Research Article

THE REPRESENTATIONS UNDERLYING INFANTS' CHOICE OF MORE: Object Files Versus Analog Magnitudes

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Abstract—*A new choice task was used to explore infants' spontaneous representations of more and less. Ten- and 12-month-old infants saw crackers placed sequentially into two containers, then were allowed to crawl and obtain the crackers from the container they chose. Infants chose the larger quantity with comparisons of 1 versus 2 and 2 versus 3, but failed with comparisons of 3 versus 4, 2 versus 4, and 3 versus 6. Success with visible arrays ruled out a motivational explanation for failure in the occluded 3-versus-6 condition. Control tasks ruled out the possibility that presentation duration guided choice, and showed that presentation complexity was not responsible for the failure with larger numbers. When crackers were different sizes, total surface area or volume determined choice. The infants' pattern of success and failure supports the hypothesis that they relied on object-file representations, comparing mental models via total volume or surface area rather than via one-to-one correspondence between object files.*

Data from many paradigms suggest that infants represent quantity: both numerical quantity and quantity along dimensions of continuous extent such as surface area or volume (Antell & Keating, 1983; Bijeljac-Babic, Bertoncini, & Mehler, 1993; Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, in press; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Van Loosbroek & Smitsman, 1990; Wynn, 1996). In habituation studies, infants are sensitive to matches or mismatches in number: Habituated to arrays of 2 items, infants from a few days through 7 months old dishabituate to an array of 3. Conversely, when habituated to 3 items, infants dishabituate to 2. Recently, Xu and Spelke (2000) extended this finding to a discrimination of 8 dots from 16. Further evidence comes from studies showing that infants represent the outcomes of addition to and subtraction from hidden sets, looking longer at outcomes of 1 object than outcomes of 2 objects in 1 + 1 events, relative to 2 – 1 events (Feigenson et al., in press; Koechlin, Dehaene, & Mehler, 1997; Simon, Hespos, & Rochat, 1995; Uller, Huntley-Fenner, Carey, & Klatt, 1999; Wynn, 1992).

Understanding infants' representations of quantity requires progress on two fronts: characterizing the format of those representations and characterizing the computations infants can perform over them. As for the computations infants can perform, the results just summarized suggest that in at least some circumstances infants are sensitive to the numerical equivalence between sets, and in some circumstances they are sensitive to equivalence of continuous extent between sets.

Granting that infants represent quantity, both numerical and continuous, leaves open the question of representational format. Do infants represent number as a symbol, perhaps via a system of analog magnitudes or number-line representations (Gallistel, 1990; Wynn, 1998)? According to this proposal, the number of items in a set is represented as a single magnitude proportional to number (Fig. 1a). This magnitude exhibits scalar variability, and thus quantity discrimination is subject to Weber's law, according to which the discriminability of two quantities is a function of their ratio (Gallistel & Gelman, 1992; Whalen, Gallistel, & Gelman, 1999; Wynn, 1998). This kind of mental magnitude could also serve as a representation of continuous quantity. In this case, rather than being proportional to the number of individuals in an array, the magnitude would be proportional to the total surface area or volume contained in the array.

An alternative to representing quantities as analog magnitudes is representing the total number of individuals only implicitly, as in object-file systems of representation. According to this proposal, each individual in the array is represented by a distinct symbol (a file), and numerical equivalence is established by evaluating one-to-one correspondence between the files in two models (Simon, 1997; Uller et al., 1999) or between attentional indices and objects in the array (Leslie, Xu, Tremoulet, & Scholl, 1998; see Fig. 1b).

What kind of evidence might distinguish between analog-magnitude and object-file systems? Success in tasks supported by analog-magnitude representations is determined by Weber's law; the ratio between quantities determines whether they are successfully discriminated. Success in tasks supported by object-file representations, in contrast, is determined by the total number of individuals in the set (Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, 1989, 1994). The absolute limit on the number of individuals that can be represented in parallel and stored in short-term memory yields an empirical *set-size signature*: success at representing sets of about 4 or fewer objects, and failure with larger numerosities.

