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Infants Make Quantity Discriminations for Substances

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Infants can track small groups of solid objects, and infants can respond when these quantities change. But earlier work is equivocal about whether infants can track continuous substances, such as piles of sand. Experiment 1 ($N = 88$) used a habituation paradigm to show infants can register changes in the size of piles of sand that they see poured from a container when there is a 1-to-4 ratio. Experiment 2 ($N = 82$) tested whether infants could discriminate a 1-to-2 ratio. The results demonstrate that females could discriminate the difference but males could not. These findings constitute the youngest evidence of successful quantity discriminations for a noncohesive substance and begin to characterize the nature of the representation for noncohesive entities.

Infants have the ability to discriminate numerical quantities in the 1st year of life. We know that they can represent both the *number* of individuals in a set (Brannon, Abbott, & Lutz, 2004; Lipton & Spelke, 2003; vanMarle & Wynn, 2009; Xu & Spelke, 2000) and the *continuous extent* (temporal or spatial) of those individuals (e.g., Baillargeon, 2004; Brannon et al., 2006; Clearfield & Mix, 1999, 2001; Cordes & Brannon, 2008a; Feigenson, Carey, & Spelke, 2002; Hespos & Baillargeon, 2001a; vanMarle & Wynn, 2006). Infants can enumerate visual items (Feigenson, 2005; McCrink & Wynn, 2007; Xu, 2003; Xu & Spelke, 2000), auditory entities (Jordan & Brannon, 2006; Lipton & Spelke, 2003, 2004; vanMarle & Wynn, 2009), and even actions (e.g., jumps of a puppet; Wood & Spelke, 2005; Wynn, 1996). For continuous quantities, infants can discriminate visual items differing in surface area (Brannon et al., 2006; Feigenson et al., 2002) and contour length (Clearfield & Mix, 1999, 2001), as well as tones that differ in duration (Brannon, Suanda, & Libertus, 2007; vanMarle & Wynn, 2006). They are also sensitive to the spatial dimensions (e.g., height) of three-dimensional objects and can use this information to predict possible object relations (Baillargeon, 2004).

Given all these demonstrations of success with quantity discriminations, it may be surprising that infants of the same age appear to have much more difficulty representing amounts of a continuous noncohesive substance, such as a quantity of sand (Huntley-Fenner, Carey, & Solimando, 2002; Rosenberg & Carey, 2009) or a pile of blocks or Cheerios (Chiang & Wynn, 2000; vanMarle & Wynn, 2010). It is not the case that all bets are off when it comes to infants' expectations about substances because they appear to understand many facts about the properties of liquids. For example, 5-month-olds are sophisticated enough about substances to be able to predict that when a liquid is emptied from a glass, it will pour rather than tumble as solids do. They also expect that when a cylinder is lowered into a liquid, it will proceed to the bottom rather than remaining on top as it would for solids (Hespos, Ferry, & Rips, 2009). In action tasks, Bourgeois, Khawar, Neal, and Lockman (2005) demonstrated that infants between 6 and 10 months carry out material-specific actions toward objects and surfaces, depending on whether the objects are hard or soft and whether the surfaces are hard, soft, liquid, or discontinuous (e.g., a surface made out of netting). Where infants seem to run into trouble is reckoning with a substance's quantitative properties.

Objects and substances share many of the same quantitative dimensions. Quantitative dimensions

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are abstract stimulus attributes, such as number, volume, or area, and in order to discriminate quantities, people must compare entities along these dimensions. Infants' ability to discriminate quantities shows similarities across many domains, such as duration (vanMarle & Wynn, 2006) and area (Brannon et al., 2006), suggesting that a common representational mechanism could underlie these skills (Feigenson, 2007). Yet research implies that infants' grasp of quantities of substances lags behind that of objects. For example, Huntley-Fenner et al. (2002) showed 8-month-olds a single pile of sand and then hid the sand behind a screen. The experimenter then poured a second pile, either behind the same screen or a separate screen. In neither case, however, were infants surprised if the screens were removed to reveal just one pile rather than two. By contrast, infants did look longer at one object if they had witnessed two similar-looking but solid objects placed behind the screens.

Not all studies paint so bleak a picture of infants' understanding of quantities of substances. Gao, Levine, and Huttenlocher (2000) found that 9-month-olds were able to keep track of the amount of water poured into a hidden container, and vanMarle & Wynn (2010) found that 10- to 12-month-olds could discriminate two piles of Cheerios if the ratio between piles was 1 to 4. Nevertheless, infants' grasp of noncohesive substance quantities appears fragile, since relatively small variations in the experimental procedure can cause them to fail the discrimination task (vanMarle & Wynn, 2010).

Why do infants perform better with quantitative dimensions of solid objects than with those of noncohesive substances? In the Huntley-Fenner et al. (2002) study, continuous quantity was a reliable cue in both the object and sand conditions, but 8-month-old infants did not detect this attribute with sand. Many studies of this sort have focused on the ability to keep track of the number of items that appear during a trial—either the number of objects or the number of piles of substances—where the size of the individual objects or piles is constant. But solid objects, by their nature, tend to maintain their distinctness in space by virtue of their shape and rigidity, whereas noncohesive substances tend to coalesce and separate much more easily. For this reason, the difference between one versus two sand piles may be less salient in dealing with noncohesive substances than it is in dealing with solid objects. For objects, both the size of the individual objects and the number of the objects may matter, and infants may attend to either number (Cordes & Brannon, 2008a, 2008b; Feigenson & Carey, 2003) or size (Clearfield & Mix, 1999; Feigenson et al., 2002), depending on experimental conditions. For noncohesive substances, however, infants may ignore the number of distinct piles, noticing only changes in intrinsic properties of the piles. (i.e., infants may ignore or forget qualitatively duplicate piles, retaining information from only a single pile in these displays.) We elaborate this idea in the General Discussion. It suggests, however, that infants may be better able to notice a substance's quantity if a change in quantity occurs with a single pile instead of multiple piles. In these experiments, we pursue this hypothesis by habituating infants to a sand pile of one size and testing them on a pile of the same or different size.

Experiment 1

Experiment 1 attempts to find out whether infants are sensitive to changes in the quantity of a substance—a pile of sand—when it appears as a single entity. Of course, factors other than variable pile size may contribute to infants' ability to register quantity. For example, one of the few studies to find successful detection of a substance's quantity used a substance within a transparent container—red water within a rectangular jar (Gao et al., 2000). Use of a container makes it uncertain whether the resulting benefit is due to infants' reacting to properties of the contained substance (e.g., its volume) or to the substance's relation to the container (e.g., the percentage of the container that is filled; see Duffy, Huttenlocher, Levine, & Duffy, 2005). Eliminating all relative cues to quantity is a practical impossibility, for reasons we discuss later. Our study attempts to minimize these cues, however, by pouring sand onto a flat surface, as in Huntley-Fenner et al. (2002). This procedure meant that the shape of the resulting piles varied, but infants witnessed multiple examples of the pouring on each trial to give them more experience with the variation in shape.

