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Tracking and Quantifying Objects and Non-cohesive Substances

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The present study tested infants' ability to assess and compare quantities of a food substance. Contrary to previous findings, the results suggest that by 10 months of age infants can quantify non-cohesive substances, and that this ability is different in important ways from their ability to quantify discrete objects: (1) In contrast to even much younger infants' ability to discriminate discrete quantities that differ by a 1:2 ratio, infants here required a 1:4 ratio in order to reliably select the larger of two substance quantities. And (2), unlike with objects, infants required multiple cues in order to determine which of two quantities of substance was larger. Moreover, (3) although 14.5-month-olds were able to compare amounts of substance in memory, 10- to 12-month-olds were limited to comparing visible amounts of substance. These findings are discussed in light of the mechanisms that may underlie infants' quantification of objects and substances.

Research investigating infants' quantification reveals that they are able to represent both discrete and continuous quantity. That is, they are sensitive both to the *number* of individuals in a set (Brannon, Abbott, & Lutz, 2004; Lipton & Spelke, 2003; vanMarle & Wynn, 2009; Xu & Spelke, 2000) and to the *continuous extent* (spatial or temporal) of those individuals (e.g., Baillargeon, 2004; Brannon, Lutz, & Cordes, 2006; Clearfield & Mix, 1999, 2001; Cordes & Brannon, 2008; Feigenson, Carey, & Spelke, 2002; Hespos & Baillargeon, 2001; vanMarle & Wynn, 2006). For example, infants can enumerate 2-dimensional visual elements (McCrink & Wynn, 2004; Xu, 2003; Xu & Spelke, 2000), 3-dimensional visual objects (Feigenson, 2005), auditory entities (voices: Jordan &Brannon, 2006; sequences of sounds: Lipton & Spelke, 2003, 2004; vanMarle & Wynn, 2006), and even actions (e.g., jumps of a puppet, Wood & Spelke, 2005). For continuous quantities, infants can discriminate 2- and 3-dimensional visual items differing in surface area (Brannon et al., 2006, Feigenson, Carey, & Spelke, 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 3-dimensional objects and can use this information to predict possible object relations (e.g., Baillargeon, 2004).

Based on this body of findings, it appears that infants' quantification abilities are quite broad. They apply to objects, sounds, and events, items presented sequentially and items presented simultaneously, as well as stationary items and moving items. Note, however, that in all of these studies, the entities being quantified were discrete individuals. What about entities that are not

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natural individuals? What about substances[1]? Unlike objects, sounds, and events, substances are inherently continuous (i.e., non-individuated), and as a result, do not lend themselves to counting. But despite being "uncountable", substances are nonetheless quantifiable. They are extended in space and can be quantified in terms of their continuous physical extent (e.g., volume, surface area, height, width). Indeed, recent studies with nonhuman primates suggest that rhesus monkeys and capuchin monkeys can choose the larger of two hidden quantities of a nonsolid substance in a task analogous to that used here (vanMarle, Aw, McCrink, & Santos, 2006; Wood, Hauser, Glynn, & Barner, 2007). The present study examines whether infants, who are capable of representing the continuous extent of discrete entities, can also quantify substances.

To date, the few studies investigating infants' quantification of substances have produced mixed results (for work investigating infants' reasoning about substances in the physical domain, see Hespos, Ferry, & Ripps, 2009). In one study, Gao, Levine, & Huttenlocher (2000) examined infants' ability to quantify liquids. Experiment 1 showed that 6-month-old infants could discriminate between a container that was 1/4 full of red liquid and one that was 3/4 full (Gao et al., 2000). Unfortunately, infants in this experiment never saw the liquid being poured into the containers (in fact, the liquid never underwent any motion), so one cannot be sure they interpreted the red stuff as liquid, rather than as a feature of the container. Thus, it is not clear whether the infants were discriminating on the basis of amount of liquid per se, or a continuous property of the container (e.g., amount of redness).

In a second experiment, Gao et al. (2000) presented 9-month-old infants with a container 1/4 full of red liquid, which was then hidden behind an occluder. A hand brought out a pitcher of red liquid, held it visibly over the location of the container (higher than the top edge of the occluder), and poured more liquid into the container. The occluder was then removed to reveal the container either 1/4 full (no change) or 3/4 full (expected change). Infants looked longer at the former, apparently predicting a change in amount with the addition of liquid (Gao et al., 2000). This result is potentially impressive but can be explained without appeal to substance quantification. That is, since infants had more visual experience with the 1/4 full than the 3/4 full container, it is possible that their preference was due to perceptual familiarity (e.g., Cohen & Marks, 2002). Moreover, infants could have succeeded by ignoring the addition event entirely and merely discriminating between the 1/4 and 3/4 full containers like the 6-month-old infants in the first experiment. To show that they were actually expecting the amount of liquid to change *because of the addition of liquid*, one would have to show that infants respond differently in other situations, for example, that they expect a reduced amount to result if liquid is *removed* from a 3/4 full container; or that they expect the amount in the container to remain the same if the pitcher pours no additional liquid into it. Without such contrasting conditions, it is impossible to tell whether the infants were attending to the context event (i.e., the addition of liquid) in a meaningful way.

More closely related to the present experiments are studies investigating infants' ability to track and quantify substances not

[1] Throughout this paper, we use the term "substance" to refer specifically to non-cohesive substances like *sand* and *water*, rather than solid substances like *wood* or *glass*. With respect to properties that might impair visual tracking and object representation (e.g., non-rigidity, non-cohesion), a portion of solid substance (e.g., a hunk of wood) is much more like an object than it is like a portion of non-cohesive substance (e.g., a pile of sand). Therefore, I restrict the present discussion to non-cohesive substances.

held in containers. Following the design of Wynn's (1992) addition task, Huntley-Fenner, Carey, & Solimando (2002) asked whether 8-month-old infants could predict how many piles of sand should result following two spatially separated pouring events. In the critical version of the task, infants first saw sand poured in a pile on a puppet stage. Two spatially separated screens were then raised, so that one occluded the pile and the other occluded a location to the left of the pile. A hand then brought out a pitcher of sand, and poured some behind the leftmost occluder. Finally, the screens were removed to reveal either two piles of sand (one behind each occluder – the expected outcome) or just the original pile (the unexpected outcome). In contrast to when the task involved the lowering of discrete objects behind the occluders, infants in the sand condition did not appear to have any expectations about how many piles there should be, looking equally at the expected and unexpected outcomes (Huntley-Fenner, 1995; Huntley-Fenner et al., 2002). Note that these infants failed to detect not only that there were *half as many piles* as there should have been (a discrete quantity), but also that there was *half as much sand* as there should have been (a continuous quantity). The authors explained infants' failure by suggesting that the processes that track the location of objects are limited to tracking cohesive, bounded entities. And, since sand fails to exhibit these properties, it does not count as input for the object tracking mechanism and cannot be represented by it (Huntley-Fenner et al., 2002). In fact, recent research corroborates this suggestion. Like infants, human adults have relative difficulty tracking entities that move in the manner of non-cohesive substances compared to entities that move like cohesive objects (vanMarle & Scholl, 2003).