In a previous study (Hauser, Carey, & Hauser, 2000), we obtained the set-size signature of object-file representations in an experiment with rhesus macaques. Each monkey participated in only one trial, choosing between two quantities of apple slices. For example, some monkeys saw an experimenter place 1 apple slice in a box on the left and 2 slices in a box on the right. The dependent measure was which box was approached first. The monkeys successfully chose the greater number with comparisons of 1 versus 2, 2 versus 3, and 3 versus 4, but failed with 4 versus 5, 4 versus 6, 4 versus 8, and 3 versus 8. Contrary to the pattern of performance expected under an analog-magnitude representation of quantity (success determined by the ratio between apple slices, with no upper limit on success), success was determined by the size of the larger set. The monkeys failed when the larger set contained more than 4 items, even with the extremely favorable 3-versus-8 ratio. From this pattern, we concluded that the monkeys relied on object-file representations to make more/less judgments in this task.

An open question, then, is whether human infants rely on object-file representations or on analog-magnitude representations in any given quantity task. Contrasting the set-size signature of object files with the Weber-fraction signature of analog magnitudes provides a way of knowing which system of representations is deployed. It is only upon knowing which system is deployed in a task that researchers may use data from it to constrain models of that system.

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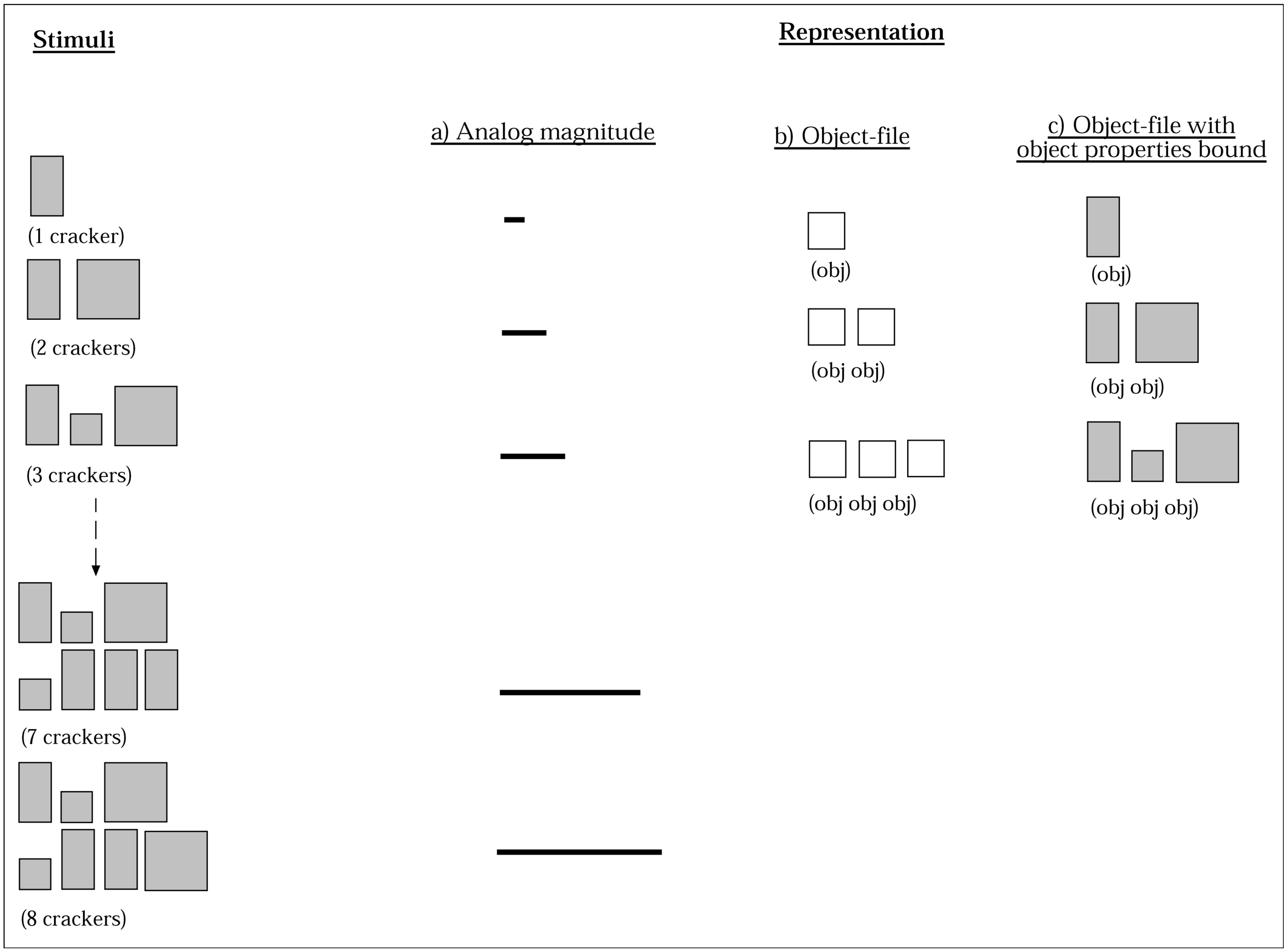

