Title
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Authors
Chen, Marian L.
Leslie, Alan M.

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Marian L. Chen (chenml@ruccs.rutgers.edu)
Rutgers University Center for Cognitive Science
152 Frelinghuysen Road, Piscataway, NJ 08854, USA

Alan M. Leslie (aleslie@ruccs.rutgers.edu)
Rutgers University Center for Cognitive Science
152 Frelinghuysen Road, Piscataway, NJ 08854, USA

Abstract

Many studies have found that infants in the first year use only continuous quantities to represent small sets of objects. We show that 12-month-olds use discrete quantity representations even when continuous quantity information is available. In three studies, infants are required to track the changing locations of objects and sets of objects on a trial-by-trial basis. In the first study, infants are surprised to see two objects behind a screen when one was expected. In the second study, infants were surprised to see both one and three objects when two objects were expected, despite the total surface area of the sets remaining constant. A final study demonstrates that infants tracked the locations of a singleton and a pair and were surprised when the sets unexpectedly swapped positions. Infants can flexibly tailor their use of discrete and continuous quantity information according to the nature of the task.

Keywords: infant development; number; object tracking; discrete quantity; continuous quantity.

Young infants track multiple physical objects through occlusion (Baillargeon, 1986; Spelke, 1990; Wynn, 1992; Xu & Carey, 1996). What kind of representations do infants generate for the objects they are tracking? Two broad possibilities have been proposed. The first is that infants sum across continuous properties of the objects, such as area or perimeter, and store the resulting total in memory (Clearfield & Mix, 1999, 2001; Feigenson, Carey and Spelke, 2002; Feigenson, Carey and Hauser, 2002). The second is that infants store a representation of the individual objects, either by enumerating them non-verbally (Gallistel and Gelman, 1992; Simon, Hespos and Rochat, 1995; Wynn, 1992; Xu and Spelke, 2000) or by maintaining attentional indexes to each of the objects (Leslie, Xu, Tremoulet, and Scholl, 1998; Scholl & Leslie, 1999). In contrast to summing continuous magnitudes, both counting and indexing represent a set of individuals discretely.

One outstanding issue in multiple object tracking is whether infants really track discrete quantity (Clearfield and Mix, 1999, 2001). For example, Wynn's findings (Wynn, 1992) can be re-interpreted as showing that infants simply track the total amount of "Mickey Mouse stuff." Almost all the evidence for sensitivity to discrete quantity comes from studies using large sets of texture elements (Lipton & Spelke, 2003; Xu, 2003; Xu & Spelke, 2000). Addressing this issue with small sets of physical objects requires controlling both total area and total perimeter of the objects displayed.

Another issue, methodological in nature, is that infants may prefer numerically unexpected but familiar displays (Cohen and Marks, 2002). For example, in Wynn's (1992) study, infants looked longer at an impossible result of 1+1=1. Wynn interpreted these results as showing that infants expected that 1+1=2 and looked longer when this expectation was violated. Cohen and Marks (2002) proposed an alternative explanation that infants prefer to look at the unexpected outcome of 1, as they were familiarized to displays of 1. Wynn's test outcomes confounded familiarity and expected number. Infants may thus not be tracking the numerosity of a given set of objects but rather responding in a more superficial way.

Two studies provide evidence that infants can represent sets discretely where they might have represented the sets continuously. The first, using a reaching task, found that 12-14 month-olds appear to represent up to three objects hidden inside a box, even when objects retrieved are larger than the objects that were concealed (Feigenson and Carey, 2003). Infants tracked how many objects came out of the box, not a total amount of stuff. Familiarity could not have played a role as it was not a looking time study.

The second study to show evidence for discrete representation of small sets by infants found that 7-month-old infants detected changes in numerosity when habituated to displays of objects that differed in both color and texture (Feigenson, in press). These results contrasted with the results of Feigenson, Carey and Spelke (2002), who found that infants failed to track changes in number when objects differed only in color.

To our knowledge, these are the only studies to date that provide evidence of discrete quantity tracking for small sets of occluded physical objects under controlled conditions. The problem of controlling for continuous variables when using real-world objects remains intractable. Previous studies attempted to control for area and perimeter by varying total extent while keeping number constant or introducing texture information as a way to equate perimeter. Bearing in mind that changes in area necessarily result in changes of perimeter, we designed our studies so that we could look separately at the effect of changes of total number, total area, and total perimeter.

