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Quantitative competencies in infancy

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Abstract

We review recently published papers that have contributed to our understanding of how the preverbal infant represents number, area and time. We review evidence that infants rely on two distinct systems to represent number nonverbally and highlight the similarities in the ratio-dependent discrimination of number, time and area. Contrary to earlier assertions that continuous dimensions are more salient (and thus more discriminable) to the infant than numerosity, we argue that the opposite conclusion is better supported by the data. The preverbal infant may be better able to extract numerosity than continuous variables from arrays of discrete items.

Introduction

Research beginning in the late 1970s and into the mid-1990s overturned Piaget's characterization of the sensorimotor infant and preoperational child as bereft of an ability to quantify the world abstractly. This research employed new methods that measured looking-time in infancy and reported that infants were capable of detecting changes in the numerosity of a set of items, matching the number of sounds they heard to the number of objects they saw, and even performing simple addition and subtraction operations using a suite of methods such as visual habituation, preferential looking and violation of expectancy procedures.

More recently, limitations of these early studies were exposed, casting doubt on infants' numerical competencies (e.g. Clearfield & Mix, 1999; Cohen & Marks, 2002; Feigenson, Carey & Hauser, 2002; Mix, 2002). Many of the early studies failed to control for the myriad of alternative stimulus attributes, such as surface area, perimeter, and density, which often covary with number. Research published in *Developmental Science* over the last few years has contributed to a more nuanced view of infants' numerical abilities. Central to this new view is the idea that infants use two disparate context-dependent cognitive systems to quantify the world around them, tracking number both independently and in concert with continuous variables.

Analog magnitude system

In light of concerns raised about the stimuli used in the pioneering studies on infant numerical cognition, recent studies have stringently controlled continuous variables that often covary with numerosity (surface area, contour, density). Even with these controls, results continue to reveal that infants are sensitive to the numerosity of sets. Xu and colleagues conducted a set of studies which demonstrate that at 6 months of age infants detect a twofold change in the number of elements in a dot array but fail to detect a 1.5-fold change (e.g. Xu, 2003; Xu & Spelke, 2000; Xu, Spelke & Goddard, 2005). Using an elegant design in which number is held constant in habituation while continuous variables (cumulative surface area and contour length) vary fivefold (e.g. Figure 1A), results have revealed that 6-month-old infants look longer to the novel compared to the familiar number of dots with contrasts such as 4 vs. 8, 8 vs. 16, and 16 vs. 32 (twofold changes) but fail to show a novelty preference for 4 vs. 6, 8 vs. 12 and 16 vs. 24 (1.5-fold change). These results suggest that infants can ignore large changes in continuous variables (area and contour) and instead hone in on the constant numerical value of habituation displays.

The finding that 6-month-olds succeed in discriminating a twofold but not a 1.5-fold change in number holds across a variety of stimuli. For example, infants successfully discriminate a sequence of 8 tones from 16 (but not from 12) and 4 puppet jumps from 8 (but not 6) suggesting that the ratio-dependence of numerical discrimination in infants generalizes across experimental paradigms and sensory modalities (Lipton & Spelke, 2003; Wood & Spelke, 2005). Furthermore, with age infants become more sensitive to numerical disparities such that by 9 months they detect a 1.5-fold change in number (but fail to notice a 1.3-fold change, e.g. 8 vs. 10; Lipton & Spelke, 2003; Wood & Spelke, 2005). These findings are

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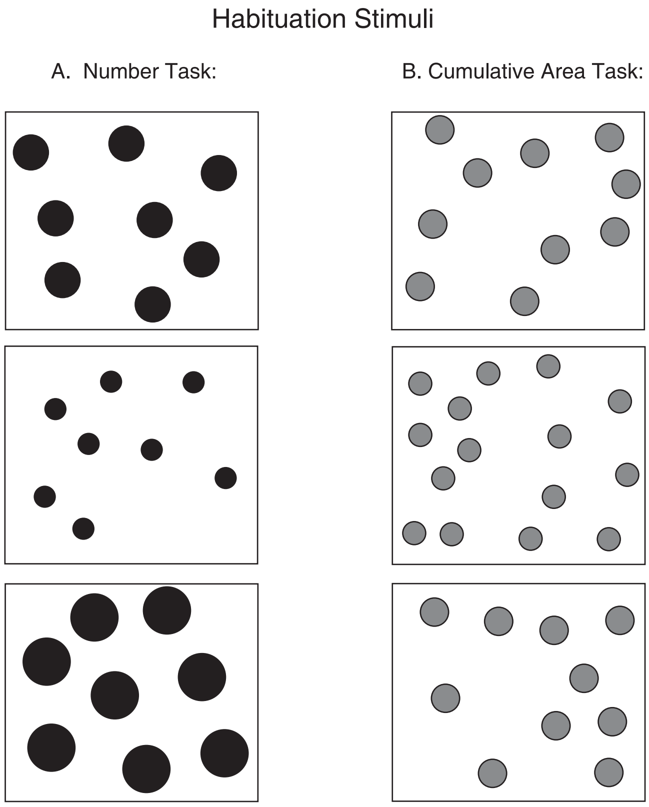