Fig. 1. Representations of number. In analog-magnitude representations (a), the number of individuals in the stimulus set is represented by a magnitude that is a linear function of the cardinal value of the set. In object-file representations (b), one file is opened for each individual in the stimulus set, regardless of stimulus properties. Object files are limited to sets of no more than 3 (for infants) or 4 (for monkeys) objects. In object-file representations with properties bound to the files (c), one file is opened for each individual in the stimulus set, and object properties such as surface area are bound to each file. Object files are limited to sets of 3 or fewer objects.

In addition to determining the representational format of infants' quantity representations, researchers need to know what computations can be performed over these representations. Habituation studies provide evidence that infants recognize quantitative equivalence between sets. A separate question is whether infants also represent quantitative relationships between sets—besides seeing 2 as different from 1, do infants recognize that 2 is more than 1, either in number or in continuous quantity? The addition-subtraction experiments do not bear on this question, for they show only that infants are sensitive to a match versus a mismatch between the expected number of individuals (or amount of total continuous extent; see Feigenson et al., in press) and that in the revealed set.

The results of several experiments suggest that infants might recognize more/less relationships. Strauss and Curtis (1984) found that 16- to 18-month-old infants learned to select the numerically greater of two arrays of dots. This ability was limited to comparisons of 1 versus 2 and 2 versus 3; infants failed with 3 versus 4. In another demonstration, Cooper (1984) habituated infants to sequential display pairs in which the first array contained more items, fewer items, or the same number of items as the second array. Ten- to 12-month-old infants dishabituated to changes from pairs containing the same number of items to pairs containing different numbers. However, they did not respond to changes in more/less relationships. Cooper reported that 14- to 16-month-olds successfully discriminated both same/different and more/less relationships, but did not present data on performance with particular numerosities. Finally, Sophian and Adams (1987) gave children of 14, 18, 24, and 28 months choices between arrays of varying numerosity. With 1-versus-2 comparisons, the oldest and the youngest age groups chose the array with the greater numerosity. These three studies provide preliminary evidence that infants recognize more/less relationships.

The present experiments had three aims. First, we wanted to develop a new, naturalistic method for exploring whether infants spontaneously represent more/less relationships between object sets. Second, we asked whether infants' pattern of performance, like that of the monkeys we had studied earlier, would reveal the set-size signature of object-file representations. Finally, we investigated whether infants' relational choices were based on number or total quantity.

EXPERIMENT 1

In Experiment 1, we adapted the choice task from our study with monkeys (Hauser et al., 2000) to explore whether infants spontaneously represent more/less relationships. Ten- and 12-month-old infants were tested to probe for a developmental change in ability (Cooper, 1984). We included the comparisons 1 versus 2 and 2 versus 3 because infants have successfully discriminated these in habituation tasks. Infants were also tested with three larger comparisons, 3 versus 4, 2 versus 4, and 3 versus 6, so we could discern the upper limits of spontaneous discrimination and assess whether the results showed the Weber-fraction signature of analog-magnitude representations or the set-size signature of object-file representations.