We used Káldy and Leslie's (2003) two-screen methodology to test whether infants track discrete or continuous quantities through occlusion. To succeed, infants had to attend to the locations of the objects as well as the objects themselves. We pitted discrete number against area in test displays. Either numerical outcome changed or total area changed, but not both. If infants tracked based on continuous quantities, they should have looked longer only at outcomes where area or perimeter changed even when number remained the same. If infants tracked based on discrete variables, they should have looked longer only at numerically different outcomes, even if area remained constant. Because perimeter and area cannot be simultaneously controlled, all non-control outcomes had changes in total perimeter. However, in conditions where number did not change, total perimeter change was always equal to or less than perimeter change in number change conditions. In this way, we were able to investigate the role of perimeter change separately from that of area change.

This methodology also allows us to rigorously test for a familiar-number preference Looking-time patterns will show whether infants developed a familiarity preference for the total number (three). In test trials, if we remove the screen covering the pair, we can test for outcomes of one (unexpected), two (expected), and three (unexpected, but possibly 'familiar'). If infants look longer only at the outcome of three but not also at the outcome of one, this would be consistent with a familiarity preference for total number. We can also determine if infants develop a familiarity preference for the pair. If so, then they will look longer only at (expected) outcomes of two. However, if infants have a novelty preference for number, they should look longer at *both* of the unexpected outcomes, namely one and three.

Experiment 1

Design

The design is illustrated in Figure 1.

Apparatus

Infants sat on their caregiver's lap about one meter away from the display. Displays were shown on a white poster-board stage, 90 cm wide x 50 cm deep x 45 cm high. The floor of the stage was covered with blue contact paper. The back of the stage concealed two trap doors, which allowed the experimenter to make surreptitious substitutions during test trials. Two 40W light bulbs illuminated the stage. At the end of trials, a yellow felt curtain was raised to cover the display. A metronome ensured consistent timing between subjects.

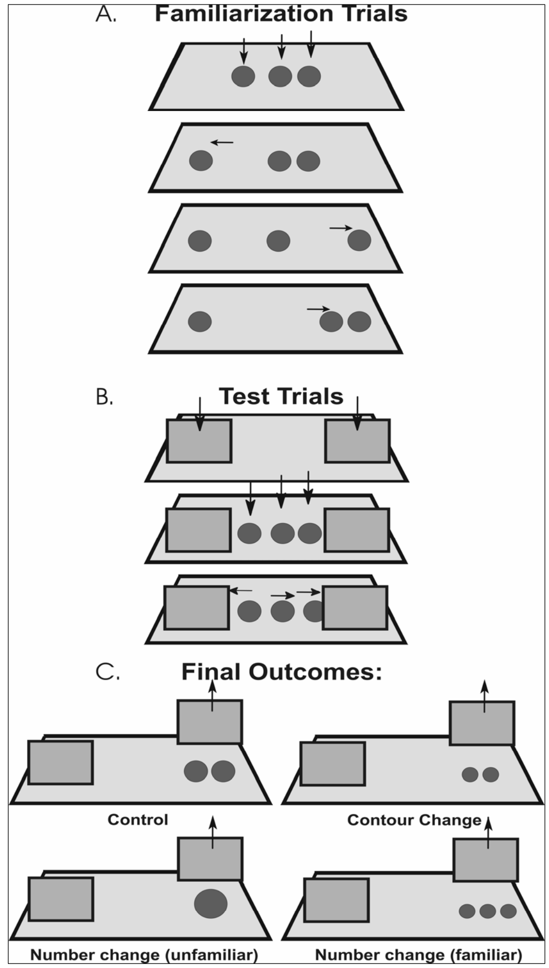

Figure 1: Experiment 1. Infants were familiarized to three discs of radius 1.41", introduced individually and placed on their edges in the center of the stage in a group of one and a group of two. The group of one was always introduced first and in trials 1 and 3 appeared to the infants' left; in trials 2 and 4, to the infants' right. The group of two was always on the side opposite to the group of one. The sidedness of a group reversed on alternate trials. Discs were tapped twice on the floor of the stage to ensure that infants attended to the discs' placement. The discs were moved individually to the far sides of the stage. In test trials, two screens were first lowered simultaneously onto the stage. The three discs were then introduced following the same protocol as familiarization trials and moved behind the screens. The screen occluding the group of two was lifted to reveal one of four possible outcomes. The disks are depicted only roughly to scale; see Table 1 for their dimensions.