Figure 1 *Representative stimuli used in infant habituation experiments. Panel A depicts an example of stimuli from a numerical discrimination task in which infants are habituated to displays with the same number of dots (8) but area varies fivefold across habituation displays (e.g. Xu & Spelke, 2000). Panel B depicts habituation stimuli from the inverse design of Cordes and Brannon (2008), used to examine infant discriminations of cumulative area. In these displays, number varies across habituation (alternating between 10 and 15 dots), but cumulative surface area (total amount of grey dots) remains constant across displays.*

	1.5-Fold	2-Fold	3-Fold	4-Fold
Time	X	√		
Large Number	X	√	√	
Area (1 item)	X	√	√	√
Cumulative Area		X	X	√

Figure 2 *The pattern of successes and failures obtained in quantity discrimination tasks with 6-month-old infants. (Time: Brannon, Suanda & Libertus, 2007; vanMarle & Wynn, 2006; Large Number (> 3 items): e.g. Brannon, Abbot & Lutz, 2004; Cordes & Brannon, 2008; Lipton & Spelke, 2003; Wood & Spelke, 2005; Xu, 2003; Xu & Spelke, 2000; Xu, Spelke & Goddard, 2005; Area (1 item): Brannon, Lutz & Cordes, 2006; Cumulative Area: Brannon, Abbot & Lutz, 2004; Cordes & Brannon, 2008).*

consistent with a vast corpus of data demonstrating that number discrimination in nonhuman animals, children, and adults follows Weber's law whereby the ease with which two values are discriminated is dependent upon their ratio (e.g. Barth, Kanwisher & Spelke, 2003; Brannon & Terrace, 2000).

Remarkably, recent studies have found that 6-month-old infants also require at least a twofold change in duration or the size (surface area) of a single item in order to notice a change (see Figure 2). For example, Brannon, Lutz and Cordes (2006) found that 6-month-old infants were capable of discriminating a threefold and a twofold change in the size of an Elmo cartoon face but not a 1.5-fold change. Similarly, vanMarle and Wynn (2006) and Brannon, Suanda and Libertus (2007) found convergent evidence that 6-month-olds discriminate a twofold but not a 1.5-fold change in the duration of a teddy bear's dance (accompanied by a tone) or the duration of a cow puppet mooing. Further, temporal discriminations in infancy appear to follow the same developmental trajectory as numerical discriminations such that by 10 months of age infants discriminate a 1.5-fold change in duration (Brannon *et al.*, 2007). The ubiquity of this Weber-characteristic suggests that number, time, and surface area may all be represented via the same noisy continuous mental magnitudes (Feigenson, 2007).

Evidence for an object-file system

Infants do not always, however, show ratio-dependent number discrimination. Ratio-dependence breaks down in two interesting ways. First, infants appear to represent small numerosities (< 4) with greater precision than they represent large values (> 3). Second, infants often fail to discriminate a small from a large set even given a twofold change in number. To make sense of these surprising exceptions to ratio-dependence, a two-system account has been put forth. According to this account, infants possess both an analog magnitude system that represents number via continuous mental magnitudes which adhere to Weber's Law and an object-file system which allows infants a discrete, exact representation of a limited number of items (≤ 3). We first describe the evidence for exceptions to ratio-dependence and then discuss the object-file system in more detail.

