

Multiple Cues for Quantification in Infancy: Is Number One of Them?

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A review and synthesis of the literature on quantification in infancy and early childhood is provided. In most current conceptualizations, early quantification is assumed to be number based. However, the extant literature provides no clear-cut evidence that infants use number to perform quantitative tasks. Instead, new research suggests that quantification is initially based on nonnumerical cues, such as area and contour length, whether or not a task involves discrete items. The authors discuss the implications of these findings with respect to early quantification and its relation to later numerical development.

For any given situation, there are usually many kinds of quantitative information available. A child's decision to take one plate of food or another could be influenced by a range of cues including the food's total area, its edge length, its volume, the number of pieces, the ratio of food size to plate size, the length of time it took to dish the food up, or the rate of the dishing. Most of the time, these cues are consistent with one another. When the food on one plate has more area than another, it also tends to have more edge length, take longer to dish up, and so forth. In fact, these cues are so tightly interwoven in real experience that it is difficult to design tasks where one cue is tested separately from all of the others.

However, rather than seeking to understand how infants and young children sort out these complex relations, most research has focused on proving that infants can perceive numerosity in isolation. Many investigators have assumed that once numerical competence has been shown, all subsequent development must be guided by a discrete number bias. Some have argued that this bias reflects an innate domain-specific learning mechanism for discrete number (e.g., Gallistel & Gelman, 1992; Wynn, 1995). Others have claimed that infants use general-purpose mechanisms for quantification (Simon, 1997; Uller, Carey, Huntley-Fenner, & Klatt, 1999). However, even in these domain general accounts, it is assumed that infants view quantities primarily in terms of discrete number. At best, these perspectives do not acknowledge

the complexity of quantitative information that people must process. At worst, they may be based on a premise that is utterly false.

The goal of this article is to critically evaluate the idea that quantitative development is guided by an inborn ability to represent discrete number. We begin by describing two number-based models of early quantification and reviewing their empirical support. We conclude that the published findings do not necessarily demonstrate the processing of discrete number in infants. Instead, these findings could reflect processing of other perceptual variables, such as contour length, area, or rhythmic patterns. We next discuss several studies that provide direct evidence that infants use cues such as these, rather than number, in habituation and calculation tasks. The implications of these findings are discussed with respect to early quantification and its relation to later numerical development.

Number-Based Models of Early Quantification

Any entity or set of entities can be quantified in a variety of ways including, but not limited to, discrete number. When an entire quantity is presented all at once, there are a variety of spatial cues available, such as surface area, volume, contour length, and density. When quantities are presented sequentially, they can be estimated using rate, duration, and rhythmic patterns. Because all of these quantitative cues tend to yield roughly the same answer to a given problem, such as which sets are equivalent, it is not safe to assume that when infants and young children respond in a quantitative task, they have perceived the quantities in terms of number. Nonetheless, that is the basic assumption underlying two influential models of infant quantification: (a) the preverbal counting-accumulator model (Gallistel & Gelman, 1992; Wynn, 1995) and (b) the object tokens model (Simon, 1997; Uller et al., 1999).

The accumulator model of infant quantification is based on a mechanism proposed by Meck and Church (1983) to explain timing and counting behavior in rats (see Figure 1). The mechanism works by emitting pulses at a constant rate. To begin timing or counting, a switch is used to gate pulses into a container (or accumulator). If the mechanism is timing, the switch stays open until timing has stopped. If the mechanism is counting, the switch opens and closes in response to each item. Because the pulses are emitted at a constant rate, the quantity of pulses accumulated for

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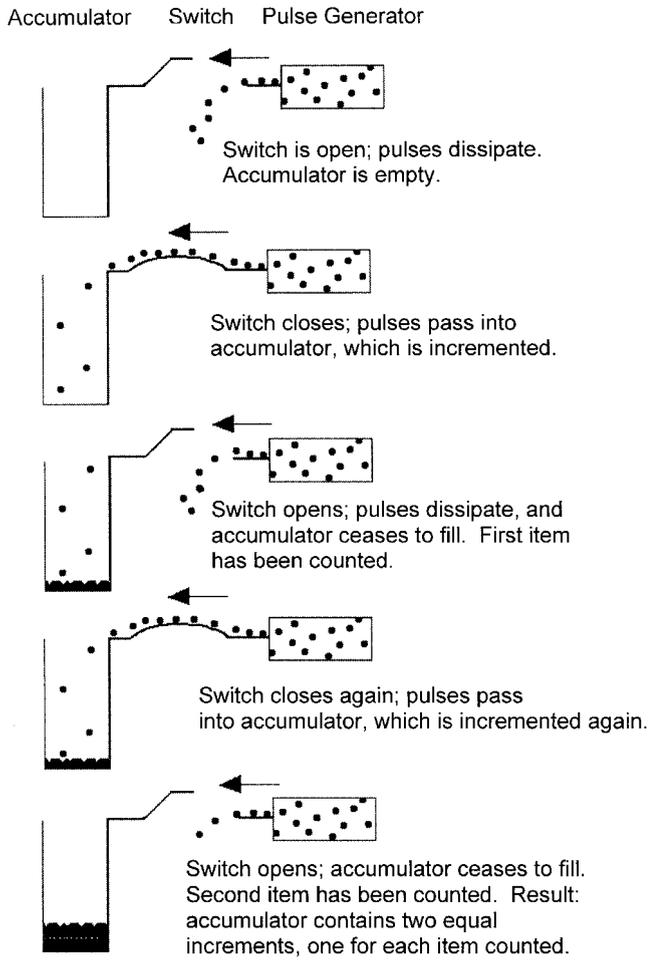


Figure 1. A graphic depiction of the accumulator mechanism. Adapted from *Trends in Cognitive Sciences*, 2, K. Wynn, "Psychological Foundations of Number: Numerical Competence in Human Infants," pp. 296–303, Copyright 1998, with permission from Elsevier Science.

each opening (and hence, each item) will be roughly equivalent. Thus, the resulting fullness of the accumulator can represent either total number or duration, depending on which mode has been in operation.

Some developmentalists have co-opted the accumulator mechanism as an explanation for infant and early childhood performance on quantitative tasks (Gallistel & Gelman, 1992; Wynn, 1995). These investigators have argued that infants tag each individual item in a set by opening the switch and gating in pulses. The total number of items is represented with the resulting magnitude—much as cardinality is represented by the last count word when people count verbally. In fact, Gallistel and Gelman called this process *preverbal counting* because it seems to operate according to the principles of verbal counting (e.g., one-to-one correspondence, stable order, etc.).

An alternative to the accumulator model is a model based on object tokens (see Figure 2). Object tokens are symbols that stand for the individual items in a set. They have been postulated in models of spatial individuation (Kahneman, Treisman, & Gibbs, 1992; Trick & Pylyshyn, 1994). For example, Trick and Pylyshyn

proposed that people assign a reference token called a *finger of instantiation* (FINST) as they identify each distinct feature cluster in a scene. FINSTs act as pointers that distinguish one object from another in terms of spatial location. They are assigned in parallel but can be used to track an individual's location as long as it remains visible.

Some researchers have proposed that infants and young children use such markers to respond in quantitative tasks (Simon, 1997; Uller, Carey, Huntley-Fenner, & Klatt, 1999). However, although object tokens may originate in spatial individuation, on these accounts, they are more than pointers that give an initial estimate of numerosity. Instead, they become symbolic representations of the items in a set that contain featural information, endure even when the objects are hidden, and can be mentally manipulated (as in establishing equivalence by means of one-to-one correspondence).

Although there are important differences between the accumulator and object tokens accounts (see Mix, Huttenlocher, & Levine, in press, for a discussion), they share a common assumption—that infants use discrete number when they perform quantitative tasks. In fact, some have claimed that infants represent small numbers exactly, just as adults do when they count. Wynn (1992a) concluded that "infants are able to calculate the precise results of simple arithmetical operations" and that this indicates that "infants possess true numerical concepts" (p. 750). Similarly, Starkey (1992) claimed that infants can enumerate sets by using either a symbolic tagging process or a one-to-one mapping that directly

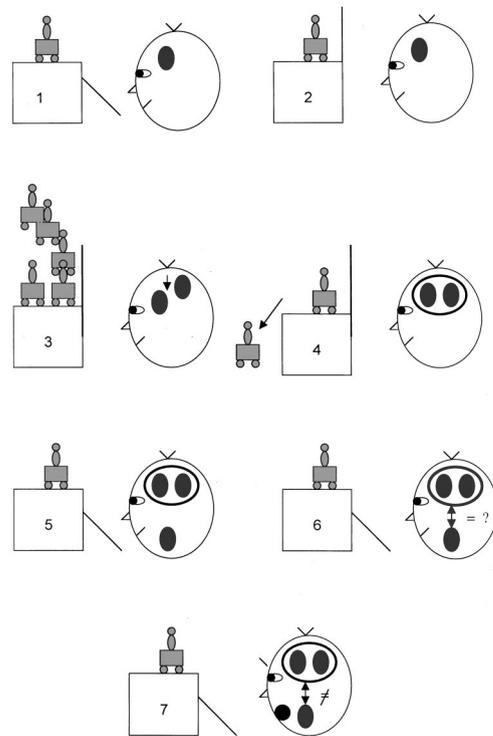


Figure 2. A graphic depiction of an object tokens representation. Adapted from *Cognitive Development*, 12, T. J. Simon, "Reconceptualizing the Origins of Number: A 'Non-Numerical' Account," pp. 349–372, Copyright 1997, with permission from Elsevier Science.

compares the numerosities of sets. In either case, an exact representation of number is needed. We turn next to the evidence that has been cited in support of these claims and ask whether the data actually compel them.

Do Infants Have “True Number Concepts?”

Those who claim that infants represent the number of individuals in a set draw support from a large and varied literature. Within this literature, there have been attempts to rule out infants’ use of nonnumerical cues. However, problems with these manipulations leave open the possibility that infants’ responses were not number based. We organize our review of this literature into two sections based on the competence being tested. The bulk of the evidence, including attempts to control for nonnumerical cues, comes from studies of set size discrimination. Therefore, we discuss these studies at length in the following section. In the *Complex Quantitative Tasks Used With Infants* section, we review studies of more complex tasks, such as recognizing equivalence, ordering sets, and calculating.