Stimuli

The stimuli consisted of two or three R1.15" discs, three R1.41" discs, and one R2" disc. All discs were wooden and painted red. All discs were presented on their edges. The total areas and perimeters are shown in Table 1.

Table 1. Dimensions of stimulus sets used in experiment 1

	Total Area	**Total Perimeter**
1 x 2" disk	12.56 in^2	12.56 in
2 x 1.41" disks	12.56 in^2	17.76 in
3 x 1.41" disks	18.84 in^2	26.64 in
2 x 1.15" disks	8.31 in^2	14.46 in
3 x 1.15" disks	12.56 in^2	21.7 in

Procedure

Infants were familiarized to three discs in a group of one and a group of two (all R1.41"), which were introduced and then moved individually to the sides of the stage. Sidedness of the presentation of the discs alternated trial by trial. Infants saw four familiarization trials, in which they saw the pair and singleton equally often on both sides. This side alternation was continued through three test trials. Test trials were identical to familiarization trials except at the beginning of each test trial two screens were introduced on either side of the stage. The discs were then presented in the same way as during the familiarization. When moved to the sides of the stage, they were placed behind their respective screens. The screen occluding the pair was then lifted.

Infants saw only one of the four test outcomes in a between-subjects design. In two of the outcomes, Control and Area/Perimeter Change, the numerical outcome remained the same. However, in the Area/Perimeter Change condition, the total area of the resulting display was only 81% of the total area of the original two circles while total perimeter decreased by 34%. In Number Change outcomes, total area remained the same, but number changed either to a familiar numerical outcome (3) or an unfamiliar numerical outcome (1). We considered three to be the familiar numerical outcome because infants were familiarized to a total of three items. In the Familiar Number condition, total perimeter increased by 22%; in the Unfamiliar Number condition, total perimeter decreased by 30%. Crucially, the total perimeter change in the Area/Perimeter Change condition is larger than in either of the Number Change conditions. As it is impossible to simultaneously equate area and perimeter of the numerical outcomes, this allows us to take into account infants' reactions to changes of total perimeter. If infants look longer in both Number Change conditions but not in the Area/Perimeter Change condition, then we can rule out the possibility that infants reacted to changes in total perimeter. If infants look longer in all non-control conditions, changes in total perimeter, rather than changes in total area, would be the most likely cause.

Subjects

83 infants (40 girls, age 47-56 weeks, mean age 51 weeks) were recruited as described in experiment 1. An additional 39 infants were tested but dropped due to fussiness/sleepiness (18), experimenter error (9), equipment failure (8), parental interference (3), and being a statistical outlier (1). Subjects were randomly assigned to one of four conditions, Control (n=20), Unfamiliar Number Change (n=22), Familiar Number Change (n=20), or Area /Perimeter Change (n=21).

Results

Mean looking times on all three test trials were analyzed in a repeated measures ANOVA with factors Trials (3) x Condition (4). One infant was dropped from the analysis because the third trial was not completed. There was no significant main effect of Trials and no Trials interactions. There was a significant main effect of Condition ($F_{3,\ 78}$ = 3.45, p = .021, η^2 = .117).

The same pattern of results was found when only first test trial looking times were analyzed (see Figure 2). Data from all infants were analyzed. Again, a significant main effect of Condition was found ($F_{3,\ 79}$ = 3.04, p = .034, η^2 = .104). Post-hoc Dunnett's *t* revealed that infants in both the Familiar Number Change (3) and Unfamiliar Number Change (1) groups looked significantly longer than Controls (t_{38} = −2.83, p = .015 and t_{40} = −2.246. p = .033, respectively). Infants in the Area/Perimeter Change group did not look significantly longer than Controls despite changes in both area and perimeter (t_{39} = −0.98, p = .43).