These few studies represent virtually all of the work investigating infants' ability to quantify substances (see Huntley-Fenner, 2001, for related work with preschoolers). One possible explanation for the discrepant findings is that the ratio between the 'expected change' and 'no change' outcomes was more discriminable (1:3) in the Gao et al. study, than in the Huntley-Fenner et al. studies (1:2). It could be that infants require a larger proportionate difference in order to discriminate amounts of substance than numbers of objects (1:2 at 6 months of age; e.g., McCrink & Wynn, 2004; Xu & Spelke, 2000).

Given the mixed findings, the present experiments were designed to assess the conditions under which infants do and do not quantify substances and to examine the developmental progression of this ability.

EXPERIMENT 1a

Experiment 1a asked whether10- to 12-month-old infants could choose the greater of two hidden quantities of a food substance, and whether their performance was influenced by the ratio between the quantities to be compared. Food was used for two reasons. First, given the evolutionary importance of maximizing one's food intake, food seems like a domain in which organisms would be especially motivated to attend to and encode quantity information. Second, using food afforded the use of a simple and straightforward "Choice" paradigm (e.g., Feigenson, Carey, & Hauser, 2002; Hauser, Carey, & Hauser, 2000). In this paradigm, subjects are given a choice between two hidden amounts of food. If they can tell the difference between the two quantities, they are expected to select the larger of the two quantities.

Previous research indicates that infants succeed in this task when the food items are discrete objects (i.e., graham crackers – Feigenson, Carey, & Hauser, 2002), and interestingly, that success is based on a comparison of amount of cracker stuff, not number of crackers. For example, when infants saw one huge cracker (with volume = 2x) placed into one cup and two small crackers (each with volume = x/2) placed into the other cup, infants reliably selected the one huge cracker. They (wisely) chose to maximize the amount of food they got, rather than the number of crackers. Moreover, when the two amounts are equal in volume, infants do not prefer the container with more crackers, but instead choose randomly (Feigenson, Carey, & Hauser, 2002). Thus, it seems that when faced with food, infants are inclined to represent the total amount of food present, even if the food consists of discrete items that can be represented by number. It was hoped that the use of food in the present experiments would help infants demonstrate competence in substance quantification by directing their attention towards amount and away from number.

Experiment 1a had three conditions: 1 vs. 2 objects, 1:2 ratio of substance, and 1:4 ratio of substance. Cheerios were chosen as the food substance because they are liked by 10-month-olds, are safe for this age, and are less messy than many infant foods. While Cheerios are a food substance, they are not a *nonsolid* substance, being composed of many small solid "O"s as they are. It is reasonable to ask, then, whether Cheerios might engage infants' system of reasoning about solid objects rather than their processes for reasoning about substances. However, previous work has found that objects of about this size and smaller tend to be conceptualized and treated as substances rather than as objects when presented with grouping cues similar to those used here, both for adults (e.g., Bloom, 1994; Bloom, 1996; Middleton, Wisniewski, Trindel, & Imai, 2004) and infants (e.g., Chiang & Wynn, 2000)[2].

Method

Participants

Forty-eight healthy 10- to 12-month-old infants participated (Range = 10m 0d to 12m 15d; M = 11m 4d), 16 in each condition. Half of the infants in each condition were female. Ten additional infants were tested but excluded from the final sample due to failure to choose (five infants), parental/sibling interference (four infants), or experimenter error (one infant). There were not equal numbers of 10- and 12-month olds in each condition because previous research indicated no difference in the performance 10- and 12-month-olds in the Choice task (Feigenson Carey, & Hauser, 2002). Indeed, analyses comparing the performance of the older and younger infants (determined by median split) showed no differences in performance in this or any of the experiments reported in this paper.

Design

Infants were randomly assigned to one of three test conditions (1 vs. 2 objects, 1:2 ratio of substance, or 1:4 ratio of substance). Following a short warm-up trial, infants received a single test trial in which they were given a choice between two hidden quantities of food. The order in which the amounts were

[2] Moreover, infants' performance in our Cheerios conditions can potentially reveal whether they are treating the Cheerios portions as amounts of substance or as collections of discrete objects. A wealth of data suggests that by 6 months, infants can discriminate discrete quantities at a 1:2 ratio (e.g., Feigenson, 2005; Lipton & Spelke, 2003; McCrink & Wynn, 2004; Xu, 2003; Xu & Spelke, 2000), and by 9 months, they can discriminate discrete quantities differing by a 2:3 ratio (Lipton & Spelke, 2003, 2004). Therefore, if the 10- to 12-month-old infants in our experiments treat the Cheerios portions as sets of discrete objects they should successfully discriminate the portions in both the 1:2 and 1:4 ratio conditions. In contrast, if infants do not discriminate the substance quantities at a 1:2 ratio (as in Huntley-Fenner et al., 2002), but succeed in the 1:4 ratio condition, this would suggest that they are treating the Cheerios portions as substance quantities.

presented (large-first or small-first) and the side on which the larger amount was hidden (right or left) was counterbalanced across participants. This was accomplished by randomly assigning infants to one of four counterbalancing conditions: *lg-R* (large amount first, on the right), *lg-L* (large amount first, on the left), *sm-R* (small amount first, on the right), *sm-L* (small amount first, on the left).

Stimuli/Apparatus

Stimuli consisted of a yellow medium-sized bucket (11 cm high x 16-22 cm wide) and a small toy cow (approx. 4cm wide x 7cm long x 7cm tall), both used in the warm-up trial, and two identical blue plastic cups (approx. 12cm tall x 8-10cm in diameter) into which the experimenter placed the food items during the test trial. In the object condition, the experimenter drew the crackers out of a small, paper cup one at a time before placing them in the plastic cups. In the substance conditions, two small, white plastic plates (15.25cm in diameter) were used to present the Cheerios portions. Plates were prepared with Cheerios prior to the infants' arrival at the lab and were hidden from infants' view until they were brought out during the test trial.