We also attempted to make the task easier by reducing memory demands. In many earlier studies (Chiang & Wynn, 2000; Gao et al., 2000; Huntley-Fenner et al., 2002), the experimenter first presented the substance piles to the infant, then covered them, and finally revealed the new number of piles. Our study used multiple examples of pouring and no covering in an attempt to reduce cognitive load unrelated to tracking quantity. In addition, we tested a broad range of ages with the same paradigm. Studies of quantities of substances have focused on infants 6 months or older. (Studies of the number of solid objects have sometimes looked at younger infants; e.g., Antell & Keating, 1983, showed that newborns discriminated two from three dots but not four from six dots.)

In short, our goal was to set the foundation of whether infants can distinguish different quantities of substances, using a simplified task. The study is distinct from previous work in that: (a) infants view only one pile of sand at a time, (b) there were no occluding screens, and (c) we used a repeating event within each trial to give multiple examples of the sand's quantity. In addition, we tested infants at 3, 7, and 10 months to chart the developmental trajectory of quantity discriminations, since (to our knowledge) no earlier experiments have looked for such changes. Our aim was to determine whether infants habituated to a specific quantity of sand (either small or large) would show a novelty reaction to a new quantity of sand in test trials.

Method

Participants

The participants were 88 healthy infants, 34 female and 54 male, comprised three age groups. The youngest age group was approximately 3 months of age, ranging from 2 months 15 days to 4 months 11 days (n = 30; M = 3 months 10 days). The middle age group was approximately 7 months of age, ranging from 6 months 16 days to 7 months 16 days (n = 30; M = 6 months 27 days). The oldest age group was approximately 10 months of age, ranging from 9 months 1 day to 11 months 7 days (n = 28; M = 10 months 3 days). Half the infants in each age group were assigned to the small quantity condition; the other half, to the large quantity condition. Ten additional infants were tested but eliminated from the final analysis, 6 because of fussiness, 1 because he looked the maximum amount on every test trial, and 3 from the youngest group because they had bowel movements during the experiment. Of these infants, 7 were from the youngest, 1 from the middle, and 2 from the oldest age groups.

Participants for this and the subsequent experiment were obtained by purchasing addresses of families with infants from commercial mailing lists. The participants' parents were contacted by letters and follow-up phone calls. They were given a t-shirt or book as a thank-you gift but were not compensated for their participation. The ethnicity of the sample was 79% non-Hispanic and 16% Hispanic (5% did not answer). The racial makeup was 69% White, 4% Asian, 3% African American, and 14% multiracial. The remaining 10% did not answer. The highest education level for the mothers of the infants who participated was: 1% did not have a high school diploma, 6% had a high school diploma, 12% had some college, 78% had a college degree or higher, and 3% did not answer. The highest education level for the fathers of the infants who participated was: 1% had some high school, 7% had a high school diploma, 12% had some college, 77% had a college degree or higher, and 3% did not answer.

Apparatus

The apparatus consisted of a wooden display box, 213.5 cm high, 106 cm wide, and 78 cm deep that was mounted 77 cm above the room floor. Parents sat in a chair facing an opening 60 cm high, 99 cm wide, and 77.5 cm deep in the front of the apparatus. The opening revealed a stage that displayed all stimulus objects. The back wall had beige fringe covering the bottom 15 cm to allow the experimenter to manipulate the stimuli on stage, as shown in Figure 1. A screen that covered the view of the stage was raised and lowered between trials.

There was a small hole in the front face of the stage containing a camera that captured a video image of the infant's face. Two research assistants in a separate room viewed this image. Each researcher depressed a computer button when the infant attended to the objects on stage and released the button when the infant looked away. Xhab software (Pinto, 1996) recorded looking times and habituation criteria.

The stimulus consisted of blue sand (Scenic Sand, Activa Products, Marshall, TX). The small quantity was 30 g, and the large quantity 120 g. The experimenter poured the sand from a blue plastic cup (Solo 9 oz, Lake Forest, IL) onto a round white Pyrex plate that measured 26 cm in diameter.

We used a 1-to-4 ratio between the small and large quantities of sand because previous work had found evidence that older infants could discriminate this ratio (though with different stimuli). vanMarle & Wynn (2010) showed that 11-month-old infants could detect changes in the quantities of Cheerios in a 1-to-4 ratio but failed when the ratio was 1 to 2. For solid objects, evidence indicates that even 6-month-olds can discriminate quantities whose ratio is 1 to 2 (but not 2 to 3). This