Planned comparisons found no difference in first trial looking to the Familiar and Unfamiliar Number Change conditions (t_{40} = 0.3, p = 0.38, one-tailed). We therefore collapsed data from these groups (mean 11.8 seconds) and compared them with first trial looking in the Area/Perimeter Change condition. Exploration of this data set indicated severe departures from normality. We therefore examined the data in two ways. First, we entered log transformed looking times into a t-test which showed longer looking in the Number Change condition (t_{61} = 2.37, p = 0.021, two-tailed). Second, we entered the raw looking times into a non-parametric analysis, which confirmed longer looking to Number Change (Mann-Whitney U = 281.5, z = 2.33, p = 0.02, two-tailed).

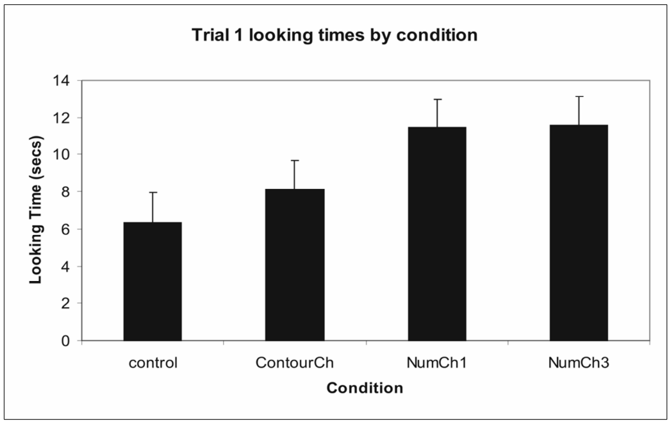

Figure 2: Experiment 1. First test-trial looking times to each of four outcome conditions.

Discussion

Infants did not look significantly longer at a numerically-expected outcome when area and perimeter both decreased. They did look significantly longer at both unexpected number outcomes even though the total area of both number change displays was the same as in the Control condition. The design of Experiment 1 also allows us to rule out changes in perimeter as driving longer looking times. If infants reacted to perimeter, they should have looked longer at the Area/Perimeter Change condition, which had the largest amount of perimeter change. They did not.

The results of Experiment 1 also cannot be accounted for by familiarity preference. Familiarity would not account for why infants preferred to look longer at displays of 1 and 3 objects, but not 2. Infants did not appear to adopt either a global (3) or local (1 or 2) number preference. These results indicate that unexpected number outcomes were indeed unexpected, and are consistent with a novelty preference for unexpected outcomes.

Neither changes in continuous quantity nor familiarity preferences account for our results. Infants form a discrete representation of numerosity; but do they use this representation to track the sets?

Our design failed to rule out one possibility: infants are not tracking the sets, but simply look longer at any unfamiliar group of objects. We did not test with the familiarized sets in the wrong location. If infants track sets using discrete number, they should be surprised to see the expected sets in unexpected locations.

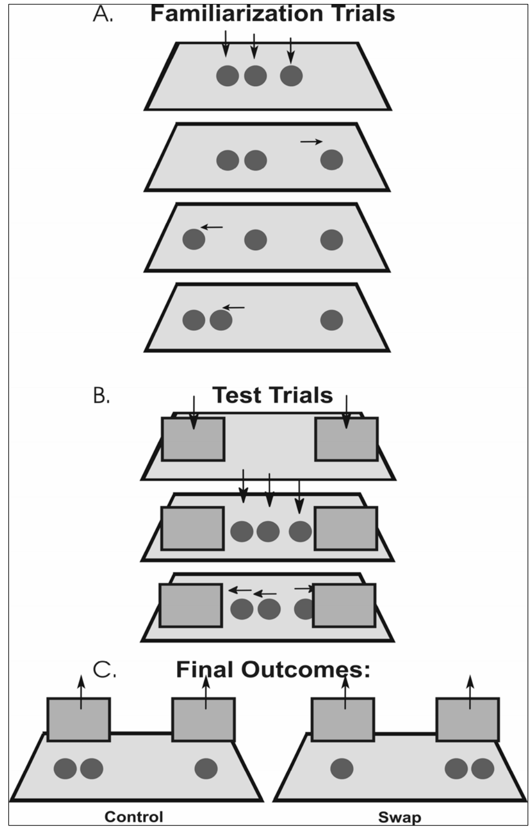

Figure 3. The design of experiment 2 was the same as experiment 1 except that in test trials both screens were removed to reveal one of two outcomes, the disks in their expected locations (control) or in swapped locations (swap).