The food items in the object condition were graham crackers (6.5 x 3cm), while small portions of Cheerios breakfast cereal (either 5, 10, or 20 O's, each O being approximately 1 cm in diameter) served as the food in the two substance conditions. To make the Cheerios portions perceptually substance-like, they were bunched together on the plates, so that the sides of individual O's were touching, but not overlapping (i.e., not piled up), giving the portion a single bounding contour. In addition, the Cheerios were poured into the cups, rather than lowered individually like the crackers. Given these characteristics, and based on previous research (Bloom, 1996; Chiang & Wynn, 2000; Middleton et al., 2004), it was expected that infants would be more likely to construe the Cheerios quantities as portions of a substance, rather than as individual objects to be enumerated.

Procedure

The procedure was based on that used by Feigenson, Carey, & Hauser (2002) and consisted of two trials: Warm-up and Test. Parents sat on the floor approximately six feet from the experimenter (E), holding their infant on their lap. Once situated, Warm-up began when E brought out the bucket and the toy cow. After showing the infant that the bucket was empty (by shaking it upside down), E placed the bucket right side up on the floor halfway between herself and the infant, hid the toy in the bucket, and verbally encouraged the infant to retrieve it. This served to get the infant interested in crawling and to introduce them to the idea of retrieving something that has been hidden.

The Test trial immediately followed. The bucket and the toy were placed out of sight and the parent was asked to hold their infant on their lap again. Once the infant was situated, E brought out two cups with the open ends facing the infant. With the infant watching, E turned the cups upside down and shook them, to further show that they were empty. She then placed the cups (right side up) on the floor, about two feet from herself (i.e., four feet from the infant) and about four feet apart, positioning them so they were equally spaced to the right and left of the infant.

1 v 2 object condition. After the cups were placed, E reached inside the paper cup, pulled out a cracker and showed it to the infant. She then ate the cracker while commenting about how "yummy" it was. This was necessary to show the infant that the crackers were food (only some infants had actually eaten graham crackers before), and to motivate them to participate. Following this, E placed crackers into the cups one at a time (one cracker into one cup and two crackers into the other cup) while the infant watched. After all the crackers were hidden, the infant was allowed to crawl towards the cup of his/her choice. To avoid cueing the infant in any way, E looked down at the floor rather than at the infant or at either of the cups. E frequently engaged in verbal encouragement whenever the infant was hesitant to approach; this was done equally enthusiastically regardless of the experimental condition or the infant's path of progress.

1:2 and 1:4 substance conditions. Infants in these two conditions were given a choice between two portions of Cheerios, differing by a ratio of either 1:2 or 1:4. The procedure in these conditions differed slightly from the cracker condition. E again modeled eating by pulling a few Cheerios from the paper cup and eating them. Next, she hid the cup behind her back, pulled out a plate with Cheerios on it, and, with the infant watching, placed it next to one of the cups. She then reached behind her back, brought out the second plate (also with Cheerios on it), and set it next to the other cup. To ensure the infant clearly saw both quantities, the experimenter pointed to each (in the same order in which they were brought out) while saying, "Look, 'baby's name'!" She then poured the contents of each plate into their respective cups in the same order, always making sure the infant was watching. Once both portions were hidden, the experimenter looked down at the floor and the infant was allowed to approach.

Note that this procedure differs from that used by Feigenson, Carey, & Hauser (2002) in an important way. In Feigenson, Carey, & Hauser's study, infants only ever saw one cracker at a time, requiring them to mentally sum how many crackers (and how much cracker stuff) went into each cup, and then mentally compare the total amounts in order to choose correctly. In contrast, infants in the substance conditions of the present experiment initially saw both portions simultaneously, allowing them to visually compare the portions before they were hidden. As a result, the task was substantially less difficult than that used in previous studies. This simplified procedure allowed infants every opportunity to succeed, in order to establish whether they can quantify substances at all.

Data collection

The dependent variable (in this and all subsequent experiments) was whether the infant chose the larger or smaller amount of food. The experimenter manually recorded which amount the infant chose immediately following the test trial. Sessions were also videotaped to allow for offline reviewing and reliability coding of the experimental sessions. A trained secondary observer naïve to the purpose of the experiment viewed only those portions of the videotaped sessions showing infants' choices and recorded whether each infant had chosen the cup on the left or the right. These data were correlated with the original observations as a measure of reliability and agreement was shown to be very high (r = .99).

Based on the standards used by Feigenson, Carey, & Hauser (2002), the following inclusion/exclusion criteria were adopted: (a) Infants were considered to have made a choice when they either approached a cup and reached into it, or if they approached a cup and sat next to it for at least 8 seconds. (b) If infants failed to approach either cup after ~20 seconds, the experiment was terminated. (c) Infants who approached one of the cups and looked into it, and then crawled over to the other cup, were considered to have made an "unclear" choice and were excluded from the data set. This occurred in only a small subset of the participants (n=3, all 14.5-month-olds in Experiment 3b). (d) An infants' data were excluded if the infant was not centered between the cups before beginning his/her approach, or if a parent/sibling interfered in any way (e.g., pointing to one of the cups, crawling up to one of the cups, providing verbal encouragement that might bias the infant's choice, etc.)

Results

1 vs. 2 object condition. Twelve of 16 infants chose the cup containing two graham crackers ($p < .05$, 1-tailed sign test). There were no effects of side or order of presentation (*p*s > .1, 2-tailed sign test), nor did gender interact with choice, side, order, or side x order (all *p*s > .1, 2-tailed Fisher Exact Tests). Replicating Feigenson, Carey, & Hauser's (2002) finding, infants in this condition reliably chose the cup containing the larger number of crackers.

1:2 substance condition. Eight of 16 infants chose the larger quantity ($p > .1$). There were no effects of side or order of presentation (*p*s > .1, nor did gender interact with choice, side, order, or side x order (all *p*s > .1).

1:4 substance condition. Twelve of 16 infants chose the larger amount ($p < .05$). There were no effects of side or order of presentation (*p*s > .1), nor did gender interact with choice, side, order, or side x order (all *p*s > .1). (See Figure 1.)