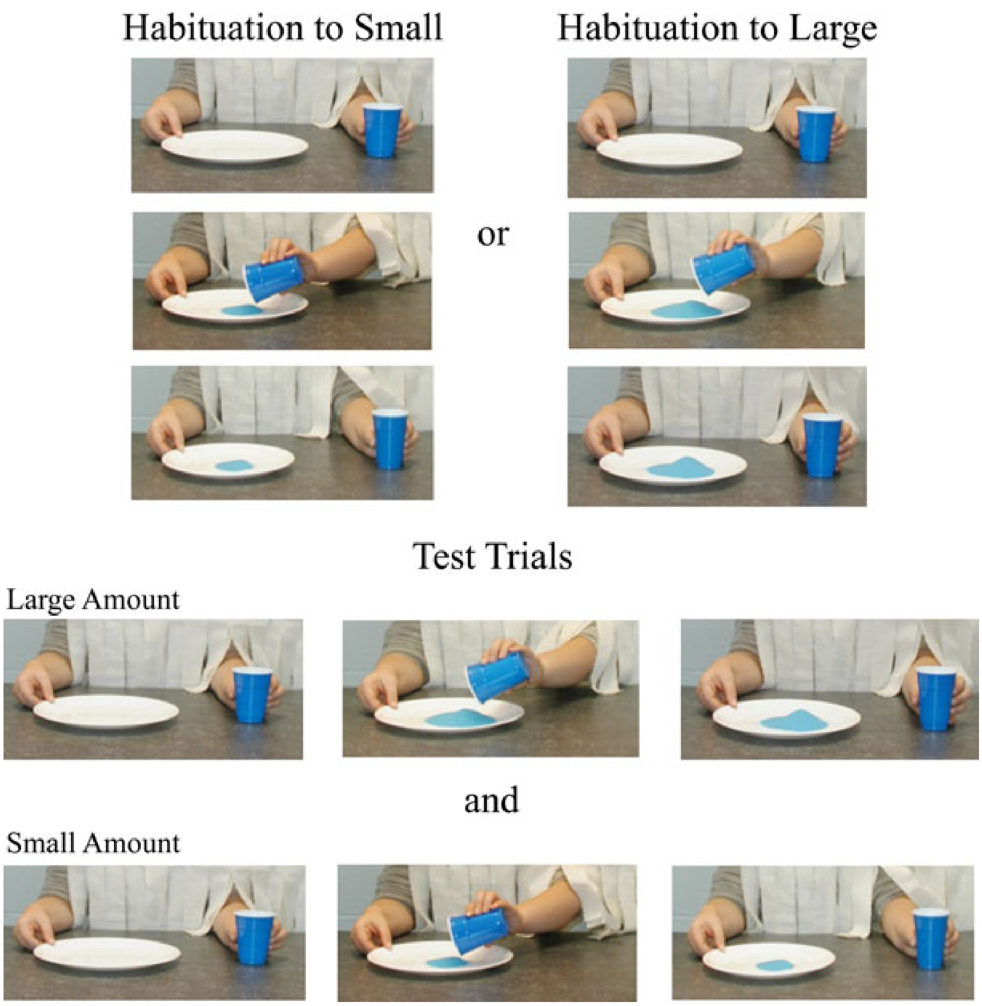

Figure 1. Schematic of the habituation and test trial events for Experiment 1.
Note. In the habituation and test trials, the experimenter poured the sand on the plate, then the cup was replaced and the plate was emptied. This 15-s cycle was repeated continuously until the trial ended. Infants saw either small or large piles during habituation trials. During test trials, all infants saw an alternation between the small- and large-pile trials.

discrimination has been demonstrated with visual displays consisting of dots (Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). Similar findings exist for discriminating a change in the size of a cartoon face (Brannon et al., 2006) and a change in temporal duration (vanMarle & Wynn, 2006). However, none of these latter experiments used substances.

Events

Habituation trials. When the screen went up at the start of a trial, infants saw on the stage a blue plastic cup containing blue sand and a white plate. The experimenter's left hand grasped the cup and her right hand grasped the right side of the plate. The experimenter completed a 15-s sequence of motion (the numbers in parentheses indicate how long it took to complete each part of the sequence): The cup was lifted vertically approximately 25 cm (1 s) and moved horizontally until it was centered over the plate (1 s); the cup was lowered to 5 cm above the plate and the contents of the cup were poured out (3 s). The cup was then lifted back up and moved horizontally above the starting point (1 s) and then returned to its initial position (1 s). Next, the cup was removed and replaced with an identical cup with the same amount of sand (3 s). After placing the cup back on stage and resting (1 s), the plate was removed, the sand was dumped in a bowl off stage, and the empty plate was put back in its initial position (4 s). The entire sequence was repeated continuously until the trial ended. Half of the infants were habituated to the small quantity (30 g) and the other half to the large (120 g). The intertrial interval was about 3–5 s for all trials.

Test trials. The procedure for the test trials was identical to the habituation trials except that the quantity of sand alternated between small and large amounts across trials. All infants saw the same test trials.

Procedure

During the experiment, the infant sat on the parent's lap in front of the apparatus. The parents were asked to refrain from interacting with their infant during the experiment, and to close their eyes during the test trials. As we noted earlier, each infant's looking behavior was monitored by two research assistants who watched video images of the infant from the hidden camera. All trials ended when the infant either looked away for two consecutive seconds after having looked at the event for at least 2 s, or looked at the event for 60 cumulative seconds without looking away for 2 consecutive seconds. A computer determined the end of the trial and signaled the experimenter to lower the screen. The habituation criterion was at least a 50% decline in total looking duration from the first three to the last three habituation trials or a maximum of nine trials. The average number of trials to reach criterion was eight. Each infant viewed six test trials, alternating between the small and large quantities. The type of test event shown first was counterbalanced across infants. Agreement between the two research assistant observers averaged 94% per trial per infant.

Preliminary Analyses

Preliminary analyses using analysis of variance (ANOVA) with age (3, 7, or 10 months), sex (female or male), test trial order (novel first or familiar first), and habituation condition (small or large) as between-subject factors and event (novel or familiar) as a within-subject factor revealed a significant main effect of sex, $F(1, 64) = 5.84$, $p = .018$, qualified by a Sex × Age interaction, $F(2, 64) = 4.45$, $p = .015$. These factors do not interact with any remaining variables. On further inspection, we discovered that the effect was due to several 3-month-old males, who tended to look less long overall than other participants (although even these participants looked longer at the novel than the familiar displays).

We removed outlier participants according to a criterion suggested by Mosteller and Hoaglin (1991). There were nine data points that had outlier values (all in the familiar test). Six of the data points were from the 3-month-old group, three were from the 7-month-old group, and none were from the 10-month-old group. When we rerun the preliminary analysis without the outlier data points neither the effect of sex, $F(1, 55) = 3.27$, $p = .076$, nor the Sex × Age interaction, $F(2, 55) = 2.62$, $p = .082$, remained significant. Because this effect is fleeting and has nothing to do with the variables of interest, the data reported in the results section include the entire data set. The significant effects reported in the Results section remain significant regardless of whether the outliers are retained.

Results

The results indicate that 3-, 7-, and 10-month-old infants discriminate between small and large quantities of sand. Mean looking times to the habituation and test trials, separated by age, appear in Figure 2. For each infant, we calculated the mean looking time for both novel test events (large if the infant had habituated to the small amount or vice versa) and familiar test events (small if the infant had habituated to the small amount or large if habituated to large). Three-, 7-, and 10-month-olds looked longer at the novel test events than at the familiar test events (23 of 30 three-month-olds, 21 of 30 seven-month-olds, and 23 of 28 ten-month-olds, all *p*s < .01, by binomial comparison).

We also conducted a repeated measures ANOVA of looking times with test event (novel or familiar) as a within-subject factor and age (3, 7, or 10 months) and habituation condition (small or large) as between-subject factors. There was a main effect of event, $F(1, 82) = 23.69$, $p < .001$, $\eta^2 = .22$, indicating that infants looked longer at novel than familiar outcomes. The effect of age was also significant, $F(2, 82) = 9.74$, $p < .001$, $\eta^2 = .19$, in that younger infants tended to look for longer amounts of time (irrespective of whether it was a novel or familiar display).

The novelty effect was evident in each age group individually. Separate analyses found a significant main effect of test event for the 3-month, $F(1, 29) = 8.14$, $p = .008$, $\eta^2 = .22$; 7-month, $F(1, 29) = 5.51$, $p = .026$, $\eta^2 = .16$; and 10-month, $F(1, 27) = 17.09$, $p < .001$, $\eta^2 = .39$, age groups.

