1, 19) = 0.24$. Further, quantity did not have a significant effect on looking times in the testing phase, $F(1, 16) = 2.78$. These data from Experiment 1 suggest that the significant effect of impossible versus possible trials found in Experiment 2 is unlikely to be due to the development of a preference for the one-fourth full container over the course of experiment.

GENERAL DISCUSSION

There has been considerable work on infant sensitivity to number of discrete objects (Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981; van Loosbroek & Smitsman, 1990) and to their anticipation of change in number after addition and subtraction (Simon, Hespos, & Rochat, 1995; Wynn, 1992a). In contrast, there has been little work on whether infants show similar sensitivities to continuous amount and changes in amount. Here we used methodologies that parallel those used with discrete entities to investigate whether infants can distinguish between different amounts of continuous quantities, and whether they expect a change in amount after the addition of continuous quantities. Parallel to the findings on discrete sets, the results of Study 1 indicate that infants are able to distinguish different amounts of continuous quantity, and the results of Study 2 indicate that when an amount is added to a continuous quantity, infants expect a change in amount. Future studies will be needed to test whether infants differentiate between addition and subtraction with respect to the direction of the change in amount.

It should be noted that it is not clear that there are two distinct forms of quantitative representation in infants—continuous and discrete. As Huttenlocher et al. (1994) pointed out, the results of studies using habituation and violation-of-expectation procedures with discrete sets can be explained without positing exact number representation. In fact, Huttenlocher (1994) suggested that the results can be explained without positing representation of number at all. It is known that several continuous variables correlate with number, including area, mass, and contour length (amount of black to white border). Past studies have not adequately controlled for continuous variables. For example, Strauss and Curtis (1981) habituated infants to slides of different objects, such as a house, a cat, and a butterfly, photographed at different distances in an attempt to equate sizes. However, it is not clear whether they systematically varied the sizes of these objects so that the contour length for three objects in a display was equal to the contour length for two objects in another. Since studies of infants' sensitivity to number did not control for amount of "stuff," it is possible that infants represent discrete objects in terms of amount of "stuff" rather than in terms of number.

Indeed, recent results by Clearfield and Mix (1999) indicate that infant representations of the number of entities in discrete sets is based on amount rather than approximate number. In particular, when infants habituated to a small set of objects, they dishabituated to a set that differed in amount but not in number, but not to a set that differed in number but not amount. The present findings of infant sensitivity to continuous amount, together with the Clearfield and Mix results, suggest the possibility that a common representation of quantity in infancy might underlie sensitivities to both number and continuous amount. At the very least, the current findings indicate that infants are sensitive to continuous amount, contrary to previous claims that sensitivity to discrete number constitutes a privileged domain. Reasons for the difference in findings between the present study and Wynn's (1993) study are not yet clear. It is possible that infants' approximation of continuous amount could be easily disrupted by variation in container sizes and shapes. Further investigation of early representation of continuous quantity is needed to allow us to understand the role of these and other factors more completely.

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