As reviewed above, 6-month-old infants consistently fail in discriminating a 1.5-fold change in number when sets are 4 or larger (e.g. 4 vs. 6; 8 vs. 12). However, infants at the same age seem quite able to discriminate numerical contrasts at this ratio when the number of items is fewer than 4; that is, they succeed in discriminating 2 from 3. For example, Kobayashi, Hiraki and Hasegawa (2005) asked whether infants could use sounds to form expectations about the number of objects they expected to see behind an occluder. Six-month-old infants were first familiarized to objects that emitted a tone upon impact when dropped onto a stage. In test trials, a screen was raised to block the infant's view of the stage and the only cue as to how many objects were being dropped onto the stage were the tones that were emitted as the objects impacted the stage. Looking times indicated that, once the screen was raised, infants expected to see two objects on the stage if they had heard two tones and expected three objects when they heard three tones. Using a different cross-modal paradigm, Jordan and Brannon (2006) also found successful 2 versus 3 discrimination. In that study, when 7-month-old infants heard two female voices saying 'look' in chorus, they looked significantly longer at a two-women compared to a three-women video display but looked longer at the three-women display when they heard three voices. Collectively such results indicate that 6-month-old infants track number cross-modally and are capable of discriminating a 1.5-fold change in number for small sets.

The second break from ratio-dependence is that infants frequently fail to discriminate small from large sets even when these contrasts involve large numerical disparities. For example, Feigenson and Carey (2003) used the manual search paradigm in which 12–14-month-old infants blindly reached into a box to retrieve toys. When 3 toys were placed in the box and the experimenter retrieved 2 of them in front of the infant, the infant searched longer for the remaining toy compared to when 2 toys were placed in the box and the experimenter retrieved 2. Thus, it appears that the infant represented the number of items originally placed inside the box (3), the number of items retrieved from the box (2), and noticed the numerical mismatch between the two sets ($3 \neq 2$), and this disparity motivated continued manual search efforts. In contrast, when 4 toys were placed in the box and only 2 were retrieved, infants did not search longer, suggesting that they failed to notice the mismatch between 4 and 2 toys.

In another experimental paradigm 10–12-month-old infants were shown crackers being serially dropped into each of two containers (Feigenson & Carey, 2005; Feigenson, Carey & Hauser, 2002). When infants were subsequently allowed to crawl to the container of their choice, they reliably crawled to the container with more food when the number of crackers in each container was 3 or fewer. That is, they successfully chose the container with 3 over the container with 2, 3 over 1, and 2 over 1. However, when 4 or more crackers were placed in one of the containers (2 vs. 4, 3 vs. 6, or even 1 vs. 4) the infants responded at chance, suggesting that they were unable to represent 4 or more crackers in one location.

The same set-size limitation has been observed for younger infants in visual habituation paradigms. For example, 6-month-old infants discriminate 4 from 8 dots or puppet jumps (twofold change in number), but not 2 from 4 or 3 from 6, despite a similar twofold change in number (Cordes & Brannon, submitted; Wood & Spelke, 2005; Xu, 2003). These repeated failures of discriminating small from large sets, combined with the demonstrated increased precision when discriminating exclusively small sets, suggest that infants use two distinct systems for representing number. For large sets, infants invoke noisy mental magnitude representations that are ratio-dependent. In contrast, infants use a limited capacity system for sets of three or fewer in which each object has its own discrete representation or 'object-file'. As opposed to the analog magnitude system which can operate over a wide range of values, attentional demands on the object-file system allow infants to open only three object-files simultaneously.

Another major difference from analog magnitude representations is that the object-file system represents number implicitly by creating a one-to-one correspondence between items in the world and object-files but does not provide a cardinal summary representation of the set (Feigenson, Dehaene & Spelke, 2004). And, because object-files are representations of individual items in the world they can contain identifying information, such as object shape (Kaldy & Leslie, 2003; Leslie & Chen, 2007), and are maintained despite visual interruptions (Cheries, Wynn & Scholl, 2006).

According to the two-systems hypothesis, infant failures to discriminate small from large sets result from an incompatibility between the object-file and analog magnitude systems (Xu, 2003). However, it is important to note that infants can in fact compare small and large values in some contexts. Wynn, Bloom and Chiang (2002) found that infants successfully discriminated 2 groups of moving dots from 4 groups of moving dots, and Cordes and Brannon (submitted) found that infants could discriminate a small from a large static array of dots when the ratio was fourfold but not when it was twofold (i.e. they succeed in discriminating 2 vs. 8 and 1 vs. 4, but not 2 vs. 4 or 3 vs. 6). It is possible that infants, like nonhuman animals and adults, may sometimes recruit analog magnitudes to represent small values (e.g. Cordes, Gelman, Gallistel & Whalen, 2001; Brannon & Terrace, 2000). Alternatively, infants may represent small values with both analog magnitudes and object-files, and contextual variables may determine which type of representation controls behavior (Cordes & Brannon, submitted). Further research is needed to clarify the specific contexts that lead infants to rely on object-files or analog magnitudes to guide behavior.