Experiment 2

The previous experiment showed that babies are sensitive to number. In this experiment, we repeated experiment 1, but modified the test trials by removing both screens to show both sets of discs. In the control condition, infants saw the expected groups in their expected locations. In the swap condition, the locations of the expected groups were swapped (Fig. 3). Infants will be surprised to see the expected groups swap locations only if they have a definite expectation for both number and location of the items behind the screens. This design also controls precisely for continuous quantity, as infants see the exact same sets in both conditions.

Design

The design is illustrated in Figure 3.

Apparatus

Same as Experiment 1.

Stimuli
Same as Experiment 1.

Procedure
The familiarizations were the same as in experiment 1; two test trials followed; these were also the same, except that both screens were removed simultaneously to reveal either a control outcome (Figure 3a) or a swap outcome (Figure 3b).

Subjects
24 infants (9 girls, 43.7 weeks to 56.7 weeks, mean age 50.7 weeks, sd 3.75 weeks) were tested, with 12 in each condition. A further four infants were excluded for fussing.

Results
Infants in the swap condition looked significantly longer than controls (15.54s vs 7.65s); ANOVA with Condition (2) x Trials (2) showed only a significant effect of Condition ($F_{1, 22} = 6.68$, $p = .017$, $\eta^2 = .23$, *p-rep* = .919).

Discussion
Infants not only encode the discrete numerosity of two sets, they can also use number to track the locations of the sets. The total continuous and discrete variables of the displays are identical across conditions; only the location of the sets changes. Infants not only track the total number of objects, they also track the location of sets across trials and are surprised when their expectations are violated.

General Discussion
Previous studies have largely failed to find unambiguous evidence that infants attend to discrete as opposed to continuous quantity in representing small sets of objects. Our findings indicate that infants represented discrete quantity, while ruling out total area, total perimeter, and individual diameter (experiment 1). Adults readily extract the average area from a set of disks (Ariely, 2001). In our sets individual diameter was proportional to average area but infants did not respond to diameter; looking times in the Number Change (3) group were longer than in the Area/Perimeter Change group, though both have the same average area ($t_{39} = 2.26$, $p = 0.03$, two-tailed).

Why did we find for discrete quantity where others have found for continuous? Our two-screen method requires infants to track objects trial by trial (Káldy and Leslie, 2003, 2005). Infants have to keep track of objects or sets as they change location. Over trials, each object or set is associated with all locations equally. This may force infants to rely upon a constantly updated working memory for object location. Experiment 2 showed that infants notice discrepancies in the locations of object sets. This can only be done via trial-by-trial tracking. Perhaps we found discrete number effects because we made it critical for tracking set identities.

Many number tasks require infants to extract number as the common feature across several successive displays; our two-screen method encourages infants to compare the number of two concurrently displayed sets. Concurrent displays are known to simplify other tasks (Xu & Carey, 1996). Although infants could have used either discrete or continuous quantity information to track the sets in experiment 2, they used only discrete. However, our findings do not rule out the use of continuous quantities for object tracking with larger differences in area totals (Brannon, Lutz and Cordes, in press).

A further advantage of the two-screen methodology is that it allowed us to test for familiarity preference. Dividing the total number of objects in two groups enables us to vary the number of objects within individual sets so that all possible familiar numerical outcomes are tested. If the preferred familiar number was the global total 3, infants would prefer only the outcome of 3; if the preferred familiar number was one of the local sets (1 or 2), then they would prefer either the outcome of 1 or the outcome of 2. What we found instead was a preference for both 1 and 3, a novel number preference.