Detecting Changes in Set Size

One of the most robust findings in the early quantitative literature is that infants can discriminate between different set sizes. Even before investigators tested numerical discriminations per se, there were hints from the research on pattern perception that infants could make quantitative discriminations. Specifically, when infants were shown pairs of displays that differed in set size (e.g., 32 vs. 128), they demonstrated a significant preference for the larger of the two sets (Fantz & Fagan, 1975). This suggested that infants were sensitive to the quantity of elements in sets that were highly discrepant. However, these studies did not provide a good test of the ability to distinguish between specific numerosities because they left open the possibility that infants’ discriminations were based on differences in overall area, brightness, contour length, or complexity, rather than the number of individual items.

To determine whether infants perceived more fine-grained differences in number alone, subsequent studies tested infants’ discrimination between very small sets. Most of this work has used *habituation*—the tendency to look at a stimulus less after it has become familiar. In habituation studies, infants are shown a series of stimuli that share a common characteristic, such as set size (e.g., all arrays of two items). If infants detect the commonality, their looking time decreases over trials (see Figure 3). At test, a novel stimulus, such as an array of a different set size (e.g., three items), is shown. If infants exhibit a significant increase in looking time when the novel stimulus is shown, they are said to *dishabituate*. Dishabituation is interpreted as evidence that infants perceived the invariant characteristic presented in the habituation trials and detected the novelty of the test stimulus.

Studies using spatial arrays. Starkey and Cooper (1980) used habituation to test whether infants could discriminate between small sets that were close in number. They presented 4-month-olds with linear arrays of either two or three dots until looking time decreased to a set criterion. The spacing of the dots was varied across trials so that infants could not base their responses on changes in total line length or density (see Figure 4). At test, infants were shown arrays with either the familiar number of dots

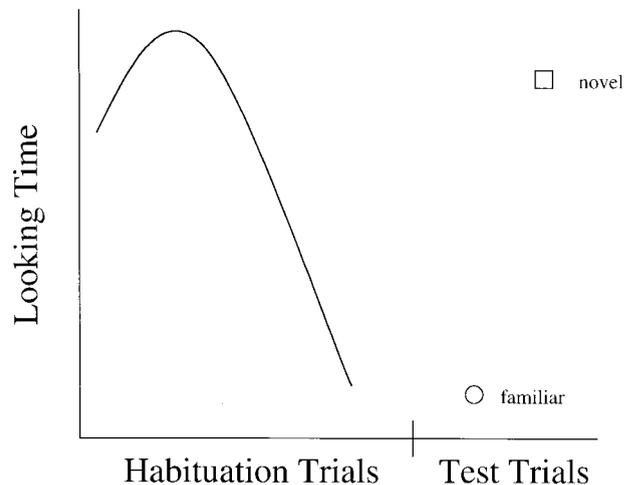


Figure 3. Hypothetical looking time data in an idealized habituation curve.

or a novel number of dots. Looking times significantly increased in response to the novel arrays—4-month-olds had detected the change. A subsequent study reported the same finding with neonates (Antell & Keating, 1983).

Other investigators have shown that infants can discriminate between small sets when the items varied in type, size, and configuration. Strauss and Curtis (1981) presented 10- to 12-month-olds with sets of color drawings (e.g., chicks, dogs, houses, etc.) that were arranged randomly on an imaginary four by four matrix. The drawings were photographed from one of six different distances to vary the sizes across displays. Half of the infants were habituated to slides that varied in item type, size, and position across trials (e.g., two large dogs, two small houses, etc.), and half were habituated to slides that varied in size and position across trials, but not item type (e.g., two small chicks, two large chicks, etc.). At test, infants were shown arrays of a novel numerosity that consisted of either unfamiliar items (for infants in the heterogeneous condition) or chicks (for infants in the homogeneous condition). As in the studies with arrays of dots, infants in both conditions discriminated two from three items.

Similar results were obtained using sets that were heterogeneous both within and across trials (Starkey, Spelke, & Gelman, 1990). In this study, the habituation displays consisted of photographs depicting either two or three different household objects. At test, 7-month-olds were shown a series of novel photographs that alternated between two and three items. During the test phase, infants looked significantly longer toward the numerically novel displays than they did toward the numerically familiar displays.

In the studies described so far, all of the stimulus sets have been static displays of photographs or drawings. Infants also have been tested with sets of items in motion. Van Loosbroek and Smitsman (1990) habituated infants to small sets of rectangular figures moving continuously on a computer screen. At test, infants saw two trials of the familiar numerosity and two trials of a novel numerosity (i.e., the familiar numerosity either plus or minus one). The same group of infants was tested at three age periods: 5 months, 8 months, and 13 months. At 8 months and 13 months, infants

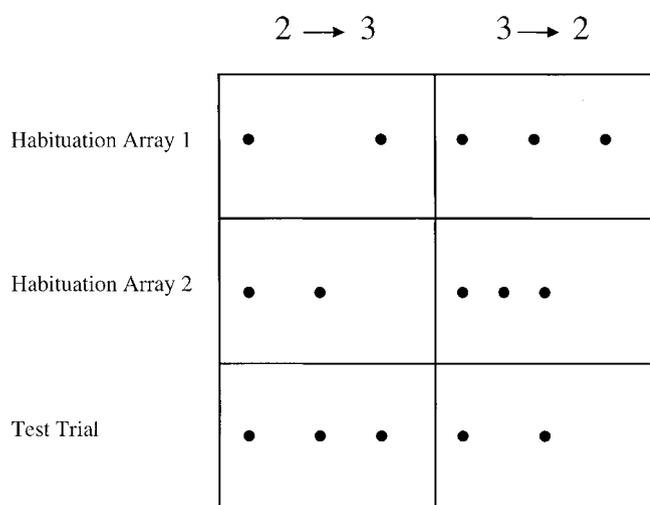


Figure 4. Sample stimuli used in number habituation studies with infants. From "Perception of Numbers by Human Infants" by P. Starkey and R. G. Cooper Jr., 1980, *Science*, 210, p. 1034. Copyright 1980 by the American Association for the Advancement of Science. Adapted with permission.

dishabituated to the novel number of moving rectangles. There was weak evidence of this ability at 5 months of age.

Are these discriminations number based? It seems clear from these studies that infants can discriminate between visual sets presented all together. However, it is less obvious what forms the basis of these discriminations. As noted above, many cues typically change as the number of items changes, including those for spatial extent. Thus, infants could detect the change from two items to three items based on the contrast in overall contour length or surface area rather than number. How can one know which was the case?

Previous researchers have addressed this confound in several ways, but on close examination, none of these controls have adequately ruled out infants' use of nonnumerical cues. One approach was to vary the sizes of individual stimulus items, either randomly or across a specific range of sizes (Starkey et al., 1990; Strauss & Curtis, 1981). However, unless size is manipulated so as to equate for total spatial extent while varying number and vice versa, the two still co-vary (see Figure 5). The stimulus descriptions in the published reports do not specify how much contour length or area was contributed by each item, but given the tight relations among these cues, it seems likely that the change from two to three items resulted in roughly the same proportional change in amount as it did in number.

In another approach, infants were tested with slightly larger sets, such as four versus six items, that maintain the same proportional difference in amount as for two versus three items (Antell & Keating, 1983; Starkey & Cooper, 1980). Indeed, infants failed to dishabituate in these large number conditions. It was concluded that infants do not use differences in amount to discriminate two from three, because if they did, then the same approach would allow them to discriminate four from six. However, that is not the only possible interpretation. For example, suppose infants use the total activity of edge-detecting neurons as a representation of amount. The "center-surround" ganglion cells in the retina could

serve this purpose (Tessier-Levigne, 1991). The variance of such a representation would increase as more objects, and hence more edges, are involved. When the set sizes are large and the ratios are small (as for four vs. six), the representations of amount might overlap enough to be confusable (Drake, Mix, & Clearfield, 2000). Another possibility is that infants need more trials to habituate in the large number condition because there is more information to process. Four-month-olds failed to habituate in Starkey and Cooper's (1980) four versus six condition. The number of habituation trials presented was not reported, but if it was roughly the same as in the small number condition, it may have been insufficient. Perhaps with a longer habituation phase, infants would have discriminated these larger sets. In any case, the failure to discriminate large sets in the same ratio provides only indirect evidence that infants do not use overall amount in the small number condition. As we discuss in the next section, when these cues have been manipulated within the two versus three comparison, there is positive evidence that infants actually use amount, rather than number, to discriminate small sets.

A third approach to controlling overall amount has been to vary item size across habituation displays. In a study of large number discrimination (e.g., 8 vs. 16), Xu and Spelke (2000) presented habituation displays with dots that varied in size across a particular range (see Figure 6). At test, alternating displays with both the novel and familiar number were presented. Both test displays contained the same size dots, so the test display with 16 dots had twice the area as the display with 8 dots. However, the total areas of the two test displays were equidistant from the average area of the habituation displays. Xu and Spelke reasoned that if infants were habituating to the overall amount of area, they would respond equally to both test displays. However, infants looked longer at the novel number of dots than they did toward the familiar number, suggesting that they had discriminated 8 from 16. When the contrast between 8 and 12 dots was tested, there was no significant difference in looking time. The conclusion was that infants can make purely number-based discriminations for large sets as long as the set sizes differ sufficiently.