Discussion

Infants reliably chose the greater of two quantities of crackers in the object condition, replicating the results of Feigenson, Carey, & Hauser (2002). This is consistent with findings in the animal literature in which nonhuman primates reliably select the larger of two quantities of discrete food items (chimpanzees – Beran, 2001, 2004; rhesus monkeys – Hauser et al., 2000; capuchin monkeys – vanMarle et al., 2006). More importantly, the results of the two substance conditions suggest that by 10 months, infants can discriminate substance quantities when the memory demands of the task are substantially reduced, but only as long as the ratio between the amounts is large enough: Infants reliably chose the larger of the two portions when they differed by a 1:4 ratio, but not when they differed by a 1:2 ratio. The fact that infants were at chance in the 1:2 ratio condition suggests that they were not enumerating the individual Cheerios in each portion, as infants of this age are well able to distinguish discrete numerical values differing by a 1:2 ratio (Brannon et al., 2004; Lipton & Spelke, 2003; Xu, 2003; Xu & Spelke, 2000).

Note that the memory demands in our task were substantially different than those in previous work with substances (Huntley-Fenner et al., 2002) and objects (Feigenson, Carey, & Hauser, 2002). Unlike previous studies, in which infants never saw the final amounts to be compared, infants in our task were able to see the entire portion of each comparison amount before it was poured (violating cohesion). As a consequence, our results are not directly comparable to those in previous studies. Nonetheless, the differential performance of infants in the two substance conditions (success with 1:4, failure with 1:2) suggests that even with minimal memory demands, infants find it more difficult to represent and compare substance quantities, than quantities of objects.

EXPERIMENT 1b

Based on the results of Experiment 1a, we propose that infants in the two substance conditions construed the Cheerios arrays as portions of substance, and that infants require a larger ratio difference to discriminate quantities of substance (at least 1:4) compared to quantities of objects (1:2). Another possible explanation for infants' need for the larger ratio difference in the substance conditions, however, is that the ratio limit for infants' ordinal judgments in this task is different for large numbers and small numbers. Because previous studies have tested only small vs. small or small vs. large numbers of objects, it has been proposed that there is a strict "set size limit" of three items in this task and that infants cannot make ordinal judgments for sets that exceed this limit (Feigenson et al., 2002). It is therefore not known what ratio difference infants might require to judge which of two large sets of objects is the largest. Experiment 1b therefore tested whether infants would succeed in this task when both amounts contained large numbers of Cheerios (5 vs. 10) and the portions could not be construed as substances[3].

Method

Participants

Sixteen healthy 10- to 12-month-old infants (Range = 9m16d to 12m11d, M = 11m0d) participated in this experiment. Half of the infants were female. Five additional infants were tested but excluded from the final sample due to failure to choose.

Design

As in Experiment 1a, side and order were counterbalanced across infants by randomly assigning them to one of four counterbalancing conditions: *lg-R*, *lg-L*, *sm-R*, or *sm-L*. Males and females were distributed equally across the counterbalancing conditions.

Stimuli

Stimuli were large numbers of Cheerios. The small amount consisted of five Cheerios and the large amount consisted of ten Cheerios. The amounts thus differed by a 1:2 ratio, a ratio at which much younger infants (i.e., 6 months) successfully discriminate large numbers in both the visual (Xu & Spelke, 2000) and auditory (Lipton & Spelke, 2003) modalities.

Procedure

The procedure was identical to the object condition in Experiment 1a, and therefore to the procedure used by Feigenson, Carey, and Hauser (2002). After infants completed the warm-up trial, two empty cups were placed on the floor and an experimenter then modeled eating a few Cheerios she had pulled from a small cup and one at a time. She then hid the first amount, placing it into a cup, one O at a time, and then hid the other amount in the other cup, one O at a time. Memory demands were therefore the same as in Feigenson, Carey, and Hauser (2002)[4]. Infants had to keep track of how many Cheerios (and how much Cheerios stuff) went into each cup and then mentally compare the amounts in order to choose the larger.

Results

Twelve of 16 infants chose the larger amount (p < .05, 1-tailed sign test). There were no effects of side or order of presentation (ps > .1), nor did gender interact with choice, side, order, or side x order (all ps > .1). (See Figure 1.)

[3] One might think it more appropriate to have tested a 10 vs. 20 large number comparison so that the actual number of Cheerios was the same in this condition as in the 1:2 ratio substance condition in Experiment 1a. Pilot testing indicated, however, that the amount of time it took to present a 10 vs. 20 comparison far exceeded the attention span/patience of most 10- to 12-month-olds. We therefore chose to shorten the procedure by presenting a 5 vs. 10 comparison, in which both amounts clearly exceed the set size limit, and the ratio between the quantities is the same as in the 1:2 ratio substance condition.

[4] Indeed, one could argue that the memory demands were greater here because the amount of time it took to present the quantities was longer than in the original Feigenson, Carey, & Hauser (2002) study.

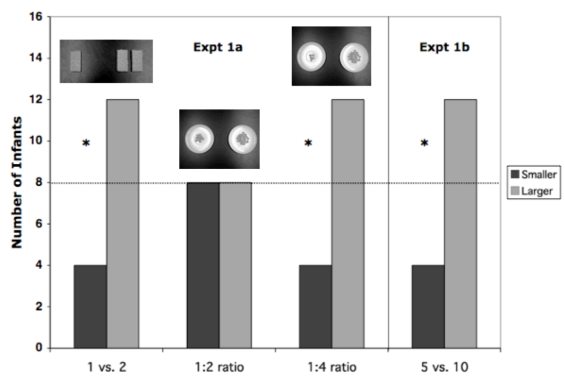

Figure 1. Number of infants choosing the larger or smaller quantity in Experiments 1a and 1b. The dotted line indicates chance performance. Infants reliably chose the larger quantity in the 1 vs. 2 object condition, 5 v 10 (large number) object condition (Expt. 1b) and in the 1:4 ratio substance condition, but were at chance in the 1:2 ratio substance condition. Thus, they required a larger ratio difference (1:4) to discriminate the substance quantities compared to object quantities (1:2 ratio).

Discussion

Ten-to-twelve-month-olds successfully chose the larger amount when both amounts were comprised of large numbers of Cheerios (5 vs. 10), suggesting that infants' failure in the 1:2 ratio substance condition in Experiment 1a was because infants require a larger ratio difference in order to discriminate large numbers of objects in this task.