The novelty preference was evident within each habituation condition, as Figure 3 illustrates. For the habituation to small condition, 39 of 45 infants looked longer at the large quantity in test trials

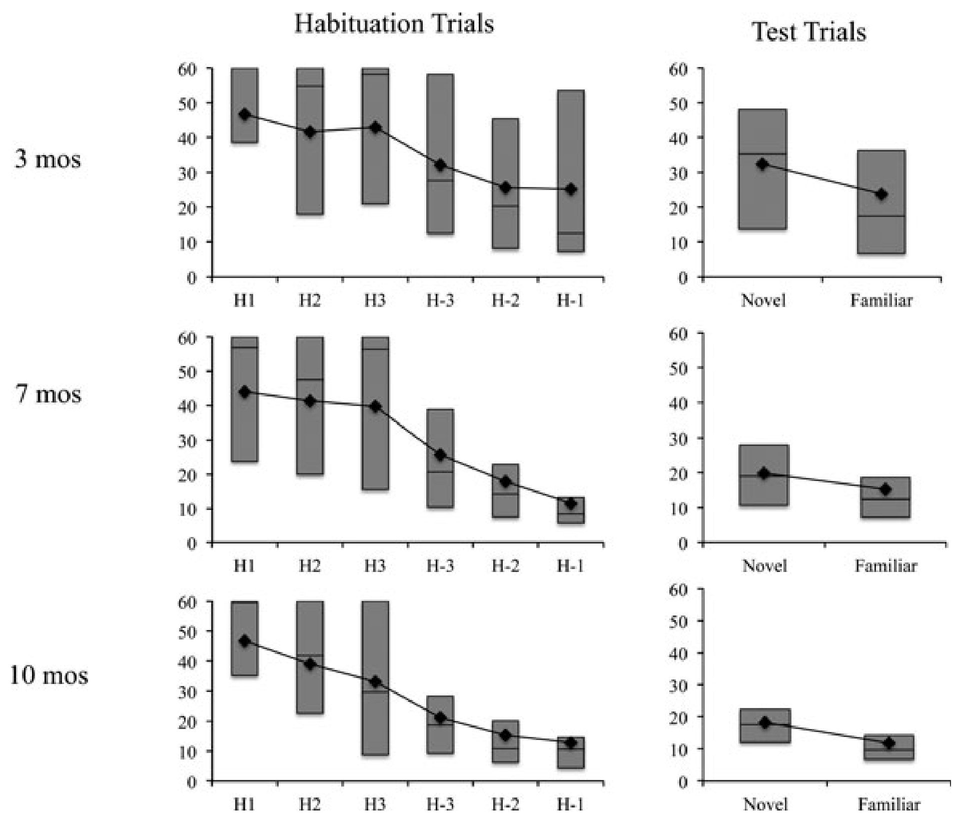

Figure 2. Experiment 1: Mean looking times during habituation and test trials separated by age.
Note. The black diamonds represent the mean, the central line in the gray box is the median, and the upper and lower portions of the box represent the third and first quartiles, respectively. In the habituation graphs, the boxes represent the means for the first three trials and last three trials before meeting the habituation criterion.

($p < .001$, binomial comparison), and an ANOVA showed a main effect of test event, $F(1, 44) = 16.68$, $p < .001$, $\eta^2 = .25$. For the habituation to large condition, 30 of 43 infants looked longer at the small quantity in test trials ($p < .05$, binomial comparison), and an ANOVA again showed a main effect of event, $F(1, 42) = 9.79$, $p = .003$, $\eta^2 = .19$.

Discussion

Infants discriminated the change in quantity of sand when the ratio of the quantities was 1 to 4. There was no age difference across 3- to 10-month-olds in this ability, nor did it matter if the infants were habituated to the small or large quantity. This finding is consistent with previous work by vanMarle & Wynn (2010) who found that 10- to 12-month-olds could discriminate two quantities of Cheerios when they differed by a 1-to-4 ratio.

Prior studies with solid objects and sounds have obtained evidence that 6-month-old infants can discriminate quantities whose ratio is 1 to 2 but not 2 to 3. Discrimination at this level has been demonstrated with visual displays consisting of (three or more) dots (Xu & Spelke, 2000; Xu et al., 2005), sizes of cartoon faces (Brannon et al., 2006), temporal duration of tones (vanMarle & Wynn, 2006), and ratio of Pac-Men to dots (Mc Crink & Wynn, 2007). Lipton and Spelke (2003) used sequences of (eight or more) discrete auditory stimuli and replicated the 1-to-2 success and 2-to-3 failure at 6 months. By contrast, vanMarle & Wynn (2010) found no evidence that 10- to 12-month-olds could discriminate quantities of Cheerios that differ in a 1-to-2 ratio. It seems possible, however, that a simplified procedure like that of Experiment 1 could turn up evidence for discrimination of nonsolid substances more in line with the results for dots, faces, and sounds. Infants in vanMarle and Wynn's experiment saw the piles of Cheerios just once before they were hidden in containers. Perhaps, repeated presentation and absence of occlusion can enhance the distinctiveness of the substance piles. In the next experiment, we addressed whether infants would detect a 1-to-2 ratio for sand.

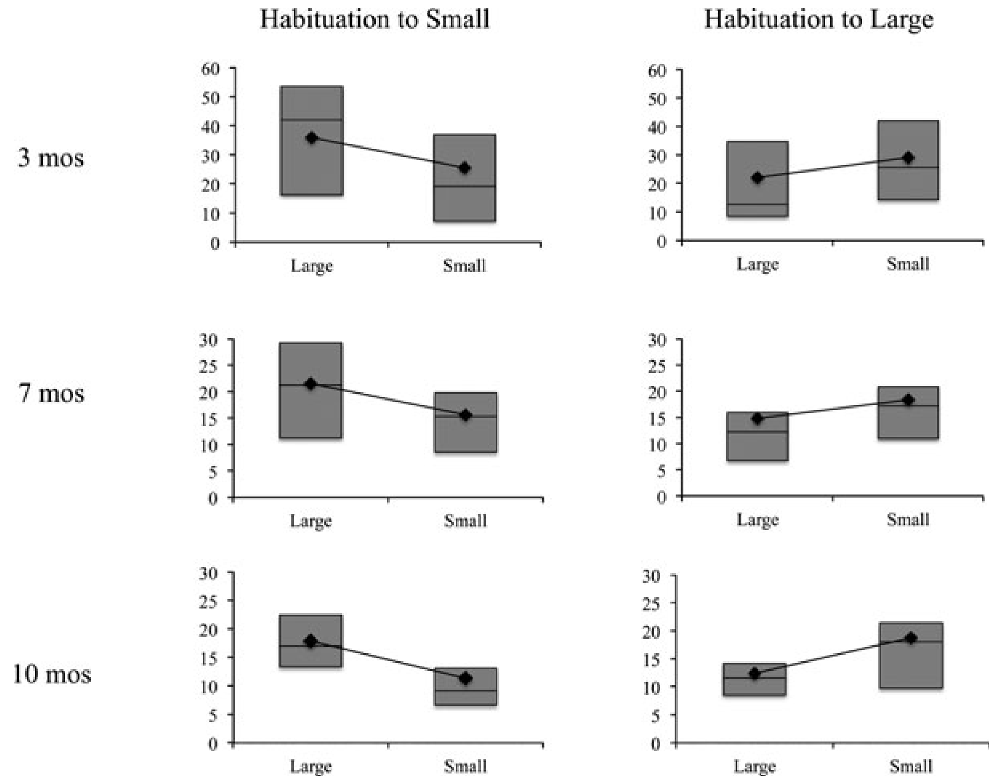

Figure 3. Experiment 2: Mean looking times during test trials separated by habituation condition and age.
Note. The black diamonds represent the mean, the central line in the gray box is the median, and the upper and lower portions of the box represent the third and first quartiles, respectively. The graphs demonstrate that all age groups gave opposite patterns of responses to identical stimuli depending on what they saw during habituation trials.