Method

Participants

Participants were 124 full-term infants, approximately half of whom were 10 months old (mean: 10 months 13 days) and half of whom were 12 months old (mean: 12 months 14 days). Approximately half of the infants were boys (50/122). Sixteen infants from each age group participated in the 1-versus-2, 2-versus-3, and 3-versus-4 conditions.[1] Sixteen 12-month-olds participated in the 2-versus-4 condition, and ten 10-month-olds and six 12-month-olds participated in the 3-versus-6 condition. An additional 46 infants were not included in the analysis because of fussiness (8 infants) or failure to make a choice (38 infants).[2]

Stimuli

Graham crackers measuring 6.5 cm × 3 cm were removed from a small plastic bucket and placed into two large opaque containers. The containers (13 cm in diameter, 14.5 cm high) were too tall for the infants to see their contents.

Design and procedure

Each infant sat on the floor, 100 cm from the experimenter. The experiment began with a warm-up trial. The infant saw a toy placed in the small bucket, and was encouraged to crawl to the bucket and retrieve the toy. If the infant did not immediately do so, the experimenter provided verbal encouragement.

For the critical trial, parents were instructed not to provide any feedback. The experimenter introduced the two large containers simultaneously and showed that they were empty. She placed them on the floor between herself and the infant, one on either side of the midline. The containers were approximately 70 cm from the infant and 35 cm from the midline, far enough apart so that the infant could not reach both containers at once. For each placement, the experimenter retrieved a cracker from the small bucket and held it above the large container. She showed it to the infant and said, "Look at this," then placed it in the container. All crackers were placed sequentially. Side (larger number on the left or right) and order of presentation (larger number placed first or second) were counterbalanced across infants, with each infant receiving only one trial. The experimenter did not place crackers into the containers unless she saw that the infant was watching her do so.

After the presentation, the experimenter looked down to avoid cuing the infant. If the infant did not approach within 10 s, the experimenter provided verbal encouragement without looking up. If the infant did not approach after an additional 10 s, the experiment was terminated. Infants were considered to have made a choice when they either reached into one of the containers or approached a container and sat in front of it for at least 8 s without reaching in. Infants who approached and looked into one container but then chose the other one were considered to have failed to make a choice, and were excluded from the analysis (2 infants). Choices were videotaped. Critical trials for 36 randomly selected infants were double-coded by observers blind to placement of the crackers. Agreement was 100%.

Results and Discussion

The results are shown in Figure 2. In no condition was there an effect of side or presentation order, nor any difference between boys and girls. Infants in both age groups chose the larger number in the 1-versus-2 condition (10-month-olds: 13/16, 12-month-olds: 13/16) and the 2-versus-3 condition (10-month-olds: 13/16, 12-month-olds: 13/16). Success on 13 out of 16 trials differs significantly from chance performance ($p < .05$, two-tailed sign test).

The infants' success in the small-number conditions contrasts with their performance with larger numbers. With 3 versus 4, neither age group showed a preference for the greater number (10-month-olds: 5/12, 12-month-olds: 8/16). The infants also failed to choose systematically in the 2-versus-4 and 3-versus-6 conditions (8/16 infants and 6/16 infants choosing the greater number, respectively).

The results of Experiment 1 demonstrate that infants recognize more/less relationships. Because each infant received only one trial, there was no opportunity for the infants to learn which presentation would yield more. They had to spontaneously track the crackers, establish the relationship between the two hidden quantities, and choose the container with more.

The infants' performance revealed a set-size effect, marked by clear preferences with small numbers (1 vs. 2, 2 vs. 3), but not with larger numbers (3 vs. 4, 2 vs. 4, 3 vs. 6). Failure in the latter cases could not have been due to the ratio between 2 versus 4 or 3 versus 6, because the infants succeeded with 1 versus 2, and even with the less favorable 2 versus 3. It therefore appears that the quantitative abilities tapped when comparing sets of hidden objects under these circumstances are limited to small numbers of items. Like rhesus macaques, 10- and 12-month-old infants spontaneously represent more/less relationships, but they are limited to comparisons in which each set contains no more than 3 items.