This is a striking result for at least two reasons. First, it contrasts with infants' failure in the 1:2 ratio substance condition in Experiment 1a. In that condition, infants failed to choose the larger of the two amounts (10 vs. 20 Cheerios), even though the ratio between the amounts was the same (1:2) in both cases. The only difference was in the presentation of the amounts. In Experiment 1a, the quantities were presented on plates, arrayed as a single portion, and poured into the cups. This was done to make the portions as substance-like as possible, hopefully leading infants to construe them as portions of substance, rather than as collections of objects to be counted. In Experiment 1b, however, the O's were presented one at a time, and placed into the cups one at a time. This was done so that infants would focus on the individuality of each O, leading them to an object, rather than a substance, construal. The differential performance in the two conditions suggests that the perceptual cues were effective in leading infants to view the Cheerios either as a portion of stuff, or as a collection of objects.

Even more striking is that infants succeeded with large numbers of Cheerios despite the fact that the number of Cheerios in each amount was clearly outside the set size limit demonstrated in previous studies using this task (Feigenson, Carey, & Hauser, 2002). In the original demonstration of infants' performance in this task, Feigenson, Carey, and Hauser (2002) showed a strict "set size limit" on infants' performance. Specifically, infants (the same age as those tested here) successfully chose two crackers over one, and three over two, but were at chance whenever there was more than three crackers in either amount (i.e., 3 vs. 4, 2 vs. 4, and 3 vs. 6), even when the ratio between the quantities is highly favorable (i.e., 1 vs. 4). Feigenson et al. interpreted this pattern as an indication that infants use a capacity-limited object tracking system to represent and compare the quantities in this task. We show, however, that infants can compare large quantities in this task.

There were only two differences between our task and that in Feigenson, Carey, and Hauser (2002). First, we used Cheerios rather than graham crackers, and second, both amounts in our task exceeded the set size limit. Since Cheerios are smaller than graham crackers, one might explain the discrepant performance by suggesting that infants simply were not hungry enough to choose the larger amount in the Feigenson et al. study. This cannot be the case, however, because infants in their study readily chose six crackers over three in a control condition in which both amounts remained visible during the choice period. Thus, it seems that having both amounts outside the set size limit somehow led infants to use a different mechanism, such as analog magnitudes, to represent the quantities in our experiment. Further experiments are necessary to determine whether infants can indeed use analog magnitudes in this task. If they can, they should show a ratio limit on their performance, succeeding at a 2:3 ratio, since infants can successfully discriminate numbers and durations at a 2:3 ratio by 9 months (Brannon et al., 2007; Lipton & Spelke, 2003), and failing at a 3:4 or a 4:5 ratio. Regardless, this result is, to our knowledge, the first to demonstrate that by 10 months, infants can make ordinal judgments about large numbers in this task.

EXPERIMENT 2

Having found initial evidence in Experiment 1a that infants can quantify substances, albeit in highly simplified circumstances, it is important to identify the limits of this ability. One of the most impressive aspects of infants' discrete enumeration ability is that they are able to represent number independently of a host of continuous quantitative dimensions. Thus, when continuous extent (spatial or temporal) is ruled out as a basis for discrimination, infants are still able to respond on the basis of number[5] (Brannon et al., 2004; Feigenson, 2005; Lipton & Spelke, 2003; McCrink &Wynn, 2004; Wood & Spelke, 2005; Wynn, Bloom, & Chiang, 2002; Xu, 2003; Xu & Spelke, 2000). Such findings suggest that infants' discrete enumeration abilities are remarkably robust. Experiment 2 asks whether the same is true of their ability to quantify substances.

Infants in Experiment 1a successfully discriminated substance quantities that differed by a 1:4 ratio when continuous extent and discrete number were completely confounded. Consequently, they could have been using any (or all) of several different cues to judge which quantity was larger. Number was effectively ruled out because infants failed to discriminate quantities differing by a 1:2 ratio, suggesting that they were using one or more continuous variables to make their judgment. Since the portions on each plate had a single bounding contour, the perimeter of the larger portion was substantially greater than that of the smaller. Moreover, since the plates themselves were identical in size, the density of the larger amount was greater than that for the smaller. The following experiment therefore tested infants' ability to quantify substances when either perimeter or density was equated between the two portions.

Method

Participants

Thirty-two healthy 10- to 12-month-old infants (Range = 10m0d to 12m14d, M = 11m10d) participated in Experiment 2. There were 16 infants in each condition and half of the infants in each condition were female. Five additional infants were excluded from the final sample due to failure to choose (three infants) or parental interference (two infants).

Design

Infants were randomly assigned to either the Perimeter control or Density control condition and all were given a choice between portions of Cheerios differing by a 1:4 ratio. As in Experiment 1a, side and order were counterbalanced across infants by randomly assigning them to one of four

[5] A possible exception is under conditions where set size is small (3 or fewer visual objects) and the objects all have identical features. Under these conditions, evidence suggests that continuous extent may be more salient than number (Clearfield & Mix, 1999; 2001; Feigenson, Carey, & Spelke, 2002; Mix, Huttenlocher, & Levine, 2002; but see Brannon et al., 2004 and Cordes & Brannon, 2008).

counterbalancing conditions: *lg-R*, *lg-L*, *sm-R*, or *sm-L*. Males and females were distributed equally across the counterbalancing conditions.

Stimuli

Stimuli were identical to those used in the 1:4 substance condition in Experiment 1a, except for the following changes. In the Perimeter control condition, the small portion was spread out on the plate so the perimeter was approximately equal to the perimeter of the large portion (see Figure 2). In the Density control condition, the Cheerios portions were presented on two white paper discs, rather than plastic plates. The disc used to present the large portion was 14cm in diameter (the same size as the plates in Experiment 1a) while the disc for the small portion was 7cm in diameter, which corresponds to a four-fold difference in surface area between the two discs. Since the individual O's were all roughly the same diameter, the density of the large and small portions when presented on the discs was roughly equivalent (see Figure 2). Note that when portion perimeter was equated, density was still available as a cue to amount, and vice-versa.

Procedure

The procedure was identical to the substance conditions of Experiment 1a. Memory demands were again minimal since infants were allowed to see both portions before they were poured into the cups.

Results

Perimeter control condition. Seven of sixteen infants chose the larger amount ($p > .1$). There were no main effects of side or order of presentation (ps > .1), nor did gender interact with choice, order, or side x order (all ps > .1). However, there was a significant gender x side interaction ($p < .05$), such that seven out of eight females chose the quantity on the left while six out of eight males chose the quantity on the right. Since males and females were distributed equally across counterbalancing conditions, this does not affect the interpretation of the choice data.