Experiment 2

The goal of Experiment 2 was to extend the results from the first experiment to a smaller ratio. All aspects of the experiment were identical to Experiment 1 with the exception that the ratio of the volumes of different-sized piles was 1 to 2 instead of 1 to 4. In addition, we eliminated the 3-month-old age group and added a 13-month-old age group.

This study also addresses a possible interpretive question about Experiment 1. To establish that the sand piles were noncohesive, we poured the sand from a cup onto a plate at each repetition of an event. This is the same method of conveying noncohesion that nearly all other experiments in this area have adopted (e.g., Gao et al., 2000; Huntley-Fenner et al., 2002; Rosenberg & Carey, 2009; vanMarle & Wynn, 2010). Our own earlier work shows that infants distinguish liquids from solids based on the way these items fall out of tipped containers (Hespos, Ferry, et al., 2009). Nevertheless, a possible objection to the findings of Experiment 1 is that the infants failed to treat the sand as substance, instead responding to the sand's final configuration on the plate as if it were a solid object. If so, we should not be surprised that the infants discriminated the size of the piles, since the ability to discriminate the spatial extent of *solids*, even at 1-to-2 ratios, is evident in earlier findings (Brannon et al., 2006). If infants in the present experiment represent the sand piles as solids, we would likewise expect them to succeed at looking longer at novel-sized piles after a 1-to-2 change in size. If infants fail at the 1-to-2 ratio (after succeeding at 1 to 4 in Experiment 1), this would lend support to the hypothesis that they were thinking of the sand as a noncohesive substance.

Method

Participants

The participants were 82 healthy infants, equal numbers of females and males, comprising three age groups. The youngest group was approximately 7 months of age, ranging from 6 months 16 days to 7 months 20 days (n = 26; M = 7 months 5 days). The middle group was approximately

10 months of age, ranging from 9 months 7 days to 10 months 19 days (n = 28; M = 10 months 0 days). The oldest group was approximately 13 months of age, ranging from 12 months 12 days to 13 months 24 days (n = 28; M = 13 months 0 days). Half the infants in each age group were assigned to the small quantity condition; the other half, to the large quantity condition. Eight additional infants were tested but eliminated from the final analysis, 6 because of fussiness, 1 because of parental interference, and 1 because of inattentiveness. Of these infants, 1 was from the youngest, 4 were from the middle, and 3 were from the oldest age groups.

Procedure

All aspects of the experiment were identical to Experiment 1 with the exception that the amount of sand in the small amount condition was 60 g of sand instead of 30 g (see Figure 4). The average number of trials to reach habituation criterion was eight. Agreement between the two research assistant observers averaged 94% per trial per infant. Preliminary analyses revealed no effect of habituation condition or test order; therefore, these factors were collapsed for subsequent analyses.

Results

Overall, the results indicate that infants did not detect a 1-to-2 change in amount of sand. Mean looking times to the habituation and test trials, separated by age, appear in Figure 5, and they show little difference in looking duration between novel and familiar test amounts. Across conditions, 44 of 82 infants looked longer at the novel test events

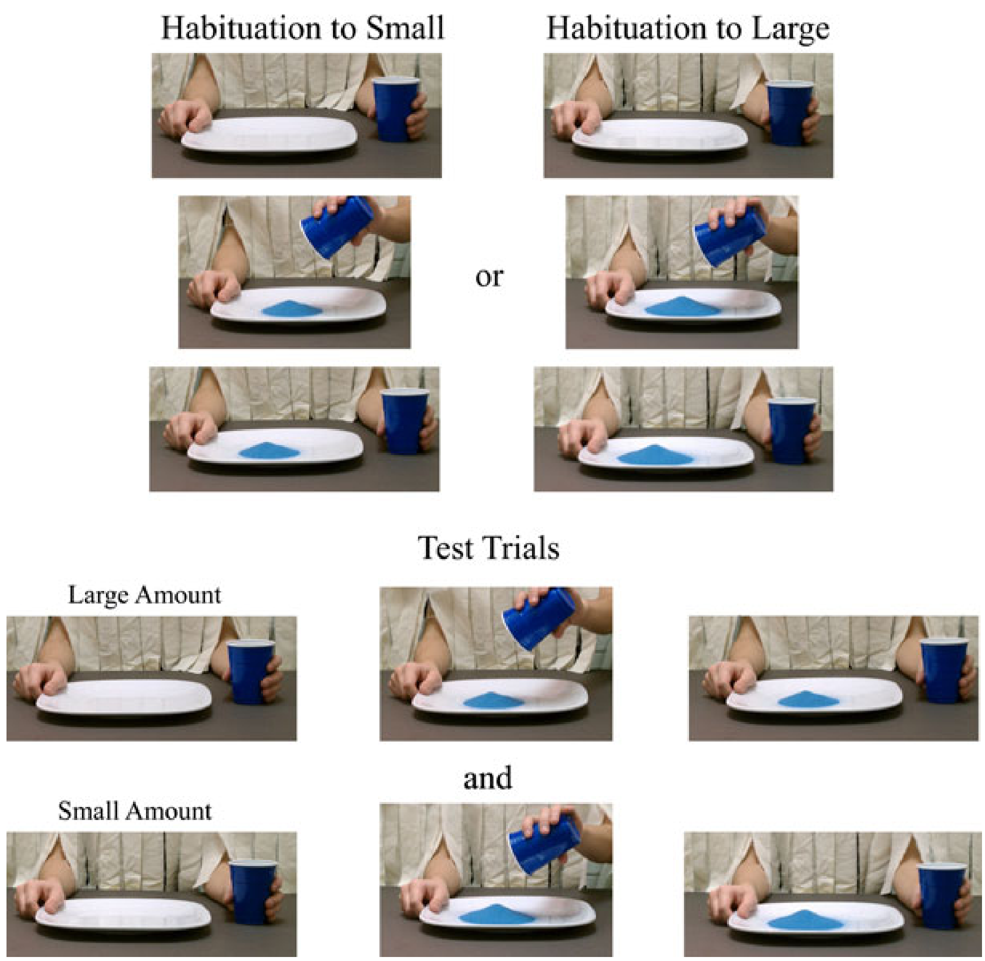

Figure 4. Schematic of the habituation and test trial events for Experiment 2.
Note. In the habituation and test trials, the experimenter poured the sand on the plate; then the cup was replaced and the plate was emptied. This 15-s cycle was repeated continuously until the trial ended. Infants saw *either* small or large piles during habituation trials. During test trials, all infants saw an alternation between the small- and large-pile trials.