There is a serious confound in this study, however, that undermines its basic conclusion. When the radius of the individual dots in the displays changes, area and contour length do not change

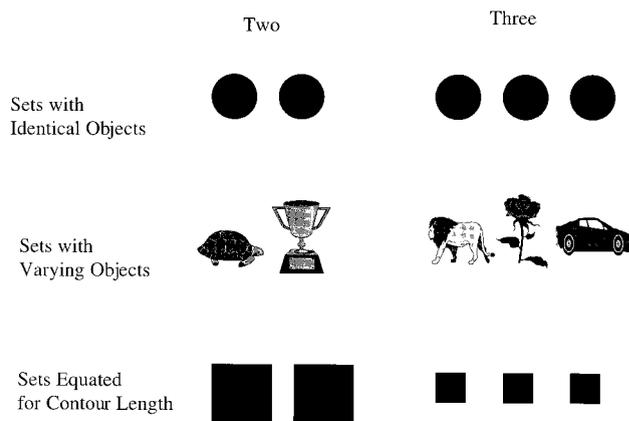


Figure 5. Many nonnumerical cues covary with number unless they are systematically varied.

linearly with respect to each other. Contour length varies as a function of the radius (e.g., $2\pi r$), whereas area varies as a function of the radius squared (e.g., πr^2).¹ This means that although Xu and Spelke's (2000) procedure may have controlled for area, it did not control for contour length.

In fact, the difference between the mean contour length during habituation and the contour lengths at test is always greater for the novel number displays than it is for the familiar number displays (see Table 1). The habituation and familiar number test displays are nearly equivalent in terms of contour length (i.e., the ratios are .82 for $8 \rightarrow 8$ and .87 for $16 \rightarrow 16$, where 1.00 would be identical). In contrast, the novel test displays were almost half (or double) the contour length of the habituation displays (i.e., ratios of .61 for $8 \rightarrow 16$ and .59 for $16 \rightarrow 8$). This larger difference in contour lengths might explain why infants looked longer toward the novel numbers at test.

The confound of contour length and number is not as strong in the 8 versus 12 condition (see Table 1). For the familiar numbers,

Table 1
The Total Contour Lengths Used in Xu and Spelke's (2000) Habituation and Test Displays

Trial type	Set size	Average radius (cm)	Total contour length (cm)
Habituation	8	0.915	46
	16	0.65	65
Test	8	0.75	38
	16	0.75	75
Habituation	8	1.12	56
	12	0.91	69
Test	8	1.00	50
	12	1.00	75

the ratios were still very high (.85 for $8 \rightarrow 8$ and .92 for $12 \rightarrow 12$), but they were also relatively high in the novel test conditions (.75 for $8 \rightarrow 12$ and .72 for $12 \rightarrow 8$). Thus, both the novel and familiar test displays were relatively close in contour length to the habituation displays. This may account for Xu and Spelke's (2000) failure to obtain a significant looking time difference in this condition.

In addition to this serious confound, there are other reasons to question the conclusions drawn by Xu and Spelke (2000). First, their interpretation rests on the assumptions that infants (a) average over irrelevant variables during habituation, such as the differing amounts in their displays, and then (b) react equally to equal deviations from that average at test. To our knowledge, there is no direct evidence that either of these assumptions is correct. In fact, if varying the areas across habituation trials is meant to convey that area information is not relevant in this task, it would be surprising if infants kept a running average of it.

It is also difficult to judge the effects of the area manipulations used in this study because critical data were not reported. First, readers are not told how many infants habituated. Because the test trials were presented after 14 habituation trials whether or not infants habituated, it is possible (especially if infants were attending to overall area or contour length) that many infants had not habituated when the test trials were presented. This is important because it is difficult to judge infants' attentional state at test if some or all of them had not fully habituated (Cohen, 2001). Also, this study claims to have controlled for all aspects of overall amount, but if infants failed to habituate because they were attending to the area variations, it would undermine this claim.

Second, only statistics that compared looking times on the two types of test trials were reported (see Figure 7). There were no comparisons between the test trials and the final habituation trials. Thus, it is not clear whether infants dishabituated on the novel test trial only, neither test trial, or both test trials. This is important because if, for example, infants dishabituated to both test trials, it would indicate that they were reacting to the change in area from the average of the habituation trials and, thus, might have been viewing the sets in terms of amount. In fact, it is possible that the reported difference in looking toward the two test trials, though significant, may be much smaller than the dishabituation to area

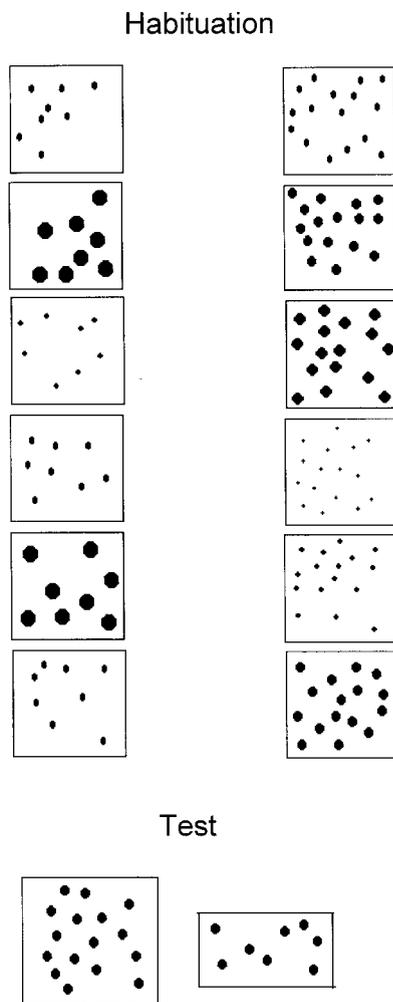


Figure 6. Sample displays used in Xu and Spelke's (2000) study of large number discrimination. Adapted from *Cognition*, 74, F. Xu & E. S. Spelke, "Large Number Discrimination in 6-Month-Old Infants," pp. 1–11, Copyright 2000, with permission from Elsevier Science.

¹ Thanks to Peter D. Drake of the Department of Computer Science at Indiana University for pointing out this confound.

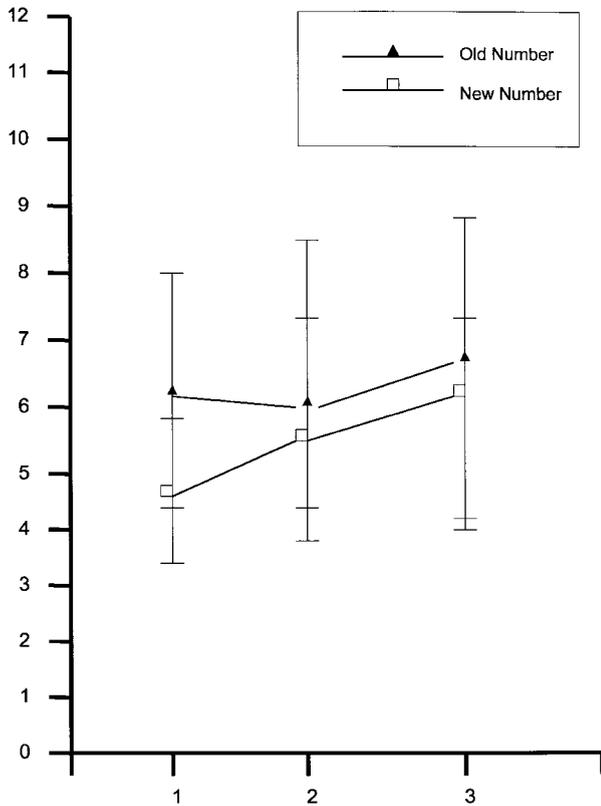


Figure 7. The results reported for Xu and Spelke's (2000) 8 versus 16 experiment. Adapted from *Cognition*, 74, F. Xu & E. S. Spelke, "Large Number Discrimination in 6-Month-Old Infants," pp. 1-11, Copyright 2000, with permission from Elsevier Science.

exhibited on both test trials. Although both differences would require explanation, this outcome would be quite different from that portrayed in the results as reported. Specifically, it would indicate that infants attend to multiple quantitative cues in this task.

In summary, several habituation studies have shown that infants react to changes in quantity as long as the set sizes are very small. Infants also may be able to discriminate large sets if the difference is great enough. A problem of interpretation arises, though, because many quantitative cues covary when sets are presented all together. Thus, it is possible that infants' responses in these habituation experiments are based on nonnumerical information, such as area or contour length. Although previous researchers have tried several approaches to rule out this possibility, the results of those manipulations have not been conclusive. In fact, as we discuss below, there is direct evidence that infants use nonnumerical cues when number and amount changes are pitted against each other.

Studies using event sets. The studies described so far used sets of pictures presented simultaneously. However, infants' ability to discriminate between temporally distributed sets also has been tested. Wynn (1996) habituated infants to sequences that contained the same number of puppet jumps, either two or three. Infants viewed a series of these sequences, each separated from the next by the puppet's wiggling from side to side, until looking decreased

to a set criterion. The rate and duration of the sequences varied, so infants could not base their discriminations on these cues (see Figure 8). At test, infants saw an alternating series of sequences with two and three puppet jumps. Wynn found that infants looked significantly longer toward the sequence that was numerically different from the habituation sequences. Sharon and Wynn (1998) reported similar results for heterogeneous combinations of actions (i.e., jumps and falls).

Canfield and Smith (1996) also found that infants could discriminate between sequences using a visual expectation procedure. In this experiment, 5-month-olds saw one of two repeating sequences of pictures on a computer screen. In one condition, infants could use the number of left-side pictures to predict the appearance of the right-side picture. For example, whenever two pictures appeared on the left side of the screen, the next picture always appeared on the right. In the other condition, infants saw the same pictures in an irregular sequence that did not signal the appearance of a picture on the right side of the screen. In both conditions, the length of time each picture was shown was varied so infants could not use overall duration of the left-side sequence as a predictor. However, within each sequence, the pictures were shown for the same amount of time. For example, the two left-side pictures appeared for 0.5 s each, then the right-side picture appeared for 1.5 s. On the next sequence, the left pictures appeared for 1 s each, then the right picture appeared for 1.5 s. Infants' patterns of responding indicated that they used quantitative information to predict the location of events in temporally distributed sequences. Specifically, infants who had seen the predictable sequence were more likely to shift fixation toward the right after the second left-side picture than they were after the first left-side picture. In contrast, infants who had seen the irregular sequence were equally likely to shift attention toward the right after either the first or second left-side picture.