Density control condition. Eight of sixteen infants chose the larger amount ($p > .1$). There were no main effects of side or order of presentation (ps > .1), nor did gender interact with choice, side, order, or side x order (all ps > .1).

Discussion

Ten-to-twelve-month-olds performed at chance when even a single dimension, either array perimeter or density, was removed as a cue to amount, despite the minimal memory demands (see Figure 2). This is in stark contrast to research showing that by 6 months, infants' object enumeration abilities remain robust even when continuous variables that co-vary with number have been eliminated as a basis of discrimination (Brannon et al., 2004; Feigenson, 2005; Lipton & Spelke, 2003; McCrink & Wynn, 2004; Wood & Spelke, 2005; Wynn et al., 2002; Xu & Spelke, 2000). The fact that removing even a single cue disrupted performance, even when infants were able to visually compare the portions, suggests that infants' ability to quantify substances is extremely fragile and that they may rely on multiple redundant cues when comparing substance quantities[6].

[6] Note that infants' failure in these conditions provides further evidence that they were not interpreting the substance portions as sets of discrete items. If they had, controlling for continuous variables should not have disrupted performance.

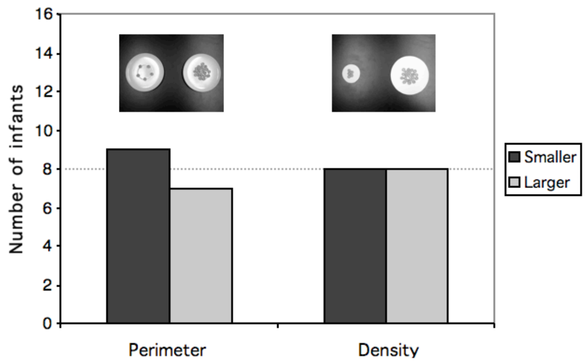

Figure 2. Results of Experiment 2. Eliminating either perimeter or density as a cue to amount led to chance performance.

EXPERIMENT 3a

Removing cues to amount is not the only way to test the limits of infants' substance quantification abilities. Another approach is to limit perceptual access to the substance portions. Experiments 3a and 3b do this by limiting infants' ability to make relative judgments about which quantity is larger. In Experiment 1a, the substance conditions differed from the object condition (and from previous work -- Feigenson, Carey, & Hauser, 2002; Huntley-Fenner et al., 2002) in an important way. In the substance conditions, infants saw both quantities simultaneously, allowing them to visually compare the portions before they were hidden. In the object condition (Expt. 1a) and the large number condition (Expt. 1b), however, the two amounts were never simultaneously visible. Even for a single cup, infants only ever saw one cracker (or O) at a time, requiring them to mentally sum the amounts of food going into each cup, and then compare the total amounts in memory in order to choose correctly. It is possible, therefore, that infants' success in the substance condition in Experiment 1a was because the memory demands were so minimal. Experiment 3a thus tested whether infants would still succeed under conditions where they see only one quantity at a time and have to compare the quantities in memory in order to select the largest.

Method

Participants

Sixteen healthy 10- to 12-month-olds (Range = 10m1d to 12m16d; M = 11m0d), participated in this experiment (eight female). One additional infant was excluded from the final sample for failing to choose.

Stimuli

The stimuli were identical to those in the 1:4 ratio substance condition in Experiment 1a.

Design

All infants chose between two portions differing by a 1:4 ratio. Side and order were again counterbalanced across infants by randomly assigning them to one of four counterbalancing conditions: *lg-R*, *lg-L*, *sm-R*, or *sm-L*. Males and females were distributed equally across the counterbalancing conditions.

Procedure

The procedure was identical to the substance conditions of Experiment 1a except that infants only saw one amount at a time. Following the Warm-up trial, the cups were introduced and set on the floor. The first portion was then brought out and set next to one of the cups. At this point, the experimenter poured the first portion into the cup (with the infant watching) and then placed the (now empty) plate behind her back. Next, she brought out the second plate, set it down next to the other cup, and making sure the infant watched, poured its contents into the cup. Once the second plate had been removed, the infant was allowed to approach the cup of his/her choice.

Results

Eight of sixteen infants chose the larger amount ($p > .1$). There were no main effects of side or order of presentation for either age group (*p*s > .1). Nor did gender interact with choice, side, order, or side x order (all *p*s > .1) (see Figure 3).

Discussion

When unable to compare the portions visually, 10- to 12-month-old infants performed at chance, suggesting that their ability to quantify substances is limited in an important way compared to their ability to quantify objects. One potential explanation for this failure is that the increased memory demands in the sequential task were too taxing for infants of this age to handle. This seems an unlikely explanation for the difference in performance with substances and objects. Although it is true that infants had to hold the first amount in memory longer in the sequential than the simultaneous version of the task, infants' memory was taxed even more in the object condition (Expt. 1a) and the large number condition (Expt. 1b), because the presentation took substantially longer, and yet they succeeded in those conditions at 10- to 12-months.

However, the additional memory demand was not simply a function of the greater amount of time infants had to hold the substance quantities in memory in the sequential version. Infants also had to compare the quantities in memory, which the procedure in Experiment 1a did not require. The results thus far leave open the possibility that infants are able to compare portions of substance, but only if the portions are simultaneously visible. Since adults (vanMarle, Gelman, & Gallistel, 2010; and monkeys, vanMarle et al., 2006) can compare amounts of substance in memory, this capacity must emerge at some point in development. Experiment 3b therefore tested whether 14.5-month-old infants could choose the larger of two substance quantities by comparing the portions in memory.

EXPERIMENT 3b

This experiment asks whether 14.5-month-old infants can reliably choose the larger of two substance portions under conditions where they see only one amount at a time. If infants are able to mentally compare substances quantities by this age, they should reliably choose the larger of the two portions.

Method

Participants

Sixteen healthy 14.5-month-olds (Range = 14m2d to 15m0d; M = 14m19d), participated in this experiment (eight female). Five additional infants were excluded due to failure to choose (one infant), parental interference (one infant), or for making an unclear choice (three infants).

Stimuli, Design and Procedure

The stimuli, design, and procedure were identical in all respects to Experiment 3a.

Results

Twelve of sixteen infants chose the larger amount ($p < .05$). There were no main effects of side or order of presentation for either age group (*p*s > .1). Nor did gender interact with choice, side, order, or side x order (all *p*s > .1). (See Figure 3.)