By 12 months of age, infants do not rely only on continuous quantity judgments to track objects in the world, but also have access to discrete quantity information. Continuous and discrete quantity representations are not mutually exclusive and infants may use both, with the most appropriate information driving their behavior. For example, infants interested in maximizing amount of food would select one large cracker rather than two smaller crackers, even though the numerical outcome is smaller (Feigenson, Carey and Hauser, 2002), while infants may resort to something like counting if the number of individuals to be attended to exceeds parallel individuation (Xu and Spelke, 2000; Chiang and Wynn, 2000). Further work must be done to clarify how infants track small sets by discrete numerosity, when that provides the critical information. There are at least three possibilities for how they do this: by object files or indexes; by the specific set representations, SINGLETON, PAIR; or by integer representations (Leslie & Chen, in press; Leslie, Gallistel & Gelman, in press). Whether this ability is truly numerical in nature remains to be seen.

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References

Ariely, D. (2001). Seeing sets: Representation by statistical properties. *Psychological Science*, **12**.

Baillargeon, R. (1986). Representing the existence and the location of hidden objects: Object permanence in 6- and 8-month old infants. *Cognition*, **23**.

Brannon, E.M., Lutz, D., & Cordes, S. (2006). The development of area discrimination and its implications for number representation in infancy. *Developmental Science*, **9**.

Chiang, W., & Wynn, K. (2000). Infants' tracking of objects and collections. *Cognition*, **77**.

Clearfield, M.W., & Mix, K.S. (1999). Number versus contour length in infants' discrimination of small visual sets. *Psychological Science*.

Clearfield, M.W., & Mix, K.S. (2001). Amount versus number: Infants' use of area and contour length to discriminate small sets. *Journal of Cognition & Development*, **2**.

Cohen, L.B., & Marks, K.S. (2002). How infants process addition and subtraction events. *Developmental Science*, **5**.

Feigenson, L. (in press). A double-dissociation in infants' representation of object arrays. *Cognition*.

Feigenson, L., & Carey, S. (2003). Tracking individuals via object-files: evidence from infants' manual search. *Developmental Science*, **6**.

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object files versus analog magnitudes. *Psychological Science*, **13**.

Feigenson, L., Carey, S., & Spelke, E. (2002). Infants' discrimination of number vs. continuous extent. *Cognitive Psychology*, **44**.

Gallistel, C.R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, **44**.

Káldy, Z., & Leslie, A.M. (2003). The identification of objects by 9-month-old infants: integrating 'what' and 'where' information. *Developmental Science*, **6**.

Káldy, Z., & Leslie, A.M. (2005). A memory span of one? Object identification in 6.5-month-old infants. *Cognition*, **97**.

Leslie, A.M., & Chen, M.L. (in press). Individuation of pairs of objects in infancy. *Developmental Science*.

Leslie, A.M., Gallistel, C.R., & Gelman, R. (in press). Where the integers come from. In P. Carruthers (Ed.), *The innate mind: Foundations and future*. Oxford: Oxford University Press.

Leslie, A.M., Xu, F., Tremoulet, P.D., & Scholl, B.J. (1998). Indexing and the object concept: Developing 'what' and 'where' systems. *Trends in Cognitive Sciences*, **2**.

Lipton, J.S., & Spelke, E.S. (2003). Origins of number sense: Large-number discrimination in human infants. *Psychological Science*, **14**.

Scholl, B.J., & Leslie, A.M. (1999a). Explaining the infant's object concept: Beyond the perception/cognition dichotomy. In (Eds.), E. Lepore & Z. Pylyshyn, *What is Cognitive Science?* Oxford: Blackwell.

Simon, T.J., Hespos, S.J., & Rochat, P. (1995). Do infants understand simple arithmetic? A replication of Wynn (1992). *Cognitive Development*, **10**.

Spelke, E.S. (1990). Principles of object perception. *Cognitive Science*, **14**.

Wynn, K. (1992a). Addition and subtraction by human infants. *Nature*, **358**.

Xu, F. (2003). Numerosity discrimination in infants: Evidence for two systems of representations. *Cognition*, **89**.

Xu, F., & Carey, S. (1996). Infants' metaphysics: The case of numerical identity. *Cognitive Psychology*, **30**.

Xu, F., & Spelke, E.S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, **74**.