Number and continuous quantity – which is more important?

Recent studies have also tackled the important question of how representations of number relate to representations of continuous quantities. As reported earlier, infant discriminations of number, time, and amount obey the same ratio-dependence rule, suggesting that these quantities (and potentially others) may be represented by the same analog magnitude system. Given the intimacy of this relationship, it seems likely that continuous variables impact the quality of numerical representations and vice versa, yet this possibility was not fully acknowledged until recently. Two important studies suggested the possibility that infants might track continuous variables at the expense of numerosity (Clearfield & Mix, 1999; Feigenson, Carey & Spelke, 2002). Clearfield and Mix (1999) habituated 6-month-old infants to displays of two or three identical squares with a constant total contour length. Infants were then tested with arrays that had a familiar number of squares but were novel in total contour length (a 1.5-fold change), and with arrays that had a novel number of squares (a 1.5-fold change) but a familiar contour length (same as in habituation). In essence, this design posed the question: Which is more salient to the infant – number or contour? Results revealed that infants looked longer at the arrays that contained the novel contour length/familiar number compared to the arrays with a novel number/familiar contour length and only dishabituated to the change in contour length, suggesting that contour length was the more salient quantity to the infant. Feigenson, Carey and Spelke (2002) obtained similar findings when they pitted changes in cumulative surface area (rather than contour length) against changes in number using a twofold change in both dimensions (1 versus 2 objects). These results have been interpreted as evidence that either (1) previous indications of infant numerical sensitivity were just wrong – infants cannot represent number whatsoever, *or* (2) infants may be able to represent number, but they do so on a last resort basis – they prefer to attend to continuous over discrete properties.

Given the wide range of recent studies that have found successful numerical discrimination in infants with experimental designs that include strenuous controls for continuous extent we can rule out the first interpretation (e.g. Wood & Spelke, 2005; Xu, 2003; Xu & Spelke, 2000; Xu, Spelke & Goddard, 2005). But, the question remains as to whether attention to numerosity is a strategy of last resort for infants.

The evidence that infants attend to changes in continuous variables at the expense of changes in number may be weaker than assumed. Two recent studies have used the Clearfield and Mix paradigm with the same age subjects and come to a different conclusion. In both cases (Cordes & Brannon, in press; Suriyakham, Erhlich & Levine, submitted), infants dishabituated to a change in continuous extent but also to a change in numerosity, suggesting that the infants attended to both dimensions simultaneously for these small sets. Although infants dishabituated to both types of change, they did not look longer to one dimension change compared to the other, suggesting that they attended equally to changes in both quantitative variables.

Moreover, one of these studies used the same design as Clearfield and Mix to separately investigate the relative salience of number and continuous extent variables for exclusively small (2 vs. 3), exclusively large (8 vs. 16) and for small–large set comparisons (2 vs. 8; Cordes & Brannon, in press). In all cases, infants dishabituated to the change in number and only in the exclusively small set experiment did infants dishabituate to the change in continuous extent. In no case did infants preferentially attend to continuous variables over number. It thus appears that changes in number are at least as salient as changes in continuous extent to the infant for both small and large sets alike. That is, number is not last resort for infants.

The 'last resort' strategy hypothesis was originally raised in the nonhuman animal literature (Davis & Memmott, 1983), positing that although animals are capable of tracking number, they fail to do so when other, more salient cues (i.e. continuous variables) are available. However, work with both monkeys and young children suggests that number is often spontaneously represented without any training, and even when other continuous extent cues are available (e.g. Cantlon & Brannon, 2007; Hauser, MacNeilage & Ware, 1996). Thus, number appears to be a salient stimulus dimension across both development and phylogeny.