EXPERIMENT 2

In Experiment 2, we used three control conditions to explore alternative explanations for the results of Experiment 1. Because Experi-

1. Because 10-month-olds performed at chance in the 3-versus-4 condition, the experiment was terminated after 12 participants.

2. Neither fussiness nor failure to choose was influenced by the comparison presented, or by side or order of presentation. Of the 46 infants excluded from the analysis, 15 saw 1 versus 2, 17 saw 2 versus 3, 10 saw 3 versus 4, and 4 saw 3 versus 6. Twenty-one infants saw the larger number placed on the right, and 25 saw the larger number placed first.

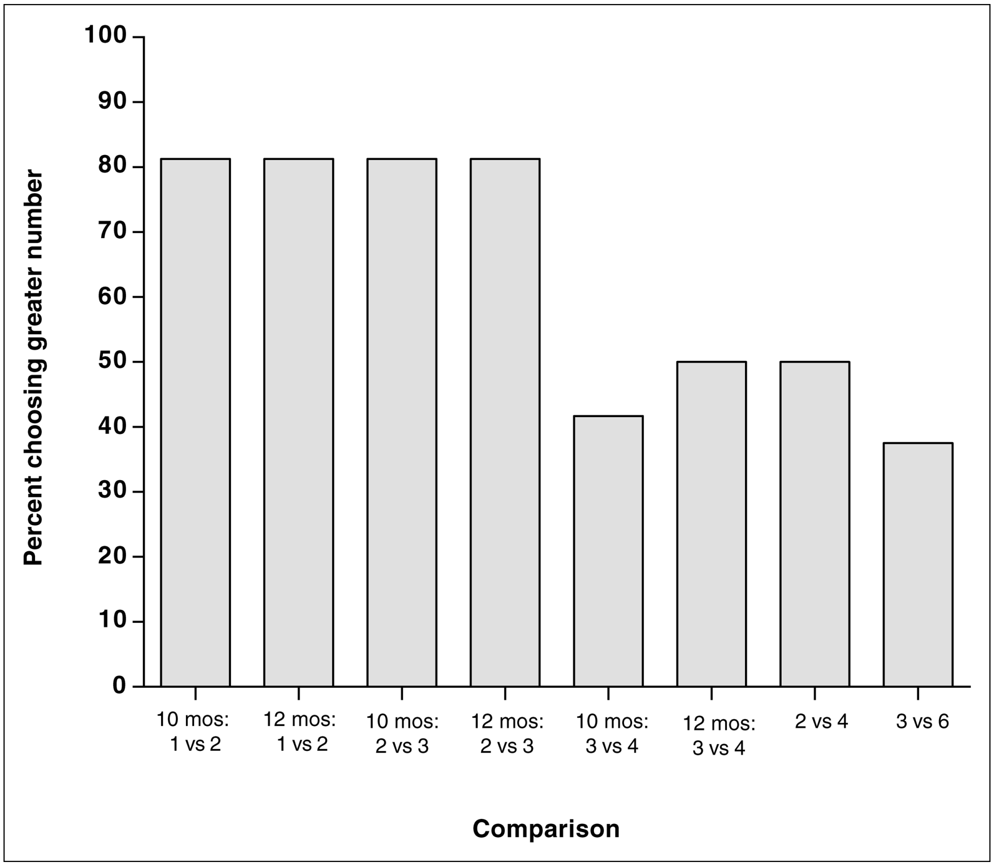

Fig. 2. Percentage of 10- and 12-month-old infants choosing the greater number in Experiment 1.

ment 1 found no difference between age groups, they were combined in Experiment 2. The participants in Experiment 2 were 48 infants: eighteen 10-month-olds (mean: 10 months 11 days) and thirty 12-month-olds (mean: 12 months 12 days). Approximately half of the infants were boys (30/48). Eighteen additional infants were excluded from the analysis because of fussiness or failure to choose.

Experiment 2a (motivation control) explored whether infants failed with large numbers for motivational reasons. If infants find 3 crackers fully satisfying, then they may not be motivated to obtain 6. We tested this possibility by giving infants a fully visible 3-versus-6 choice, with crackers presented on trays instead of placed in containers. If lack of motivation was the reason for the failure in Experiment 1, then performance would remain at chance.