Because infants could not use contour length or area to discriminate sequences of events, studies using event sets may provide the

Temporal Dimension	Trial Type	Schematic Depiction
Controlled	Habituation (2 jumps)	X--X
	Test (2 jumps)	X-----X
	Test (3 jumps)	X--X--X
Tempo	Habituation (2 jumps)	X-----X
	Test (2 jumps)	X--X
	Test (3 jumps)	X--X--X
Duration	Habituation (3 jumps)	X-----X-----X
	Test (3 jumps)	X--X--X
	Test (2 jumps)	X-----X
Tempo	Habituation (3 jumps)	X--X--X
	Test (3 jumps)	X-----X-----X
	Test (2 jumps)	X-----X

Figure 8. Schematic depiction of Wynn's (1996) puppet jump sequences. From "Infants' Individuation and Enumeration of Actions," by K. Wynn, 1996, *Psychological Science*, 7, p. 166. Copyright 1996 by Blackwell Publishing. Adapted with permission.

only evidence that infants represent discrete quantity. However, further research is needed to confirm that this is the case. Aside from replicating the findings of these studies, additional research is needed to rule out the use of nonnumerical temporal cues, such as rhythm. As an illustration, consider Wynn's (1996) procedure. When puppet jumps are presented in sets of two bounded by a brief pause, the sequence has a stable rhythmic pattern (e.g., jump-jump-pause . . . jump-jump-pause . . . , etc.). Wynn varied the speed of the sequences to prevent infants from using temporal information, but whether the sequences are presented slowly or quickly, the rhythmic pattern is unchanged. When three jumps are presented at test, the rhythm is different. It is now jump-jump-jump-pause. Thus, when infants look longer at the novel number of jumps, it might be due to this change in rhythm. At least, this interpretation was made by previous researchers who showed that infants are sensitive to changes in simple rhythmic patterns, such as those used in the above studies (Demany, McKenzie, & Vurpillot, 1977; Gibson, 1969; Lewkowicz, Dickson, & Kraebel, 2001; Mendelson, 1986).

Given that identical rhythms must have the same number of repeating elements, it might seem that number and rhythm cannot be tested separately. However, this confound can be overcome because the same number of items can be presented in different rhythms. For example, in Demany et al.'s (1977) study, infants heard a series of sound bursts every time they looked at a visual display. After 12 trials of reinforcement for one rhythm (e.g., * * * *), they heard a novel sequence of sound bursts with the same number but a different rhythm (* * * *). Infants looked an average of 5 s or more when the novel rhythm was played, even though the number of sounds stayed the same. Using another procedure, very close to Wynn's (1996; Sharon & Wynn, 1998), Lewkowicz et al. (2001) habituated 4- to 10-month-olds to a sequence of four events in one of two rhythms (i.e., either * * * * or * * * *). Duration was equated across the two sequences. At test, infants saw the familiar event sequence and a novel sequence—the same duration and number of events presented in the alternative rhythm. Infants at all ages exhibited significant discrimination of the rhythmic patterns.

These studies not only illustrate how sensitive infants are to rhythmic information but also suggest a way to control for rhythm in studies of event quantification. Consider once again Wynn's (1996; Sharon & Wynn, 1998) habituation experiments. To control rhythm, the interstimulus intervals could be varied within sequences so that the sets of puppet jumps presented during habituation would have different rhythms (e.g., * * * pause * * * pause, etc.). At test, two novel rhythms could be presented—one with two jumps (* *) and one with three jumps (* * *). If infants dishabituate to only the novel number at test, it would provide stronger evidence that they discriminate event sequences on the basis of number alone.

In summary, studies of infant quantification using events avoid many of the confounds associated with spatial displays, such as contour length, area, brightness, and so forth. However, these studies have different issues to address. Because events are temporally distributed, they can be perceived in terms of rate, duration, and overall rhythmic pattern. These three aspects of event sequences are deeply connected to one another and to numerosity, so it is not surprising that it is difficult to design studies that separate only one aspect from the rest. However, whereas there is ample

evidence that infants are sensitive to rate, duration, and rhythm (see Lewkowicz, 2000, for a review), this is not the case for numerosity. Until it has been shown that infants can perceive numerosity in the absence of these other cues, it seems reasonable to assume that they cannot.

Complex Quantitative Tasks Used With Infants

We next consider studies that go beyond simple discriminations to test whether infants can perform more complex quantitative tasks, such as recognizing equivalence, recognizing ordinality, and calculating. In the previous section, we found strong evidence that infants detected changes in set size but questioned whether these discriminations were based on number. For these more complex tasks, the evidence is not as strong in the first place. We find little or no indication that infants can detect equivalence and ordinality relations—whether based on number or otherwise. There is stronger evidence that infants can track quantitative transformations, but as in the research on set size discrimination, these studies failed to separate number from nonnumerical cues.

Recognizing equivalence. Understanding quantitative equivalence means knowing that two sets are in the same quantitative class even if they differ in every other way. For example, adults recognize that a set of two apples is equivalent to a set of two honks because both sets contain two items. This understanding has been tested as early as 7 months of age using a cross-modal matching task (Starkey et al., 1990). Infants were shown pairs of visual displays that included one display of two objects and one display of three objects. While the displays were still visible, either two or three drumbeats were played. Infants responded by looking longer toward the display that matched the number of sounds. Starkey et al. concluded that infants can perceive the number of distinct entities both in a sequence of sounds and a static visual display and can relate these sets to one another in terms of numerical equivalence.

Starkey et al.'s (1990) study received considerable attention because of its important claims. However, subsequent experiments have failed to replicate the cross-modal matching effect. In one study, infants showed a significant preference in the opposite direction (Moore, Benenson, Reznick, Peterson, & Kagan, 1987). That is, infants looked longer at the display that was not equivalent to the number of sounds. Starkey et al. attributed this reversal to differences in statistical analysis, such as excluding infants who failed to inspect both displays, and differences in experimental procedure, such as allowing irritable or fatigued infants to take breaks between trial blocks. However, in a second replication attempt, infants also looked longer at the nonmatching display even when they were not given breaks and all infants were included in the analyses (Mix, Levine, & Huttenlocher, 1997).

It is important to note that the reported effects were quite small in all three of these cross-modal studies. Because there were small effects in both directions, it is possible that the reported effects are spurious. Theoretically, if an experiment is run enough times, the results should barely reach significance a few times by chance. Thus, the published studies might be in the tails of a normal distribution with many nonsignificant findings in the center. These nonsignificant findings would not necessarily be known because of the bias to publish significant results (i.e., the "file drawer problem"; Rosenthal, 1979).

Even if these effects represent a real preference, Mix et al. (1997) found evidence in a second experiment that this preference may be based on rate and duration rather than numerical equivalence. Starkey et al. (1990) attempted to control for rate and duration by carrying out separate experiments in which the drumbeat sequences were equated for either rate or duration. In both cases, infants showed the same small preference for the numerically equivalent display. However, this control allowed infants to use duration information in one experiment and rate information in the other. In Mix et al.'s (1997) second experiment, rate and duration were randomly intermixed within the trials presented to each infant to ensure that these cues were not informative. Under these conditions, infants performed randomly—there was no preference for either the matching or nonmatching display.

These findings suggest that infants use temporal characteristics of the overall sequences, rather than the number of individual drumbeats, in this task. But, how could this influence looking time toward a visual stimulus? One possibility is that infants do perform an intermodal match, but on the basis of overall amount rather than number. For example, they might detect a relation between a longer sound sequence and more surface area. However, on this interpretation, it is difficult to explain why there would be a reversal of preference in the two published replication attempts. A more likely possibility is that infants do not match the sets per se but, rather, focus their attention in a way that optimizes overall arousal.

Several investigators have demonstrated that an infant's orientation toward a stimulus is influenced both by how arousing it is (based on its complexity, novelty, and incongruity) and the infants' state of arousal when the stimulus is presented (Berlyne, 1963; Cohen, 1969; Hunter & Ames, 1988; Lawson & Turkewitz, 1980; Lewkowicz & Turkewitz, 1981). In short, if infants are understimulated, they tend to orient toward an arousing stimulus, and if they are overstimulated, they do not. Cohen (1969) demonstrated this response pattern in 4-month-olds by varying the complexity of a visual stimulus—a blinking light. When the light remained in one position (a low-complexity display), infants' looking times were low and flat. When the light moved among four positions (a moderately complex display), looking times were high at first but eventually dropped off as they typically do during habituation. When complexity was high and the light moved among 16 positions, looking times started off low but gradually increased—the opposite of the typical habituation curve. Apparently, this display was overstimulating at first but became less so as it increased in familiarity. Similar effects have been reported in intermodal tasks. Specifically, the amount of time that infants orient toward a visual stimulus is influenced by the amount of stimulation they have received in the auditory modality (Lawson & Turkewitz, 1980; Lewkowicz & Turkewitz, 1981).

Moore et al. (1987) argued that optimal stimulation seeking can explain the reversal of preference that they observed. They speculated that undocumented stimulus differences, such as the loudness of the drumbeats or the brightness of the visual displays, could cause infants to look longer toward the numerically equivalent display in one laboratory but not in another because these differences could affect the infant's overall level of stimulation. Mix et al.'s (1997) finding that infants respond to overall temporal information in this task, rather than discrete number per se, lends support to this interpretation. Thus, whether the reported effects in

these studies are attributable to chance or to the use of rate and duration, there is sufficient cause to doubt that 7-month-olds recognize numerical equivalence across sets presented in different modalities.

A further reason to doubt this claim is that children fail to match sets in terms of intermodal numerical equivalence until 4 years of age (Mix, Huttenlocher, & Levine, 1996). In this study, a standard set was presented that contained either sounds (i.e., hand claps) or black disks. Then, children indicated which of two choice cards showed a numerically equivalent row of dots. To parallel the memory demands of the sounds condition, the disks were left in full view of the child for a few seconds and then were covered with a box. Three-year-olds performed at chance on the intermodal match, even though they performed significantly above chance when matching sets of disks to the choice cards. In contrast, 4-year-olds performed significantly above chance in both conditions. This indicates that, rather than appearing in infancy, the ability to match equivalent sets across modality may be a relatively late development.