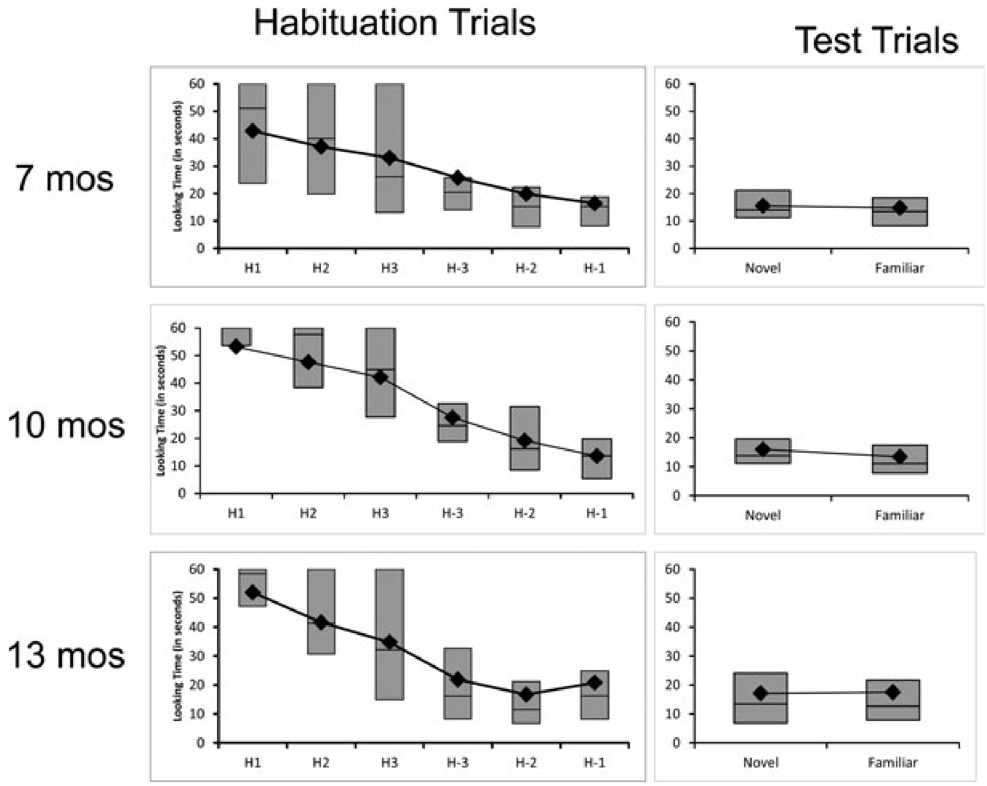

Figure 5. Mean looking times during habituation and test trials separated by age.
Note. The black diamonds represent the mean, the central line in the gray box is the median, and the upper and lower portions of the box represent the third and first quartiles, respectively. In the habituation graphs, the boxes represent the means for the first three trials and last three trials before meeting the habituation criterion.

(p = .581 by a binomial test). This finding is consistent with infants' difficulty with substances at this ratio in previous research (vanMarle & Wynn, 2010) and helps confirm that the infants were treating the sand piles as substance entities.

However, preliminary analyses revealed a significant Sex × Event interaction, $F(1, 70) = 7.78$, $p = .007$. We conducted an ANOVA with test event (novel or familiar) as a within-subject factor, and age (7, 10, or 13 months), sex (male or female), and habituation condition (small or large) as between-subject factors. Further analysis revealed that the females had significantly longer looking times to novel compared to familiar events, $F(1, 40) = 5.17$, $p = .028$, $\eta^2 = .12$ (for novel M = 16.11 s, for familiar M = 12.72 s), whereas males showed a (nonsignificant) trend in the opposite direction, $F(1, 35) = 2.12$, $p = .11$, $\eta^2 = .07$ (for novel M = 15.22 s, for familiar M = 17.1 s). Figure 6 shows the mean looking times at test trials separated by age and sex. These results indicate that only female infants discriminated the quantity change in this experiment. Table 1 represents the numbers of infants who looked longer at the novel or familiar test trials, again separated by age and sex. A Fisher's exact test confirmed a significant difference between females and males in this task (p = .004).

Discussion

We found evidence of quantity discrimination for females but not males when we used a 1-to-2 ratio. In all age groups, males tended to look longer at the familiar- than at the novel-sized piles. A developmental shift from familiarity to novelty preference, although unanticipated in the context of the current experiment, is not unprecedented in the infant looking time literature (Aslin, 2007; Colombo, 2002; Ferry, Hespos, & Waxman, 2010; Hunter & Ames, 1988; Johnson, Slemmer, & Amso, 2004; Kaplan & Werner, 1987; Roder, Bushnell, & Sasseville, 2000; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982; Wagner & Sakovits, 1986). The oldest group of males were approximately 3 months older than the oldest participants in Experiment 1, yet they showed the same trend toward longer mean looking at the familiar stimuli when the piles differed by a 1-to-2 ratio (Figure 6). Further