The crackers in Experiment 2a were the same size as those in Experiment 1, and the procedure was almost identical, except that the crackers were placed onto two green plastic trays (50×30 cm each). The experimenter sequentially placed 3 crackers on one tray and 6 crackers on the other, with side and order counterbalanced. Crackers were placed in no particular configuration, with the restriction that there was no overlap between crackers.

The infants successfully chose the greater number of crackers in Experiment 2a (Fig. 3). Thirteen out of 16 infants chose 6 crackers over 3 ($p < .05$, two-tailed sign test), suggesting that infants' failure in Experiment 1 was due to difficulty tracking large numbers of hidden objects, and not to lack of motivation.

Experiment 2b (complexity control) tested the possibility that infants failed in the large-number comparisons of Experiment 1 (2 vs. 4, 3 vs. 4, 3 vs. 6) because the events were too complex or took too long to hold infants' interest. Each infant in this control experiment received a choice between 1 versus 2 crackers, with each cracker shown to the infant, lowered into the container, raised out again, and then finally placed in the container. Because each cracker underwent twice the usual amount of motion, presentation duration and complexity were equated with the 2-versus-4 condition of Experiment 1, yet the number of crackers to be tracked remained at 1 versus 2.

The procedure was almost identical to that of the 2-versus-4 condition of Experiment 1. The experimenter showed each cracker to the infant and said, "Look at this," then lowered it into the container without releasing it, raised it out again and waved it, saying "Look," and then finally placed it in the container.

The infants succeeded (Fig. 3). Twelve out of 16 infants chose 2 crackers over 1 ($p < .08$, two-tailed sign test), suggesting that failure with 2 versus 4 in Experiment 1 was due to an inability to track large numbers of individuals, and not to presentation duration or complexity.

Whereas Experiments 2a and 2b explored alternative interpretations for the failures in the large-number conditions of Experiment 1, Experiment 2c (duration control) explored an alternative interpretation for the successes with small numbers. In Experiments 1, 2a, and 2b, number of crackers was confounded with total presentation duration