Recognizing ordinality. Next we turn to another quantitative relation—ordinality. Ordinal relations are central to the organization of number systems. For example, the notion of threeness derives its meaning not only from the number of entities involved but also from its relation to other set sizes. Three is the set size that is 1 greater than 2 or 7 less than 10. These relations also might play a role in nonverbal quantification—a child could represent his snack of two cookies as being more or less than the number (or amount) his friend has. Recognizing these relations is a crucial aspect of mature numerical understanding. However, only a few studies have evaluated preverbal understanding of this important concept.

Curtis and Strauss (as cited in Strauss & Curtis, 1984) tested whether 16- to 18-month-olds recognized ordinal relations in a discrimination learning experiment. Children were shown pairs of displays that contained different numbers of red dots that varied in size and position across displays (e.g., one dot vs. two dots). Over trials, children were reinforced for touching the side of a display that contained either greater or fewer dots than the opposite side. After the conditioning phase, two transfer tasks were presented. In one task, the previously reinforced numerosity was pitted against a novel numerosity. In the second task, two novel numerosities were pitted against each other. Children reliably transferred their ordinal responses, but only when they had been trained on small number comparisons (one vs. two or two vs. three) and were rewarded for choosing the smaller numerosity (i.e., those trained to respond to “less than” relations).

Using a different approach, Cooper (1984) examined early recognition of ordinal relations with a habituation procedure. In this task, 10- to 16-month-olds were habituated to pairs of displays presented in succession. In the *less than* condition, the first array in the pair was always less than the second array (e.g., infants saw a display of two items followed by a display of three items). In the *greater than* condition, the first array was always greater than the second array (e.g., infants saw a display of three items followed by a display of two items). At test, Cooper presented four different pairings: (a) a previously seen pair from the habituation phase, (b) a novel pair with the same ordinal relation as the habituation pairs, (c) a novel pair with the opposite ordinal relation as the habituation pairs, and (d) a novel pair with displays that were equal in number.

Cooper reported that 14- to 16-month-olds in the less than and greater than conditions “seemed to detect and remember these relations” (p. 163), presumably by showing dishabituation in response to test trials in which the opposite relation was presented. In contrast, 10- to 12-month-olds in these two conditions increased their looking times only for trials in which the pairs were equal, as if they had encoded the relation “different than” during the habituation phase, instead of “less than” or “greater than.”

This interpretation was supported by a second experiment in which Cooper (1984) used the same design but presented pairs that were equal in number during habituation. At test, 10- to 12-month-olds (the oldest age group included) looked significantly longer toward both greater than and less than test trials than they did toward equal test trials. This indicates that although infants this age did not detect specific ordinal relations in the previous experiment, they could discriminate equality from inequality. However, this sensitivity seems to develop over late infancy. When 6- to 7-month-olds were tested in this more simplified task, they were slow to habituate and failed to show any consistent pattern of dishabituation.

In summary, there is evidence that sensitivity to specific ordinal relations emerges around 14 months of age. By 10 to 12 months, infants detect the change from equivalence to nonequivalence. In contrast to the very early ability to discriminate sets, both of these achievements appear relatively late. Indeed, by 12 months of age, most children have begun to walk and acquire language and, therefore, are technically toddlers. It is conceivable that an awareness of numerical ordinality could have developed by toddlerhood, even if younger infants do not use numerical information. However, these findings should be viewed cautiously. Additional research is required to confirm the results reported by these authors, as well as to understand the apparent constraints in terms of set sizes, direction of ordinality, and age level. Furthermore, in both the equivalence and ordinality research published to date, the displays have not been varied so as to separate the number of items from the overall surface area, contour length, or volume. Thus, as in the set size discrimination studies, responses that seem to be based on number might be based instead on nonnumerical cues.

Recognizing the results of quantitative transformations. Until recently, it was assumed that children did not understand how addition and subtraction change set size until school age. However, in the past 10 years, several investigators have claimed that even young infants can anticipate the results of quantitative transformations (Simon, Hespos, & Rochat, 1995; Uller et al., 1999; Wynn, 1992a). All of the published studies have used the following “surprise” paradigm. After infants are familiarized with a puppet stage, they are shown a small number of dolls. Then, a screen is raised so that the dolls are hidden. Next, a hand appears and either adds or removes an item from the hidden array. Infants can see the transformation, but they cannot see the resulting array (see Figure 9 for an example problem). At test, the screen is lowered, and either the correct or incorrect resulting set is revealed. The consistent finding is that infants look longer when the incorrect number of dolls is presented, suggesting that they anticipated the results of the transformation.

Some investigators have challenged this interpretation based on concerns about infants’ attentional state at test. Marks and Cohen (2000; Cohen, 2001) argued that infants might look longer at the incorrect outcome to these problems because of a familiarity

preference. As we discussed previously, if a stimulus is sufficiently complex, infants may increase their looking toward it over trials, rather than looking less as they do during habituation (Cohen, 1969). Marks and Cohen noted that, in the published calculation experiments, infants saw the incorrect outcome more often than the correct outcome simply because of the way the problems were presented. For example, in the problem $1 + 1$, infants were shown one object on a stage, and then a screen was raised and a second object was added. When the screen dropped, there was one doll on half the trials and two dolls on the others. This means that over the six addition trials, infants saw one object on the stage nine times and two objects only three times.² If infants found the experiment overstimulating in general, they might have looked longer at one object simply because it would be the most familiar and, hence, least stimulating. If so, then infants’ responses in these experiments may not reflect surprise at the incorrect outcomes of quantitative transformations.

Support for this interpretation was obtained in a series of experiments based on the infant calculation procedure (Cohen, 2001; Marks & Cohen, 2000). In one experiment, Marks and Cohen simply tested how long infants looked at either zero, one, two, or three dolls without any familiarization or exposure to calculation. There was a strong linear increase in looking based on set size. In short, the more there was to look at, the longer infants looked. In the critical test of their hypothesis, Marks and Cohen simply presented zero, one, two, or three dolls on a stage following familiarization to either one or two. They replicated the number of exposures to one or two dolls that infants had had in previous calculation experiments but did not present actual calculation events. Infants still looked very little at zero dolls and quite a lot at three dolls. However, between one and two dolls, they looked longer at the number that was most familiar. Thus, the effects reported in the infant calculation experiments could actually be attributable to a preference for familiarity interacting with a preference for more dolls.

Even if we grant that infants look longer at the incorrect outcome because they have calculated and can anticipate the correct outcome, this response is not necessarily based on the number of dolls. When one doll is added to another, the surface area, volume, and contour length of the array also increase. Infants may look longer toward one doll at test because it represents half of the amount they expected following the transformation, rather than the incorrect number. As we discuss below, there is now direct evidence that supports this amount-based interpretation.

Discrete Number Concepts in Infants?

Our review of the infant literature was aimed at evaluating the claim that infants perform quantitative tasks based on exact representations of discrete number—the notion that infants possess “true numerical concepts” (Wynn, 1992a, p. 750). We focused on two areas of competence: detecting changes in set size and performing complex tasks, such as calculation. There is ample evidence for the first area of competence—infants clearly discrimi-

² The same was true of the subtraction trials—infants saw the incorrect outcome, or two dolls, a total of nine times versus seeing the correct outcome of one doll only three times.

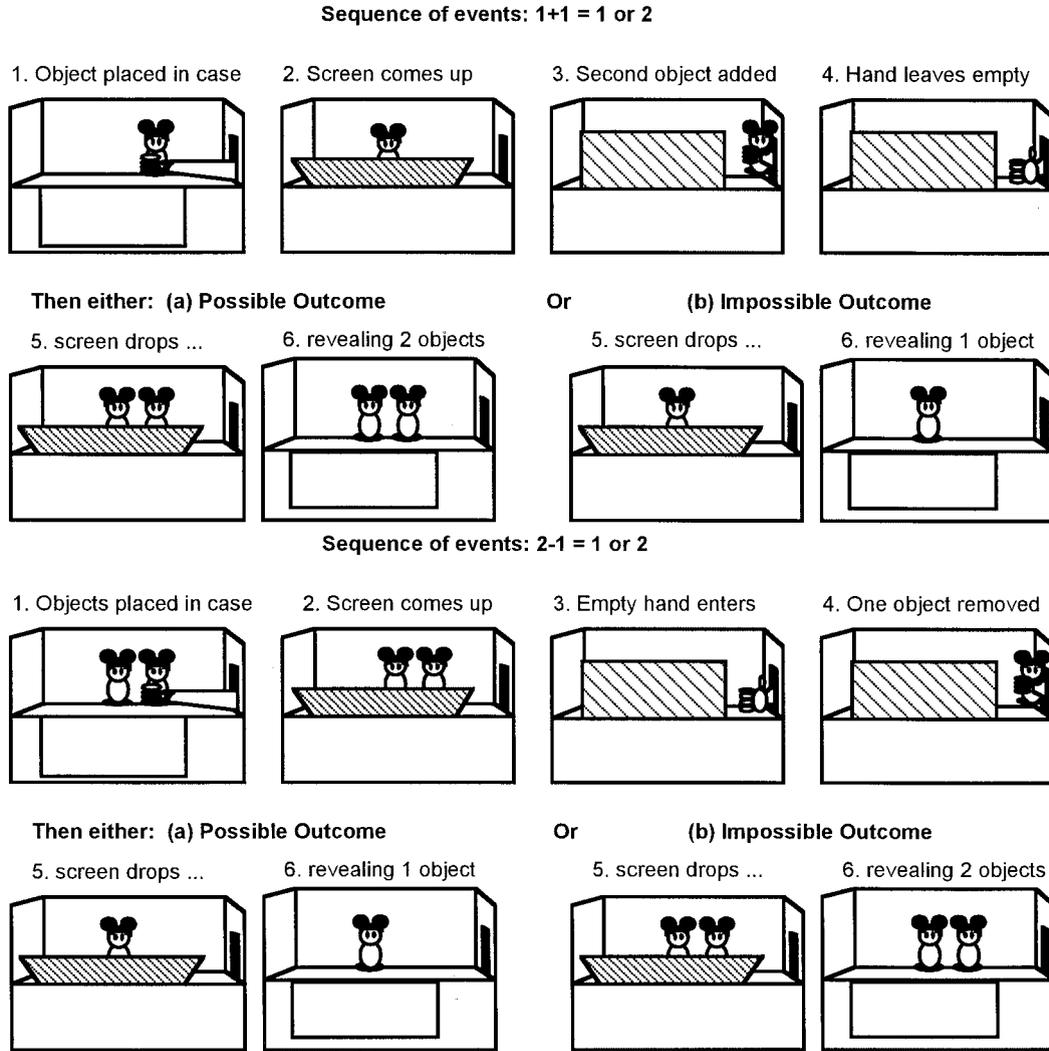


Figure 9. Sample stimuli used in Wynn's (1992a) infant calculation experiments. Reprinted by permission from *Nature*, 358, "Addition and Subtraction by Human Infants" by K. Wynn, pp. 749–750, Copyright 1992, Macmillan Magazines, Ltd.