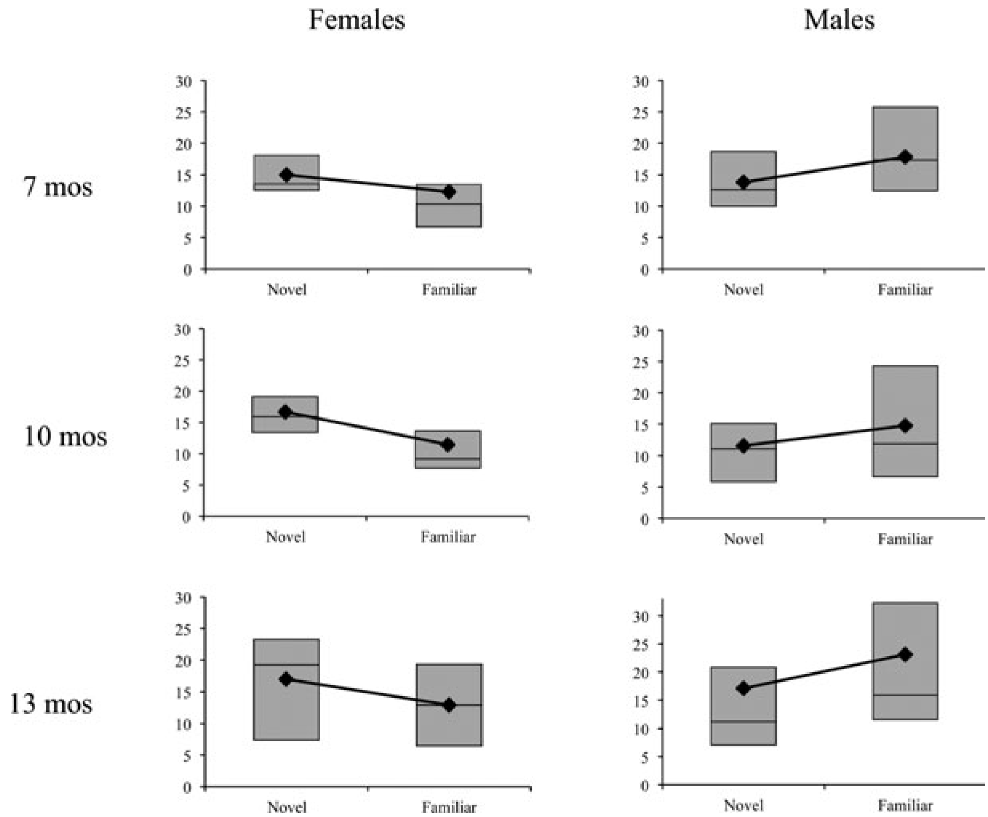

Figure 6. Mean looking times during test trials separated by sex and age.
Note. The black diamonds represent the mean, the central line in the gray box is the median, and the upper and lower portions of the box represent the third and first quartiles, respectively. The graphs demonstrate that females show significantly longer looking at novel test trials and males show a trend toward familiarity.

Table 1
Number of Infants Who Look Longer at Novel or Familiar Test Trials, Separated by Sex and Age, Experiment 2

Age (months)	Females		Males	
	Novel	Familiar	Novel	Familiar
7	7	4	4	11
10	11	4	4	9
13	11	4	7	6
Total	29	12	15	26

experiments are necessary to characterize the extent of this developmental difference for younger infants (e.g., would 3-month-old female infants succeed with a 1-to-2 ratio) and older infants (e.g., would 15-month-old males show a novelty preference for a 1-to-2 ratio). Table 1 shows that more male infants in the oldest group looked longer at the novel-sized piles than at the familiar-sized piles, and this trend may indicate the beginnings of a shift to a novelty preference. Females, though, showed a novelty preference at all ages, both in average looking times and in the number of infants who looked longer at novel versus familiar displays. Taken together these findings provide a contrast to those of Experiment 1, suggesting that the 1-to-2, unlike the 1-to-4, ratio provides a challenge to male infants' discrimination of substances.

General Discussion

Experiment 1 demonstrated that 3-, 7-, and 10-month-old infants could discriminate quantities of substances when the amount varied by a ratio of 1 to 4. These findings constitute the youngest evidence of successful quantity discriminations with noncohesive substances. However, Experiment 2 revealed null results for males but not females for a 1-to-2 ratio using an identical procedure with 7-, 10, and 13-month-old infants. We are beginning to track the time course and the representational ability that underlies quantity discrimination for noncohesive entities.

Prior evidence for discriminating a 1-to-3 ratio came from 9-month-old infants in a task in which the substance was contained—water in a glass (Gao et al., 2000). It is possible that the solid container helped infants measure amounts. In our experiment, by contrast, the sand was poured onto a flat surface so that the resulting sand piles varied in shape. Our results suggest that infants notice 1-to-4 differences in quantities of sand despite these variations of pile shape, height, width, area on the plate covered by the pile, and other variables.

Some of these factors, of course, were correlated with the volume of sand in the small versus large piles (although not perfectly correlated). For example, the small quantity had, on average, smaller height and width and covered a smaller area than the large quantity. It is therefore possible that the infants were reacting to height, width, or area rather than to volume. Future studies will need to isolate the operative variable. Nevertheless, all these variables are, like volume, continuous measures of a noncohesive substance. Infants who attend to the height (width, covering area) of the sand are detecting a quantitative dimension of a substance, just as are infants who attend to volume.

Relative Judgments of Amounts

Although no container provided obvious cues to relative amounts, other cues in the environment may have aided infants in detecting the quantity of sand. The size of the experimenter's hands and the size of the plate onto which she poured it could all serve as standards for gauging the amount (see Figure 1). Even the infants' perceived distance from the pile, as given by ocular accommodation, convergence, or other perceptual cues, could help them detect differences in continuous amounts. Eliminating all such cues would be virtually impossible. Thus, our claim is not that infants were noticing absolute amounts of sand—amounts in the absence of all possible standards—but that they were able to detect amounts under relatively natural conditions.

In addition, some of the comparative standards available to infants in our setup may have been more difficult for them to use than a direct comparison between the piles. For example, since different amounts of sand appeared on the same plate, infants could, in theory, judge the change in the quantity based on the change in ratio of blue (sand) to white (plate). To determine how easy it would be to apply this strategy, we measured the surface area of the plate and amount of area covered by the sand in the small and large quantity piles (we measured 10 pours for each quantity to assess the variation in size within a trial). In Experiment 1, the small amount of sand covered 8% ($SD = \pm 1$ percentage point) of the plate and the large amount covered 19% ($SD = \pm 2$); thus, the average ratio of change from small to large piles in Experiment 1 was 1 to 2.25. This ratio of surface area change is 50% smaller than the ratio of quantity change; it seems unlikely that infants would rather use the less discriminable surface area change than the quantity change itself. In Experiment 2, the small amount covered 11% ($SD = \pm 1$), and the large amount was identical to Experiment 1, 19% ($SD = \pm 2$), making the average ratio of change from small to large piles 1 to 1.73. Again, the ratio of surface area change is smaller than the quantity change, making it a less reliable perceptual cue for female infants to succeed in this task.

We do not mean to suggest that infants would find it impossible to use the blue area of the display to discriminate the small and large amounts. Similarly, we have not eliminated the possibility that infants employed some other perceptual cue for the same purpose. But their use of the substances' amounts seems at least as simple and as plausible as the potential rivals that have occurred to us.

How Do Infants Judge Quantity for Nonsolid Substances?

Unlike many other studies on substance discriminations, this one obtained positive findings in Experiment 1 and for females in Experiment 2. An individual pile of a noncohesive substance can vary in size in ways that are important for infants. More Cheerios or more juice matters when it comes to snack time, and more sand or more water when it comes to play time or bath time. By contrast, the number of piles may be relatively fleeting and changeable, since they can scatter or regroup quite easily. Infants may therefore register more sand versus less sand but not one pile of sand versus two piles, even though summing the contents of the piles entails more sand. The present results suggest that varying the size of a single pile enables them to notice the difference in amounts. Similarly, differences in the size of simultaneously presented piles can induce infants to reach for the larger pile under some conditions (vanMarle & Wynn, 2010). Where infants tend to fail is in discriminating one versus two piles when the piles do not vary in size and are otherwise qualitatively similar (Chiang & Wynn, 2000; Huntley-Fenner et al., 2002; Rosenberg & Carey, 2009).