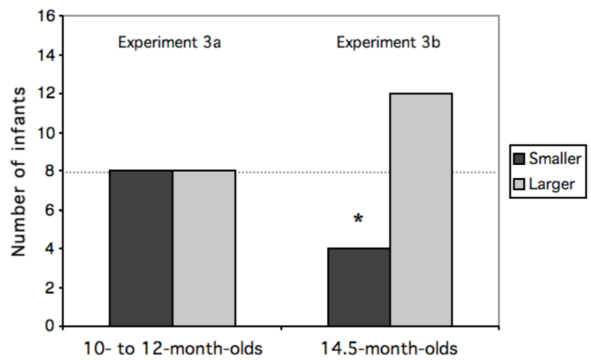

Figure 3. Results of Experiments 3a and 3b. Under conditions more comparable to Feigenson, Carey, & Hauser (2002), where infants only saw one portion at a time, 14.5-month-old infants reliably chose the larger quantity, while 10- to 12-month-olds performed at chance.

Discussion

Though unable to visually compare the portions, 14.5-month-old infants reliably chose the larger, suggesting that the capacity to make ordinal judgments for substance quantities emerges between the ages of 12 and 14.5 months. Another possibility, however, is that older infants simply have better visual tracking abilities and attentional control. Recall that adults have relative difficulty tracking entities that move in the manner of non-cohesive substances compared to entities that move like rigid objects (vanMarle & Scholl, 2003). For example, when tracking four out of eight items simultaneously, adults' performance is significantly more accurate for rigid objects (89%) than non-cohesive entities (67%) (vanMarle & Scholl, 2003). Importantly though, this difference is revealed only under conditions of high attentional load; if asked to track just one or two items, the difference in performance between objects and substances would very likely disappear. The same may be true of infants. Encoding the amounts of the two portions and comparing them in memory may be more attentionally demanding for 10- to 12-month-olds than 14.5-month-olds. On this account, the differential performance would be due to general maturation of visual attentional networks rather than the emergence of a capacity to mentally compare substance quantities. Further research is necessary before the cause of this age difference can be identified.

GENERAL DISCUSSION

Taken together, the present set of results provides initial evidence that by 10 months (the youngest age tested here), infants are able to quantify substances. However, this ability appears to be quite fragile compared to their discrete quantification abilities in a number of ways. First, discriminating substance quantities at this age required a larger ratio difference (1:4) than for (large or small) discrete quantities (1:2). Second, removing just a single perceptual cue to amount (i.e., perimeter or density) disrupted performance, even under conditions where infants could simultaneously view both portions. Third, when infants were prevented from visually comparing the portions and instead had to compare them in memory, 14.5-month-olds, but not 10- to 12-month-olds, reliably chose the larger amount.

Contrary to previous research (Huntley-Fenner, 1995; Huntley-Fenner et al., 2000), the present experiments suggest that infants can quantify substances but only under circumstances in which there is a great deal of perceptual support. The differential performance of 10- to 12-month-olds and 14.5-month-olds in Experiments 3a and 3b suggests a possible explanation for infants' failure in the Huntley-Fenner et al. (2002) study. In that study, infants never saw the second pile of sand on the stage, but instead had to infer its presence there simply by watching sand poured behind an opaque screen. Given that infants had to construct a mental representation of the final display (i.e., the number and size of piles on the stage) and compare that to the number of piles (one or two) revealed behind the occluders, it is perhaps not surprising that the 8-month-old infants failed in that study, since infants in the (arguably easier) sequential version of our task did not succeed until 14.5 months of age. In addition to this, the ratios at which infants succeeded (1:4) and failed (1:2) in Experiment 1a of the present study suggests that infants may also have failed in the Huntley-Fenner et al. (2002) study because the ratio between expected and unexpected outcomes (1:2) was not discriminable.

What mechanism underlies infants' ability to quantify substances?

If infants can indeed quantify substances, how might they do it? The recent literature suggests that two mechanisms may underlie infants' quantification of objects – an object indexing system and an analog magnitude mechanism (Brannon et al., 2004; Cheries, Wynn, & Scholl, 2006; Feigenson, Carey, & Hauser, 2002; Feigenson, Dehaene, & Spelke, 2004; McCrink & Wynn, 2004; Wynn, 1992; Xu & Spelke, 2000). The object indexing system was originally developed to explain adults' ability to simultaneously track small numbers of visual objects (Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, 1989; Pylyshyn & Storm, 1988; Scholl, 2001). It consists of a limited number of indexes that act as pointers to objects out in the world, keeping track of objects' locations as they move through space. The signature property of this mechanism is its limited capacity – it can only track as many objects as it has indexes, which in adults seems to be about four (Pylyshyn & Storm, 1988; Scholl, 2001). Evidence for this mechanism in infants comes from research (described earlier) by Feigenson, Carey, & Hauser (2002) in which infants were able to select the larger of two hidden quantities of crackers, but only as long there were no more than three crackers hidden in either location. The limit on the number of objects infants could represent in a given location was dubbed the "set size signature" and was taken as evidence that infants were using an object indexing mechanism to keep track of the crackers in that task. Using a different paradigm and different stimuli, Feigenson & Carey (2003) found a similar limit of three items on the number of hidden (non-food) objects infants could represent at a time.

The second mechanism, an analog magnitude mechanism, was originally developed in the animal literature to account for pigeons' and rats' ability to represent time (i.e., duration) and number (Gallistel, 1990; Gibbon, 1977; Meck & Church, 1983). Since then, research with adults and children suggests that humans also use analog magnitudes to represent time and number, as well as add and subtract numbers nonverbally (Barth, La Mont, Lipton, Dehaene, Kanwisher, & Spelke, 2006; Barth, La Mont, Lipton, & Spelke, 2005; Barth, Kanwisher, & Spelke, 2003; Cordes, Gelman, Gallistel, & Whalen, 2001; Cordes, Gallistel, Gelman, & Latham, 2007; Dehaene, 1997; Roitman, Brannon, Andrews, & Platt, 2007; Whalen, Gallistel, & Gelman, 1999). The signature property of this mechanism is that discrimination depends on the ratio between two values, rather than their absolute difference, in accordance with Weber's law (Gallistel & Gelman, 1992; Meck & Church, 1983). Thus, it is easier to discriminate 10 from 20 (a 1:2 ratio) than 20 from 30 (a 2:3 ratio), even though the absolute difference between the values (i.e., ten units) is the same in both cases.