nate set sizes, perhaps even from the start of life. However, the published studies do not demonstrate conclusively that infants' responses are based on number. With regard to the second competence, it is not clear that infants are at all capable of performing these tasks—whether number based or otherwise. There is very limited evidence that infants can detect equivalence or ordinality, and, even then, the most primitive form of this ability does not appear until 10 to 12 months of age. There is stronger evidence that infants can anticipate the effects of quantitative transformations as young as 5 months. However, this point remains controversial because the infant calculation procedure does not rule out the possibility of a familiarity preference at test (Marks & Cohen, 2000) or the use of nonnumerical cues.

New Evidence From Infants

The fact that existing research has not ruled out infants' use of nonnumerical cues casts doubt on the idea that there is a special-

ized learning mechanism for number, or even that infants process numerical information at all. However, this lack of adequate controls does not by itself rule out the possibility of innate number concepts. Perhaps infants really do process discrete number and not other quantitative information in these tasks, but we just cannot tell from the existing studies. There is now direct evidence that the opposite is true. Specifically, recent studies have indicated that infants use perceptual cues such as contour length and area, rather than number, in quantitative tasks that involve spatial arrays.

Evidence of Amount-Based Quantification in Infants

There are several indications that infants perceive quantities in terms of amount rather than number. First, infants respond to changes in amount when number is irrelevant. In one study, Gao, Levine, and Huttenlocher (2000) habituated 5-month-old infants to a container of red liquid that was either one fourth full or three fourths full. At test, infants were shown an identical container with

either the habituation amount or a novel amount. As in the number habituation studies, infants looked significantly longer when the novel quantity was presented, but, in this case, the change was in continuous amount as indicated by the height of the liquid. Similar evidence comes from an experiment on distance encoding in 5-month-olds (Newcombe, Huttenlocher, & Learmonth, 1999). In this experiment, infants were seated in front of a horizontal sandbox that was 3 ft (approximately 0.91 m) long. For several familiarization trials, an object was hidden and recovered at a particular distance from the edge of the sandbox. On the test trial, the object was hidden and then recovered at either the correct distance or 6 in. (15.24 cm) away from the location of hiding. Infants looked significantly longer when the object emerged at the incorrect distance, indicating that they remembered the hiding location and were surprised by the discrepancy. Just as in Gao et al.'s (2000) experiment, this task required sensitivity to differences in spatial extent.

These discrimination studies show that infants are sensitive to changes in nonnumerical cues that can be used for quantification. This alone challenges the assumption that early quantification is number based. At the least, it means that infants can represent spatial arrays in terms of either number or amount. However, when given a choice, do infants use amount cues instead of number? There is reason to think that they do.

Clearfield and Mix (1999) varied number and total contour length in the standard two-versus-three habituation task. During habituation, infants saw displays containing either two or three identical squares. At test, two new displays were presented in an alternating order. One display had a different number of squares than the habituation displays but the same amount of contour (i.e., the amount of edge summed over all the squares—see Figure 10). The other display had the same number of objects as the habituation displays but a different amount of contour. It is important to note that when contour length changed, the test amount was equal to what the contour length would have been if a square had been added or subtracted. Thus, the contour length change in this experiment was equal to the contour length changes in previous number habituation studies.

The results were unambiguous. When contour length changed and number was held constant, infants' looking times increased significantly, nearly recovering to the level of the first few habituation trials (see Figure 11). However, when the number of objects changed and contour length was held constant, infants did not dishabituate.

This effect has been replicated under several conditions and by different researchers. Clearfield and Mix (2001) confirmed that the same results were obtained when they used the same procedure and materials as in their previous study. They also showed that infants respond to total amount, rather than number, whether the amount changes in terms of surface area, contour length, or both. In one condition, area was equated over the habituation and test displays—only contour length or number changed at test. In a second condition, contour length was equated and either area or number changed at test. Note that because area, contour length, and number tend to covary when squares or circles are used, these manipulations required the use of irregular shapes (e.g., snakes, Aztec-style buildings, etc.). Regardless of which dimension changed, infants dishabituated to the change in amount, but not to

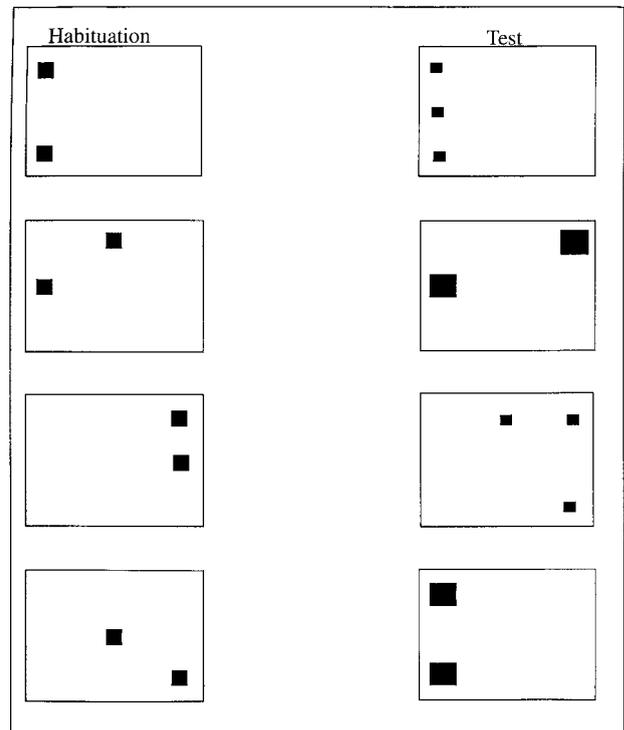


Figure 10. Sample displays used to contrast contour length and number in Clearfield and Mix's (1999) infant habituation study. From "Number Versus Contour Length in Infants' Discrimination of Small Visual Sets," by M. W. Clearfield and K. S. Mix, 1999, *Psychological Science*, 10, p. 409. Copyright 1999 by Blackwell Publishing. Reprinted with permission.

the change in number—just as they had in the original procedure where contour length and area were roughly correlated.

The same finding was reported by Feigenson, Carey, and Spelke (in press) for discriminations of one versus two. In fact, this result was obtained even when additional steps were taken to make the number change more salient. In one experiment, Feigenson et al. habituated infants to either one or two medium-sized objects. At test, infants saw two alternating displays, both of which differed equally from the habituation trials in terms of total surface area—one display was larger and one display was smaller. Only one of the displays had a novel number. The idea was that if the change in amount was downplayed, infants might reveal an underlying sensitivity to number that had been "swamped" by the amount response in other conditions. However, infants did not dishabituate to the change in number. In fact, infants failed to dishabituate in either condition. Feigenson et al. reasoned that the change in amount, which was smaller in this experiment than it had been previously, was not discriminable.

In another experiment, Feigenson et al. (in press) varied the surface area of the displays across habituation trials. For the test displays, surface areas were chosen from within the range of the habituation displays so that they were neither novel nor discriminably different from the average of the habituation displays. As before, this manipulation was meant to render the amount of area in the displays uninformative. Once again, infants failed to dishabituate to the change in number.

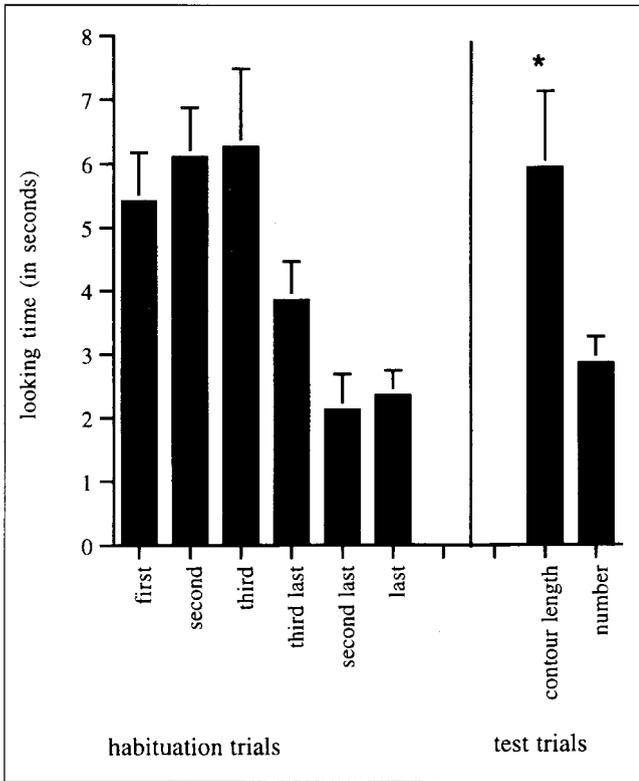


Figure 11. Infant looking times during habituation and in response to the contour length and number changes at test in Clearfield and Mix's (1999) study (Experiment 1). Error bars represent standard errors of the mean. * $p < .01$. From "Number Versus Contour Length in Infants' Discrimination of Small Visual Sets," by M. W. Clearfield and K. S. Mix, 1999, *Psychological Science*, 10, p. 410. Copyright 1999 by Blackwell Publishing. Reprinted with permission.

habituate to either test display. In fact, across four experiments in which number was pitted against amount in the standard habituation procedure, Feigenson et al. obtained no evidence that infants notice a change in number.