A different way to address the relative saliency issue is to compare the ease with which infants discriminate continuous extent to that with which they discriminate number. An important assumption behind the claim that infants might preferentially attend to continuous variables over numerosity is that infants are actually capable of summing continuous variables over sets of discrete elements. Presumably, if continuous extent is the preferred stimulus dimension, representations of continuous dimensions should be at least as precise as representations of number. Cordes and Brannon (2008; see also Brannon, Abbot & Lutz, 2004) provide a direct test of this assumption using a design that is essentially the inverse of the Xu and Spelke (2000) design. Infants were habituated to displays that changed in number but were constant in cumulative surface area (Figure 1B). For example, in their small set experiments, infants were habituated to arrays of 2 and 3 dots (alternating across trials) but cumulative surface area remained constant. Then, in test, infants were presented with a single dot that was familiar or novel in cumulative area. In the large set experiments, infants were habituated to 10 or 15 dots (alternating across trials) where cumulative surface area remained constant. Then, in test, infants were similarly presented with a novel number of dots that were familiar or novel in cumulative area. For both small and large sets, the novel area was three or four times as large or small as the total area of the habituation arrays. Although this design mirrored that of previous numerical discrimination studies, 6-month-old infants required at least a fourfold change in cumulative surface area to successfully notice a change regardless of whether sets were composed of small (2 and 3) or large (10 and 15) dot arrays. This finding is in stark contrast to the twofold ratio required for successful discrimination of numerical changes (Wood & Spelke, 2005; Xu *et al.*, 2005), or of the size of a single element (Brannon *et al.*, 2006), in this same age group. Such results suggest that numerical discriminations are actually relatively easier than discriminations of continuous extent for the infant. These findings are also consistent with findings that preschoolers have greater difficulty discriminating the amount of continuous substance than the number of items (Huntley-Fenner, 2001).

If infants require at least a fourfold change in cumulative surface area to detect a change, why have previous studies reported successful discriminations of smaller changes in area or perimeter (such as Clearfield & Mix, 1999; Cordes & Brannon, in press; Feigenson, Carey & Spelke, 2002; Suriyakham *et al.*, submitted)? Furthermore, why is it that 6-month-old infants require only a twofold difference in the area of a single element to detect a change (Brannon *et al.*, 2006)? What accounts for this dramatic drop in representational precision between one element and multiple elements?

The notable difference between the Cordes and Brannon (2008) cumulative area study design and that of the previous pitted designs (ala Clearfield & Mix, 1999) and the single element area design (Brannon *et al.*, 2006) is that the habituation arrays used in the cumulative area task required infants to ignore changes in number and attend to constancies in the summed area of a set. It thus appears that infants are significantly more sensitive to changes in continuous extent when number is held constant compared to when it varies. This finding is consistent with the intersensory redundancy literature, which reveals that redundant information presented in two sensory modalities (auditory and visual) often facilitates attention and learning in infants (Lewkowicz, 2004; Neil, Chee-Ruiter, Scheier, Lewkowicz & Shimojo, 2006), newborns (Slater, Quinn, Brown & Hayes, 1999), and even in bobwhite quail embryos (Lickliter, Bahrick & Markham, 2006). This redundancy principle has been applied to infant numerical discriminations, when 6-month-olds succeed in discriminating a 1.5-fold change in number (a difference they typically fail to notice) when numerical information is presented bimodally, but not unimodally (Jordan, Suanda & Brannon, in press). More importantly, redundant information need not be presented across sensory modalities; redundant information presented in the same modality suffices. Nine-month-olds detect reversals in the ordinal direction of visual stimuli only when both the number of dots and the area of the dots increase or decrease simultaneously (when only one quantity changes, discriminations fail – Suanda, Tompson & Brannon, 2008). Therefore, the finding that infants are more sensitive to changes in number or continuous extent when both dimensions are constant is not surprising – when infants receive redundant information, attention and thus learning are bolstered substantially.

Conclusions

In a backlash against cognitive characterizations of the infant mind we must not throw out the baby with the bathwater. Without a doubt, stringent stimulus controls and attention to alternative accounts are necessary before applying rich cognitive interpretations to the minds of babies (e.g. Bates, 1999; Haith, 1999; Spelke, 1999; Cohen & Marks, 2002; Mix, 2002). However, we cannot always know a priori which of two competing explanations is simpler (e.g. Aslin, 2007; Carey, 2002). While it may seem at first glance that representing a continuous parameter of a set of objects is a simpler process than representing the set's abstract number, recent studies suggest otherwise. Instead, the preverbal infant's mind may be better equipped to ignore continuous variables and attend to number when sets are large, and attend to both continuous variables and number when sets are small. A challenge for future research is to understand the triggers that invoke different types of quantity representations in the preverbal infant both in terms of which quantitative variables are extracted and which representational systems are invoked.

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