Figure 7 schematically summarizes studies on substances to illustrate our hypothesis. Experiments that have failed to show discrimination (Panel a) have held constant the intrinsic properties of the piles (e.g., size) and have varied the number of piles at test (Huntley-Fenner et al., 2002; Rosenberg & Carey, 2009). Experiments that demonstrate discrimination have varied the size of piles presented simultaneously (Panel b; vanMarle & Wynn, 2010) or varied size from initial presentation to test (Panel c; Gao et al., 2000, and the present experiments). We can account for the full set of results on substances by assuming: (a) infants individuate simultaneously presented piles but quickly forget about more than one of them if the piles are similar in their intrinsic properties (e.g., size), and (b) piles are seen as having different sizes if they vary by at least a 1-to-4 ratio. In the case of solid objects, infants retain both the number of objects and their intrinsic properties.

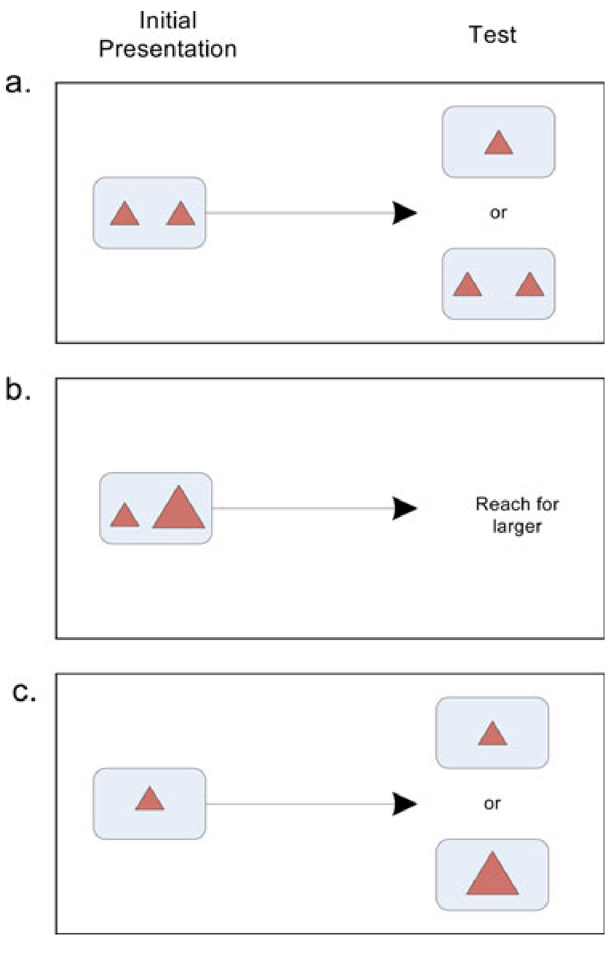

Figure 7. Three procedures employed in studies of nonsolid substances.
Note. Within each panel, the left-hand side shows the initial presentation of one or two piles of a nonsolid substance (triangles); the right-hand side shows the test conditions. Rounded rectangles group items that are presented simultaneously.

To see how these assumptions predict the results, consider first infants' failure in tasks that vary only number of piles (Panel a of Figure 7). Here, the piles have the same intrinsic properties by design, and infants may implicitly disregard all but one of them as redundant, quickly forgetting the number of piles. If the same type of encoding occurs at test, infants will again forget all but one pile, even if two appear. Because the initial and test representations match, the infants' reaction will not depend on the number of piles. Second, consider those experiments that vary the size of piles. If the piles appear simultaneously and differ in size by at least 1 to 4, infants will remember both piles and reach for the larger (Panel b). Similarly, if the piles appear successively (Panel c), infants will be able to distinguish them (provided they differ by the threshold ratio), and they will succeed at the task. Aspects of this hypothesis remain to be tested, of course, but it provides a starting point for further theorizing.

Other factors may contribute to infants' success or failure with substances, as we noted earlier, although the most obvious of these factors fail to explain the full range of findings. For example, some earlier experiments (e.g., Chiang & Wynn, 2000; Huntley-Fenner et al., 2002) required infants to remember the number of piles (or amount) of a substance while the piles were out of sight. For infants, tests of the same capacity often look different depending on whether the procedure demands memory over occlusion (Hespos, Gredeback, Von Hofsten, & Spelke, 2009; Munakata, McClelland, Johnson, & Siegler, 1997; Shinskey, Bogartz, & Poirier, 2000; Shinskey & Munakata, 2001). Memory for the items is no doubt more difficult when infants view an initial display just once, as in these hidden-items tasks, than when they see a display repeatedly, as in our experiment. However, some hidden-items tasks have led to correct performance (e.g., Gao et al., 2000; vanMarle & Wynn, 2010), while others have not (e.g., Huntley-Fenner et al., 2002), despite seemingly similar memory requirements. Moreover, memory difficulty could not by itself explain the difference between infants' performance with substances and solids: Infants often succeed with solids and fail with substances under quite comparable memory conditions (Huntley-Fenner et al., 2002; Rosenberg & Carey, 2009).

Our findings show that infants can discriminate sand quantities in a 1-to-4 ratio at 3, 7, and 10 months and females can detect a 1-to-2 ratio at 7, 10, and 13 months. Similarly, older infants have performed successfully in hidden-item tasks with a 1-to-3 ratio (Gao et al., 2000) and a 1-to-4 ratio (vanMarle & Wynn, 2010). Our findings also showed unsuccessful performance for males with a 1-to-2 ratio at 7, 10, and 13 months. Similarly, other studies show that infants in both hidden-item tasks (Huntley-Fenner et al., 2002; vanMarle & Wynn, 2010) and habituation tasks (Rosenberg & Carey, 2009) fail when the ratio is 1 to 2. Thus, the size of the ratio correlates with success across these studies, and it is possible that the 1-to-2 ratio is simply too small for some infants to register. Such an effect would be consistent with the hypothesis that Weber's Law governs discrimination of substance quantities, with a critical ratio for substances somewhere between 1:2 and 1:3. This generalization is, however, little more than a description of the results from the previous studies.

Concluding Comments

Infants at age 3- to 13-month-old are on the cusp of understanding substances' behavior, and many factors could potentially push them to make correct or incorrect predictions about their quantitative properties. The present results suggest that infants can react to variations in the size of a single pile of a substance, but they do not exclude the possibility that other variables can impact their understanding of such quantitative properties. Likewise, an open question is how far infants' knowledge of substances extends. Substances typically differ from solid objects in their tendency to change shape during motion, their inability to support other objects, and their propensity to spread unless contained. How much infants know about these properties is currently unclear (but see Hespos, Ferry, et al., 2009, for a start on these issues).

The present study helps characterize the origins and development of knowledge about substances. Further studies are necessary to determine whether the developmental course of quantity discriminations for substances is similar to that of other domains or idiosyncratic due to the fundamentally different properties that substances possess. These developmental trajectories will allow insight into the mechanisms that underlie our ability to represent the basic ontological differences among entities that we encounter in our everyday environment.

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