Finally, the same basic effect was reported when number and amount were separated in the infant calculation task. Feigenson et al. (in press) used Wynn's (1992a) procedure but manipulated the size of the dolls to control for changes in amount (see Figure 12). For example, in the 1 + 1 problem, infants saw one small doll placed behind a screen. Then a second doll of the same size was placed behind the screen. When the screen dropped, infants saw either one large doll (incorrect number but the same overall amount as the two small dolls) or two large dolls (correct number but incorrect amount). As in Clearfield and Mix's (1999, 2001) habituation experiments, infants responded to the unexpected change in amount but did not seem to notice when the number of dolls was incorrect as long as the overall amount remained constant. Thus, there is direct evidence that infants respond to amount of substance, rather than discrete number, in what had seemed to be numerical tasks.

Do Infants Simply Prefer Not to Use Number?

The studies described here provide convergent evidence that infants are sensitive to nonnumerical cues for quantification and that they use these cues, rather than a representation of discrete number, to perform quantitative tasks. But is it possible that infants still have a way to represent sets in terms of number? Perhaps all that has been demonstrated is that infants prefer to process quantities in terms of amount but are nonetheless capable of processing them in terms of number if they are compelled to do so.

There are two indications that the existing studies have demonstrated more than a preference for nonnumerical quantification. First, in all of the habituation experiments where number is pitted against amount at test, nothing prevented infants from responding to the change in number. Infants could have dishabituated to both kinds of test trials. Of course, one might argue that once infants had seen the first amount change test trial, they would construe the task in terms of amount and ignore any subsequent number changes. However, even though half of the infants received a number change test trial before seeing an amount change, there were no significant order effects in any of the published studies. In fact, Clearfield and Mix (1999, 2001) found the same pattern for

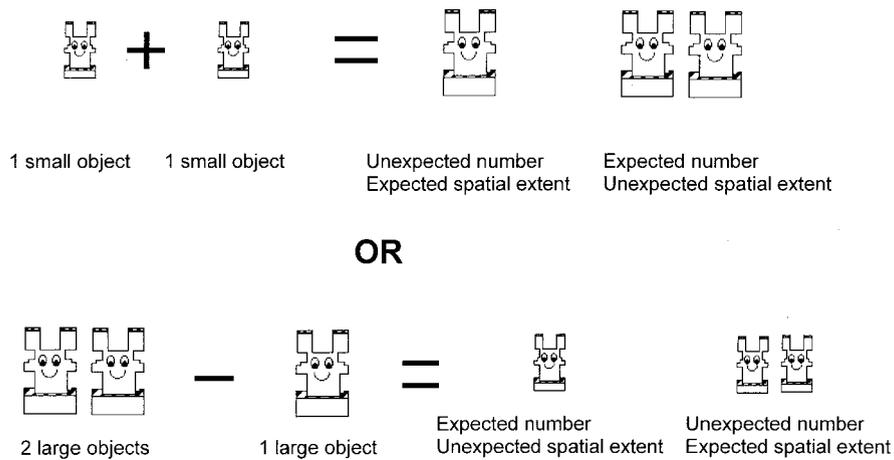


Figure 12. Sample stimuli used in Feigenson, Carey, and Spelke's (in press) infant calculation study in which responses to changes in number and surface area were contrasted.

the first test trial looking times as they did when all the test trials were included. Infants dishabituated to the change in amount, not the change in number, even when they had no reason to expect an amount change to come. Second, recall that Feigenson et al. (in press) took several steps to make the numerical information in the habituation task more salient than the amount information, but infants still did not respond to the changes in number. If infants simply preferred to respond to amount, then they should have revealed their numerical abilities under these conditions, rather than failing to respond at all.

Thus, we conclude that there is no need to posit a representation of discrete number in infancy in order to explain the current findings. Instead, a developmental account that assumes only representations of spatial extent and temporal cues in infancy would be sufficient. Of course, it is possible that future research will reveal number-based responding in other tasks. However, even if a sensitivity to discrete number is revealed under certain conditions, it would be difficult to argue for an innate number-specific learning mechanism. Given that there are many nonnumerical cues to quantity and infants use these cues under most circumstances, any numerical ability they possess would have to take on a less central role than it has in current conceptualizations.

The Undifferentiated Amount Hypothesis

If the origins of quantitative development are not numerical, then the number-based models we described at the beginning of this article are no longer viable—at least not as characterizations of infant quantification. New models would be needed. In fact, if human quantification is not rooted in discrete number, then there would be ramifications for conceptualizing the entire course of early development. Everything from the milestones that are significant to the mechanisms by which they are attained would change. In the following section, we develop a new view of quantitative development that attempts to capture these changes.

Quantification in Infancy

The evidence suggests that infants initially quantify spatial arrays using nonnumerical cues, such as contour length, area, volume, or brightness. Such cues can yield estimates of overall amount but do not indicate the number of individual items in a set. There seems to be general agreement that infants perceive continuous amount for quantities that appear as a solid mass (e.g., a blob of whipped cream or a contiguous row of boxes). However, the studies we reviewed indicate that infants can and do determine total amount whether a quantity consists of a single mass, a contiguous set of individuals, or a set of individuals in distinct locations. Thus, it could be said that early quantification of spatial arrays is undifferentiated—infants view both discrete and continuous quantities in terms of total amount.

There are at least two mechanisms by which discrete quantities could be represented in terms of total amount. First, quantity could be estimated based on the size of the overall region encompassed by the set, as if there were an envelope around the set, without any attention to the size of the individual objects. The extant studies seem to have ruled out this hypothesis. Several experiments have shown that infants respond to changes in quantity even when the line lengths and spatial arrangements of the sets are varied (Antell

& Keating, 1983; Clearfield & Mix, 1999; Starkey & Cooper, 1980; Starkey et al., 1990; Van Loosbroek & Smitsman, 1990). Thus, it appears that the alternative mechanism—representing the total amount accrued over individuals without regard for the total amount of space taken up by the set—best characterizes what infants are doing.

An amount-based representation would be inherently approximate. As an illustration, consider how one could determine the quantity of a pile of sand. Some precision could be achieved by dividing a quantity into equal measurement units and then counting the number of units (e.g., the number of buckets of sand). However, even when a unit measure is used, amount can only be determined to a certain level of accuracy because substance is infinitely divisible—it is always possible to become more accurate by using smaller units. Of course, when a unit measure is not applied, as would be the case for infants, only rough estimates of quantity may be possible. Accuracy in this case may depend on the shape of the substance. For example, a quantity of clay may be more difficult to estimate when it is in an irregular shape than when it is in a neat bar.

Accuracy also may depend on the availability of a reference quantity. To see how this might work, imagine that there are three cookies on a plate. An adult could determine the amount of area taken up by the cookies by measuring them in square inches. Although infants lack these conventional measurement skills for determining amount, they could obtain a reasonably accurate estimate of the cookie amount by using the plate as a reference quantity. One way would be to compare the amount of cookie with the total amount of plate in a part-whole fashion (i.e., three cookies cover half the plate). Alternatively, the amount of cookie could be compared with the amount of empty plate in part-part terms (i.e., three cookies cover an area that is equal to the area of empty plate). Infants could perform calculations the same way. For example, if three more cookies were added to the plate, infants could detect the change by noticing that the entire plate is now covered.

Recent research provides direct evidence that infants use reference quantities such as this to detect changes in amount. Huttenlocher, Duffy, and Levine (2000) habituated 6-month-olds to a block of a particular length. In one condition, infants saw the block in a clear container that was somewhat longer than the stick. In another condition, infants saw only the block. At test, infants in both conditions were shown a block that was either longer or shorter than the habituation block. However, only infants in the container condition noticed the change; infants who did not have a container to use as a reference failed to dishabituate.³ Thus, it appears that reference quantities play a key role in early quantification, probably because they provide a level of precision that is unattainable with estimates of absolute amount. In fact, it may not be possible to code amount unless there is a reference quantity available.

Although reference quantities were not explicitly provided for the infants in the number experiments we reviewed in the previous sections, the displays themselves may have served this function. In

³ Although distal reference cues in the room were available, this condition did not provide proximal reference cues, such as the display backgrounds that were available in previous number research.

the habituation studies, arrays of pictures were presented on cards, as slides, or on computer screens. Because these displays were the same size throughout each experiment—for example, all of the cards were 8 by 11 in. (20.32 by 27.94 cm)—a set of two items leaves more background space than a set of three items and the ratio of dark to light space changes from habituation to test. Similarly, the puppet stage could be used as the reference quantity in the calculation studies. For example, one doll on the stage leaves more open space than two dolls. Thus, the use of relative quantity could underlie responding in these experimental tasks.

In summary, the hypothesis developed here is that infants represent all spatial quantities in terms of overall amount. For discrete sets, estimates of amount are based on the combined contour length, area, and/or volume of the individual items rather than the total spatial extent of the array itself. These representations would be inherently inexact but would probably achieve some degree of accuracy through part–part or part–whole comparisons to reference quantities in the visual scene.

This account incorporates the evidence that is currently available, but there are clearly many questions that require further investigation. For example, if infants use contour length, area, and brightness to represent quantity in spatial arrays, what is the relation between quantification of these sets and quantification of sequential sets, such as puppet jumps? From the perspective of someone with fully developed quantitative abilities, these situations look like different instances of the same thing—countable entities. However, these situations might be quite distinct for infants and may well follow separate developmental trajectories before acquisition of the conventional counting system.

Another outstanding question is which nonnumerical cues infants can use and what determines whether they will use one cue or another. In the existing studies, even though one cue to amount is singled out and manipulated, the others are typically allowed to covary with it. Thus, it is unclear which specific aspect of amount infants noticed and used. One possibility is that infants have a favored cue, such as contour length, that they use whenever possible. Another is that infants alternate among different cues depending on their age or the task dynamics. A third possibility is that infants use all the cues that are available and respond when the information from enough of the cues points toward the same answer. Questions such as these have been largely ignored under the assumption that quantitative development is guided by innate processes that focus attention on number. By acknowledging the significant role that nonnumerical cues play in quantitative development, perhaps there will be interest in the basic parametric research needed to address these questions.