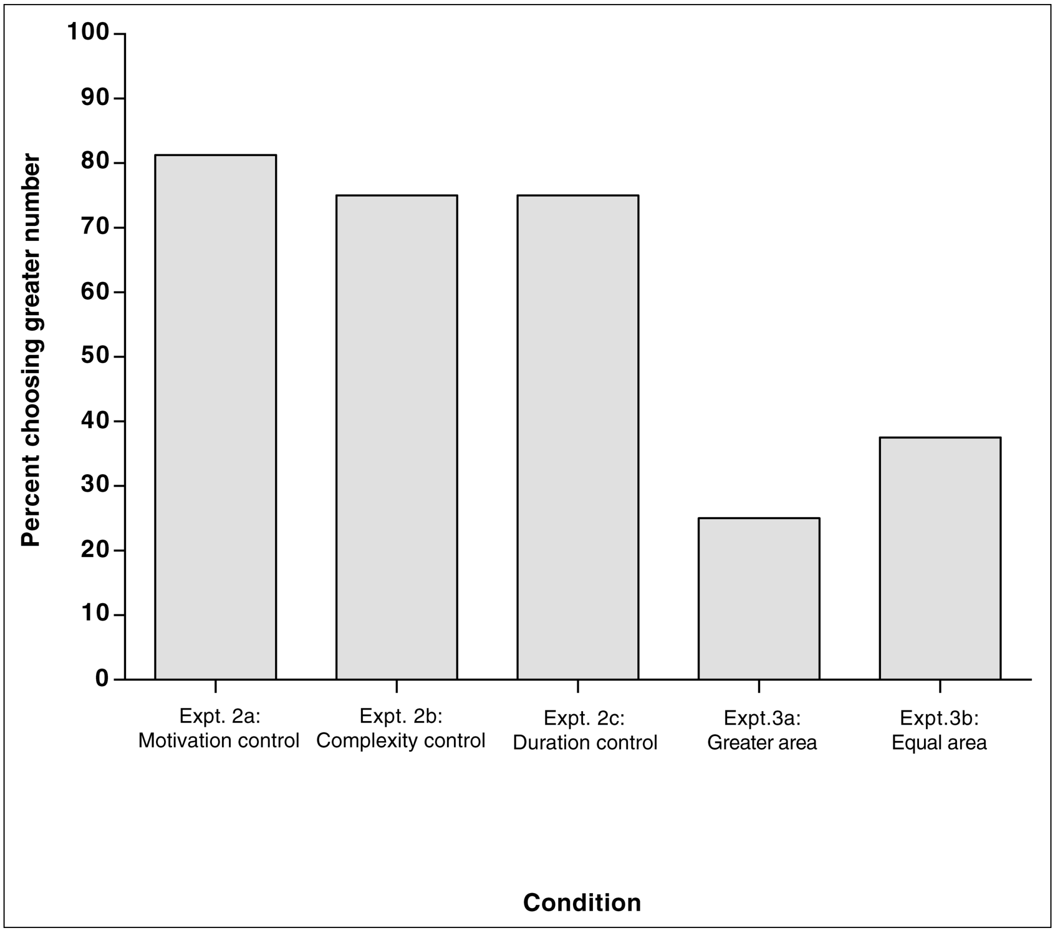

Fig. 3. Percentage of infants choosing the greater number in Experiments 2 and 3.

and with the amount of attention drawn to each container. Therefore, infants may not have been making a quantitative comparison between crackers at all. Experiment 2c tested this possibility by showing infants 2 crackers versus 1 cracker plus a hand wave. Two crackers were placed into one container, just as in the 1-versus-2 condition of Experiment 1. The experimenter placed 1 cracker in the other container, then added a wave of her empty hand over it and said, "Look at this." We thereby equated the presentation time and attention between the two containers while preserving the 1-versus-2 comparison.

Performance in Experiment 2c was not disrupted by the addition of the hand wave (Fig. 3). Twelve out of 16 infants chose 2 crackers over 1 cracker plus a hand wave ($p < .08$, two-tailed sign test).

Thus, the three conditions of Experiment 2 provide confirmatory evidence that 10- and 12-month-old infants spontaneously compare quantities of hidden crackers, but that their capacity to do so is limited to small sets of individuals.

EXPERIMENT 3

In all conditions of Experiments 1 and 2, cracker number covaried with total amount of edible material. Experiment 3 explored whether infants' choices in Experiments 1 and 2 were determined by comparisons of number of items or comparisons of total amount of cracker. In Experiment 3a, the greater-area condition, the total surface area in the 1-cracker set was twice the sum of the surface areas in the 2-cracker set. In Experiment 3b, the equal-area condition, the total surface area in the 1-cracker set was equal to the sum of the surface areas in the 2-cracker set.

Participants were 32 infants: five 10-month-olds (mean: 10 months 13 days) and twenty-seven 12-month-olds (mean: 12 months 10 days). Half of the infants were boys (16/32). Sixteen 12-month-olds participated in the greater-area condition, and five 10-month-olds and eleven 12-month-olds participated in the equal-area condition. Four additional infants were excluded from the analysis because of failure to choose.

The materials and procedure were identical to those of Experiment 1, except for cracker size. In the greater-area condition, infants saw 1 huge 6.5- × 12-cm cracker versus 2 crackers of the original 6.5- × 3-cm size. Thus, the infants could choose between a total of 78 cm^2 (1 cracker) and a total of 39 cm^2 of cracker. In the equal-area condition, infants saw 1 large 6.5- × 6-cm cracker versus 2 crackers of the original size. In this case, both choices yielded 39 cm^2 of cracker.

The infants appeared to choose on the basis of total quantity, and not number of items (Fig. 3). They chose the greater surface area over the greater number: In the greater-area condition, 12 of the 16 infants chose 1 huge cracker over 2 small crackers ($p < .08$, two-tailed sign test). In the equal-area condition, the infants chose at chance. Only 6 out of the 16 infants chose 2 crackers over 1 when total surface area was equated.