Evidence for analog magnitudes in infants has been growing over the last decade. In the temporal domain, infants' ability to discriminate audio-visual events differing in duration appears to depend on the ratio of the durations. Recent research by vanMarle & Wynn (2006) shows that 6-month-old infants discriminate audio-visual events differing by a 1:2 ratio, but not a 2:3 ratio, mirroring 6-

month-olds' number discrimination abilities (see also Brannon, Suanda, & Libertus, in press). Infants' ability to discriminate small and large numbers of items is also ratio-dependent. For example, 6- and 7-month-olds reliably discriminate 2 from 4, 4 from 8, and 8 from 16, but fail to discriminate 2 from 3, 4 from 6, or 8 from 12 (vanMarle & Wynn, 2009; Wood & Spelke, 2005; Xu, 2003, Xu & Spelke, 2000). Such ratio-dependent performance (success with 1:2 ratios, but not 2:3 ratios) suggests that an analog magnitude mechanism may underlie infants' representation of both numerosity and duration.

Infants in the present experiments did not appear to be using object indexes to quantify the substance portions. Nor should they have since the number of individual O's in even a single portion (i.e., 5, 10, and 20) exceeded the set size limit (3 items) of the object indexing mechanism. Nevertheless, it is possible that they could have indexed the plates as objects and the extent of the portions as a feature of those objects, or even each portion of Cheerios as an object. However, if this were the case they should have succeeded in the 1:2 ratio condition just as they did in the 1 vs. 2 crackers condition. Nor did they appear to be creating analog magnitude representations of the *number* of individual objects in each portion. If they had, the 10- to 12-month-old infants should have succeeded in the substance conditions in Experiments 1a and 3a, as well as in the perimeter- and density-controlled conditions in Experiment 2, since we know that they can discriminate large numbers of Cheerios at a 1:2 ratio. Indeed, their successful discrimination of 5 from 10 Cheerios in Experiment 1b strongly suggests that they were treating the Cheerios on the plates in Experiment 1a not as groups of individual objects, but as a portion of stuff.

Alternatively, they could have used analog magnitudes to represent the *total amount* of substance in each portion. One might expect that analog magnitude representations are at least adequate, if not ideal, for representing continuous spatial quantities. Analog magnitude representations are themselves continuous, not discrete, and they have long been thought to underlie the representation of at least one type of continuous quantity – duration (Gallistel, 1990; Gibbon, 1977; Meck & Church, 1983, vanMarle & Wynn, 2006). And more recently, research with infants suggests that they represent at least one type of spatial quantity with analog magnitudes. Research by Brannon et al. (2006) suggests that 6-month-old infants' ability to discriminate the surface area of a single element is ratio-dependent, and shows the same Weber function as found for time and number in infants of the same age (success with 1:2 ratios and failure with 2:3 ratios).

If infants used analog magnitudes to represent substance quantities, why did they require a larger ratio difference than has been found for enumeration of discrete objects? One possibility is that the process of estimating "amount of substance" is more variable than estimating "number of objects". That is, given that non-cohesive substances change their shape and break apart upon movement, it may be especially difficult to estimate their size because they do not present a perceptually stable form. Having to continually update an estimate of surface area could introduce a substantial amount of error into the representation.

Another potential source of error could arise when the substance portion disintegrates upon movement. For example, infants might have formed a relatively accurate estimate of amount when viewing the static substance portions, but this representation could have been destroyed when the portions were poured into the cups. In support of this possibility, recent research suggests that infants' object representations are indeed disrupted when the represented object violates cohesion. Using the same choice paradigm we used here, Cheries, Mitroff, Wynn, & Scholl (2008) showed that although infants reliably chose two crackers over one, they chose randomly when the larger number (two) was created by splitting one big cracker into two halves before hiding them in the cup. Thus, infants in the present study may have lost their original representation when the substance portions violated cohesion, and had to construct a new representation of amount from memory, resulting in a less accurate representation than the original.

It is also possible that the bigger proportionate difference needed in Experiment 1a was due not to greater error in infants' substance quantity representations, but to greater error in their cumulative area estimates for groups of objects. This is a subtle distinction. On this account, infants were viewing the substance portions as collections of individual objects and estimating their cumulative continuous extent (e.g., cumulative surface area or volume). In fact, there is some evidence in support of this possibility. Recent research by Cordes and Brannon (2008) suggests that infants' representations of cumulative surface area contain more error than their representations of surface area for a single item such that infants required a 1:2 ratio when discriminating the surface area for a single Elmo face, but a 1:4 ratio when discriminating the cumulative surface area of a set of Elmo faces. Thus, the process of cumulating surface area over multiple items engenders error in the resulting representation. Our data cannot by themselves rule out this possibility. However, given that the infants in Cordes and Brannon's study were 6 months of age, and given that we know infants' analog representations of number and time become more precise as infants get older (Brannon et al., 2007; Lipton & Spelke, 2003), one might expect that by 10 months, infants' cumulative object area representations would have become precise enough to support discrimination at a 1:2 ratio, suggesting that infants' difficulty in our studies lies in the "substancy" nature of the Cheerios portions. In support of this possibility, since Feigenson, Carey, and Spelke (2002) showed that infants in the choice task actually make their choice on the basis of total amount, not number of objects, the fact 10- to 12-month-old infants succeeded in Experiment 1b with large sets of Cheerios suggests that infants can discriminate summed area (or some other continuous variable) at a 1:2 ratio by this age.

In conclusion, the present experiments provide initial evidence that (a) infants can quantify non-cohesive substances and (b) this ability is quite fragile relative to their ability to enumerate objects. The present findings shed light on the conflicting results of earlier research by suggesting that earlier failures (e.g. Huntley-Fenner, 1995, Huntley-Fenner et al., 2002) may have been due to the fact that infants require a larger proportionate difference to discriminate substance quantities than object quantities. Additionally, the differential memory demands between the present task and that used by Huntley-Fenner et al. (2002) could also have contributed to the differing patterns of performance. Understanding how precisely infants are able to quantify different types of entities can help us identify the extents and limits of infants' quantification abilities, and provide a baseline from which to measure the development of such abilities over the first few years of life. Given that scientific and mathematical thinking require the manipulation of many different types of quantity information over entities that vary in their properties (e.g., rigidity, cohesiveness, etc.), it is important to determine what early competencies may exist so that educators can use them as a foundation to help children build basic scientific concepts.

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