Beyond Infancy: What Happens Next?

If infants initially view spatial quantities in terms of amount, then there are significant ramifications for later development. Most notably, how does a notion of discrete number emerge from these initial estimates of continuous amount? Of course, this question presupposes that there is a connection between infants' responses in these experiments and subsequent quantification. It is possible, instead, that number concepts have an entirely different origin. In fact, there is no guarantee that concepts of continuous amount grow out of infants' performance on the quantitative tasks we reviewed. What has been shown in infants could simply be a

response to different levels of visual stimulation that does not develop into anything more sophisticated than that.

If only for the sake of parsimony, we would like to entertain the possibility that there is a connection between performance on these infant tasks and later quantification. If so, then how do discrete number concepts develop? How could a notion of discrete number grow out of an undifferentiated sense of amount? In this section, we speculate about some possible answers.

How could discrete number concepts develop? In the number-based accounts we reviewed earlier, the answer to this question was straightforward—number concepts developed readily because of inborn processes that directed attention toward and provided a representation for discrete number. If these processes are not present in infants, the problem of how number concepts develop is more difficult. To begin to address it, we first turn to the preschool literature and work backward.

Children acquire the conventional counting system between 2 and 4 years of age (Fuson, 1988; Gelman & Gallistel, 1978; Schaeffer, Eggleston, & Scott, 1974; Wagner & Walters, 1982; Wynn, 1990, 1992b). Almost from the time children begin to speak, the count words are part of their vocabulary. They spontaneously label small sets and learn to recite the count word list (Wagner & Walters, 1982; Wynn, 1990, 1992b). However, it takes several years for children to coordinate pointing, counting, and set partitioning, as well as understand the relation between counting and cardinality (Fuson, 1988; Wynn, 1990, 1992b).

Children in this age range also have exhibited the ability to match equivalent sets (Mix, 1999; Mix et al., 1996) and perform simple calculations with blocks (Huttenlocher, Jordan, & Levine, 1994; Levine, Jordan, & Huttenlocher, 1992). In fact, we have found evidence that children can match numerically equivalent sets before they have acquired even a minimal level of counting proficiency (Mix, 1999; Mix et al., 1996). Thus, there is reason to believe that a nonverbal representation of number develops sometime between infancy and early childhood.

Huttenlocher, Jordan, and Levine (1994) proposed one such representation. They hypothesized that preschool children assign a symbolic token to each item in a set. The cardinal number of items is thus represented by the analogous set of symbols—or mental model. Depending on the task at hand, different features of the items would be retained in the mental model and others would be omitted. For example, in an identification task, features such as color and shape might be retained whereas number and spatial arrangement would be irrelevant. In a number task, item features such as color, shape, or texture would be irrelevant. In this case, quite impoverished tokens would suffice so long as the number of discrete items could be discerned.⁴

A one-to-one mapping process such as this would allow children to perform a variety of numerical tasks without conventional counting. If this is the way number is first represented, it seems likely that this representation grows out of concrete experience with one-to-one mappings. This assertion may seem odd given the well-documented difficulties young children have with one-to-one correspondence tasks (e.g., Piaget, 1965). However, in these stud-

⁴ This view is similar to the object tokens model of infant quantification described earlier, but there are important differences. See Mix, Huttenlocher, and Levine (in press) for a discussion.

ies, children were asked to use the logic of one-to-one correspondence to overcome the perceptual confusability of large sets that varied in length or density. Piaget himself recognized that younger children were capable of making one-to-one correspondences but considered these to be low-level perceptual acts. Still, experience with these perceptual correspondences may provide important input for the development of number concepts even if it does not represent the attainment of them.

Children could experience these mappings when they occur by chance—without intentionally applying any preexisting notions of quantity. For example, in the course of playing with blocks, three blocks might happen to line up with three blocks. If toy trains are to be shared among four children, whether each child has a train to push will be quite apparent and salient to all concerned. Through experiences such as these, one-to-one mappings could become internalized and used to evaluate equivalence, ordinality, and the results of numerical transformations. Though there are undoubtedly other factors that contribute to the development of discrete number concepts, more in-depth study of early one-to-one correspondences could add a great deal to our understanding.

How do children integrate discrete and continuous quantification? On any account of early quantification, an important yet often overlooked question is how children disentangle the intricate relations that exist between discrete and continuous quantification. How do they recognize that these are two different ways to view a given quantity? How do they decide whether to use one approach or the other to complete a particular task? In the account we have developed here, these questions take on crucial importance because we assume that all quantities are initially viewed in terms of continuous amount. In this section, we consider what might promote the differentiation of these types of quantification and help children understand how one relates to the other.

There are several conceptual and functional differences between discrete and continuous quantity that could signal to children that these are distinct situations. First, notions of discrete and continuous quantity are typically applied in different contexts. Quantification based on number is generally used for entities that change their character when subdivided (e.g., half of an elephant is no longer an elephant). In contrast, quantification based on amount is generally used for homogeneous substances that do not change their character when subdivided (e.g., sand, water). Of course, it is possible to quantify some sets either way, depending on the goal of the quantifier. For example, cookies are usually counted but they are sometimes quantified in terms of continuous substance as when they are sold by the pound.

Second, the requirements for applying unit measures are different for discrete and continuous quantity. In both cases, applying unit measures involves subdividing the set and then tagging each portion with one unit. However, when unit measures are applied to discrete sets, the subdivision process is already done—discrete items are bounded and separate by definition. Of course, one must still keep track of which items have already been tagged, but this is not the same as the subdivision problem for continuous amounts. For continuous amounts, the person doing the quantifying must physically measure and separate the units himself. This means that learning to apply unit measures to continuous amounts requires more knowledge and effort on the part of the measurer (Miller, 1984).

A final difference between continuous and discrete quantification is the level of precision that is possible. Number can be determined exactly by mapping the items in a set onto an ordered

set of tags, such as the count words. This does not mean that discrete quantification is always exact. One could approximate the number of items in a set—for example, knowing that there are about 10 candies left in the box. However, it is at least possible to quantify discrete sets exactly. In contrast, as we have discussed, quantification of continuous amount is always approximate.

Let us now return to the critical developmental question—what leads children to see discrete and continuous quantities as distinct? How do they discover for themselves that these are different notions applied in different contexts? One way would be to acquire a process that applies to one type of quantity but not the other. In particular, the preceding analysis suggests that the emergence of exact quantification processes could play a major role. An example of this is conventional counting. Once children realize that counting leads to greater accuracy than estimating, they may be especially motivated to use it whenever they can. However, counting cannot be applied to continuous amounts until they are subdivided. One pile of sand is still one pile of sand, even if it is 10 times larger than another. The contrast between situations in which counting is informative and those in which it is not corresponds roughly to the difference between discrete and continuous quantities. Thus, as children attempt to apply counting in various contexts, they could begin to see the world in terms of these two kinds of quantity.

If nonverbal processes for representing exact number emerge before conventional counting, then the same mechanism could precipitate these conceptual changes at an earlier age. For example, children could discover that they can use one-to-one correspondence to represent the number of discrete items exactly. This could be accomplished through distributive counting (i.e., “one for me, one for you” sharing) or a symbolic one-to-one process, such as the mental model described by Huttenlocher et al. (1994). However, one-to-one mappings do not provide any information about continuous amount. Because the quantitative situations that could be represented exactly using a one-to-one process and those that could not correspond roughly to the discrete–continuous distinction, the development of such processes could help children recognize that these situations are different.

In fact, there is empirical evidence that supports this account. First, whereas preschoolers can precisely quantify discrete entities (both verbally and nonverbally), even school-age children have difficulty measuring continuous substances using conventional units (Miller, 1984; Piaget, Inhelder, & Szeminska, 1960). Indeed, preschoolers have difficulty thinking about continuous quantities in terms of countable units even when they do not have to apply the measure themselves. Huntley-Fenner (1999) had 3- to 5-year-olds watch an experimenter fill two opaque containers. In one condition, the experimenter filled the containers with objects and, in the other condition, cupfuls of sand were used. When asked to judge which container had more, children chose on the basis of number in the object condition, but not for the cupfuls of sand. Rather, they based their judgments on rate (i.e., the container that was filled at a faster rate was judged to have more sand). Thus, conventional skills for discrete quantification emerge before those for continuous quantification. This difference in timing creates a window in which children might differentiate discrete from continuous quantity because only one type can be represented exactly.

Second, there is evidence that children overgeneralize discrete quantification procedures within this window. When Piaget et al. (1960) had young children indicate how a “cookie” could be divided fairly among particular numbers of individuals, he found

that preschoolers divided the cookie in terms of the number of pieces rather than amount of substance. On the basis of the preschoolers' divisions, different individuals could end up with very different amounts of cookie. Miller (1984) also found that preschool children tried to achieve equality of number but did not focus on equality of amount (i.e., the sizes of the pieces) when they were sharing continuous amounts among several recipients. A striking example of this is the behavior of a subset of the preschool children who, when they came up one piece short, resolved the situation by taking one recipient's piece and breaking it in two. Although this achieved equality of number, it clearly did not achieve equality of amount. These findings indicate that there is a period when children try to solve continuous amount problems using processes that determine exact number. In doing so, they may eventually see that these processes only yield correct solutions for discrete sets and, thus, might begin to see continuous and discrete quantities as distinct.

Conclusions

In this article, we examined the quantitative competencies of infants and young children. Contrary to what has been claimed in current models of early quantification, we failed to find evidence that discrete number is represented in infancy. Instead, there is strong evidence that infants view spatial quantities in terms of total amount of substance. There are also indications that infants view sequential quantities in terms of temporal cues, such as rate, duration, and rhythm. From this starting point, new developmental questions arise. What nonnumerical cues do infants use? How does a number-based representation develop from such origins? How do children differentiate and ultimately integrate discrete and continuous quantification? We have proposed some possible mechanisms here, but these are speculative. There is much to be learned about quantitative development during this period. It is hoped that the present synthesis suggests new directions for this research.

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