GENERAL DISCUSSION

With comparisons of 1 versus 2 and 2 versus 3, 10- and 12-month-old infants tracked sequentially hidden objects, compared representations of those objects, and chose the container with more food. Because the single-trial task was naturalistic and precluded learning, these findings suggest that like adult monkeys, human infants spontaneously make more/less comparisons.

Relational comparisons in this situation could be made over analog-magnitude representations (of number or of total surface area) or object-file representations. In displaying the set-size signature of object-file representations, infants' performance closely parallels that of the monkeys. Infants demonstrated robust success with small numbers of items (across all 1-vs.-2 conditions, 50 out of 64 infants chose the greater number; across all 2-vs.-3 conditions, 26 out of 32 chose the greater number, $p < .01$ for both conditions), and failed with larger numbers. This divergence suggests that the infants were not relying on an analog-magnitude representational system such as that described by Meck and Church (1983), Dehaene and Changeux (1993), or Church and Broadbent (1990). There is no reason to expect small numbers to be treated differently from large numbers, or small total volumes to be treated differently from large ones. Instead, the set-size signature suggests that infants, like adult monkeys, relied on a representational system dedicated to tracking small numbers of objects, such as the object files of Kahneman et al. (1992), or Pylyshyn's fingers of instantiation (FINSTs; 1989) or visual (1994) indices. Such a system, which appears to track no more than 3 or 4 items, has also been suggested to underlie infants' performance in other numerical tasks (Feigenson et al., in press; Huttenlocher, Jordan, & Levine, 1994; Leslie et al., 1998; Scholl & Leslie, 1998; Simon, 1997; Uller et al., 1999).

These data constrain the characterization of object-file models in two important ways. First, the fact that infants succeed in choices of 2 versus 3 (total number = 5) and that monkeys succeed in choices of 3 versus 4 (total number = 7) shows that models of two sets of objects, each falling within the limits of parallel individuation, may be stored in memory and compared with each other. The limit on performance is not the absolute limit on the number of object files that can be simultaneously assigned, because the results from parallel-individuation studies with human adults (for review, see Trick & Pylyshyn, 1994) suggest the limit is likely to be less than 5 for infants and less than 7 for adult monkeys. The difference we observed between human infants and adult monkeys is likely to be developmental in origin rather than a species difference. Second, the fact that infants compare models on the basis of total surface area or volume rather than on the basis of one-to-one correspondence between individuals shows that some features of the individual objects are represented in the models and enter into relational comparisons (Fig. 1c).

These data are consistent with and help make sense of two recent reports concerning the basis of infants' dishabituation to small sets. When variables of continuous extent, such as contour length (Clearfield & Mix, 1999) or surface area (Feigenson et al., in press), are pitted against number in habituation paradigms, infants are more sensitive to the continuous variable. Yet performance in habituation studies is not solely determined by sensitivity to total continuous extent, as demonstrated by infants' success at discriminating 2 versus 3 and failure at discriminating 4 versus 6 (Starkey & Cooper, 1980). The latter result is exactly as expected if each set is represented in terms of an object file for each individual; sets of 4 and 6 cannot be represented, as they exceed the limit on object-file representations. For sets within the object-file range, infants at least sometimes compare object-file representations on the basis of the physical variables bound to those representations, rather than via one-to-one correspondence. This results in infants' reliance on surface area in the task we used in the present study, and in longer looking at changes in continuous extent than changes in number in habituation tasks.

Although in these experiments infants compared object files on the basis of a nonnumerical dimension, the object-file representations themselves maintain numerical information implicitly, in that there is one file per object. It is an open question whether, under some conditions, infants could also compare object-file models on the basis of one-to-one correspondence rather than continuous extent.

We propose that object files subserved performance in the present experiments, and likely in other experiments concerning small sets of individual objects. However, infants also have access to analog-magnitude representations of number, as evidenced by their discrimination of large numbers under conditions in which confounding continuous dimensions have been rigorously controlled for (Xu & Spelke, 2000). Further research is needed to characterize when analog-magnitude models of number, or of continuous variables, are deployed and when they are not.

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