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Infants' integration of featural and numerical information

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ABSTRACT

The current study examined the integration of non-numerical (featural) and numerical information in 9-, 11-, and 13-month-old infants' performance on a number discrimination task. Infants were habituated to pictures of objects (e.g., bowl, shoe) either in groups of two or three. In the test phase, infants saw both new and old objects in both groups of two and three. Nine-month-old infants discriminated number independent of the familiarity of the object, 11-month-old infants discriminated between familiar and novel objects (but not the number of objects), and 13-month-old infants discriminated between the familiar and novel objects only in the context of a familiar number of objects. These data suggest that early number representations are dissociated from featural information, and that the integration of these stimulus properties is a developmental process that occurs across the first year.

Although studies of number perception in children have been conducted for the past 80 years, research on number perception in infants began in earnest in the early 1980s (Strauss & Curtis, 1981; Starkey & Cooper, 1980). As a result of advances in this field, we are closer to understanding how infants may process number and how this ability develops. For example, we now know that infants use an approximate number system for representing larger quantities, as do adults and primates (Feigenson, 2005; Halberda, Mazzocco, & Feigenson, 2008; Libertus & Brannon, 2009; Xu, Spelke, & Goddard, 2005). In addition, infants use a more precise exact number system to represent smaller quantities, which aligns well with findings from studies of adults' subitizing (Trick & Pylyshyn, 1994; Peterson & Simon, 2000).

While infant quantitative processing has been a topic of study largely in its own right, the maturation of this field of infant cognition provides another stimulus dimension that may be applied to study other cognitive processes. Recently, it has been argued (Banich, 2009; Colombo, 2002; Colombo & Cheatham, 2006; Colombo, Kannass, Walker, & Brez, 2012; Garon, Bryson, & Smith, 2008) that the development of higher-order processes in infancy and early childhood may be accounted for largely through integrative processes. These processes involve the coordination of cognitive components (e.g., the allocation of attention in the service of working or long-term memory), and the coordination of semantic networks, which allows information to be more readily shared and connected. One of the ways the latter hypothesis can be tested is to examine the developmental course for how presumably independent forms of information are brought together in perceptual or cognitive tasks during infancy. The perception of quantity provides a potential venue for exploring this topic, given that sensitivity to number in infancy is typically explored through the presentation (most often in some form of familiarization-novelty paradigm) of an array of multiple items. Historically, studies of infant number discrimination have used simple stimuli

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(e.g., black dots and squares), which do not contain varying featural information. More recently, however, studies have begun to use real-life photographs or objects in these tasks (Feigenson, 2005; Feigenson, Carey, & Spelke, 2002; Starkey, Spelke, & Gelman, 1990). The numerosity of those items represents one dimension of processing, but the items are often objects themselves, which possess featural characteristics (e.g., color, texture, shape). Although many studies have investigated the limits and numerical representation of the exact number system, the question of how – and when – infants process the featural characteristics of the objects that comprise the array has yet to be substantially addressed.

In the literature, three studies exist that have systematically varied featural information. Feigenson (2005), Feigenson, Carey, and Spelke (2002), Feigenson and Carey (2003) used objects with varying features to try and determine whether 7-month-old infants relied on variables of continuous extent or number to make discriminations. She found that infants use continuous extent when the objects to be discriminated are identical, but discriminate number when the objects vary in appearance. Although the focus of the study was on the nature of infants' quantitative processing, the data here suggest that the characteristics of objects in the stimulus array may interact with infants' processing of number in some situations.

Izard, Dehaene-Lambertz, and Dehaene (2008) presented 3-month-old infants a continuous stream of either a small or large number of a single object. The numerosity and object did not vary, but test trials inserted into the continuous stream featured stimuli that were novel or familiar on either the numerical and object dimension or both dimensions of the array. Visual event-related potentials (VEPs) revealed a dissociation between the areas that respond to a change in number, but not object identity and the areas that respond to a change in object identity, but not number. This study suggests that information about object identity and number are dissociable, but in the absence of behavioral data on discrimination, the degree to which this information might have interacted was not addressed.

Finally, Strauss and Curtis (1981) varied both object identity and number across habituation and test trials. In this study, 10–12-month-old infants were habituated to sets of either homogenous or heterogeneous objects. Infants discriminated two versus three items, but not four versus five; homogeneity of objects had no effect. While the results for infants' sensitivity to number was clear, the findings do not allow for conclusions regarding whether object identity interacted specifically with number because there was no difference between the homogenous and heterogeneous conditions.

Thus, the question of whether featural information interacts with quantitative information remains open; furthermore, because none of these studies were truly developmental in nature, the trajectory of the possible interaction of these two forms of information has never been comprehensively addressed. The current study was designed to address this issue with a form of the switch paradigm (Casasola & Cohen, 2002; Werker, Cohen, Lloyd, Casasola, & Stager, 1998) that has been previously used with great success in disentangling infants' responses to multiple dimensions within perceptual studies. If infants dishabituate to a change in only one dimension of the task – either number or object identity, then this suggests that infants are not integrating both dimensions whereas a response to both dimensions suggests that infants may integrate multiple dimensions.

1. Method

1.1. Participants

Participants were 28 9-month-old infants (M = 9.02 months, range: 8.57–9.46 months; 12 boys); 29 11-month-old infants (M = 10.99 months, range: 10.57–11.49 months; 15 boys); and 30 13-month-old infants (M = 13.23 months, range: 12.74–13.56 months; 12 boys). All infants were born full-term and had no hearing or vision problems. We tested additional infants, but excluded them from the final analyses because they failed to meet the habituation criterion (see procedure section below, n = 15 9-month-old infants, n = 17 11-month-old infants, and n = 22 13-month-old infants), became fussy (n = 1 9-month-old infant, n = 3 11-month-old infants, and n = 4 13-month-old infants), or other (n = 1 9-month-old infant and n = 1 13-month-old infant). Eighty-four percent of the infants were Caucasian, 4.3% were Hispanic, 2.9% were Asian and 8.7% were classified as other. Most of the mothers and fathers had at least a four-year college degree (82.4% and 80.6%, respectively). Infants' and parents' names were obtained through birth records from the State Department of Health. Parents were contacted by telephone and often sent an email describing the study and procedure. Participants were given a small gift at the end of the study, such as a bib or cup, for participating.

1.2. Stimuli and apparatus

During the testing period, infants were seated in their parent's lap in a dimly lit room directly in front of a 25-in. (64 cm) monitor at a distance of approximately 122 cm. The stimuli consisted of two-dimensional photographs of colorful, everyday objects (e.g., watch, car, and bowl; see Fig. 1). We created linear arrays of two or three items. We chose set sizes two and three because previous studies have shown that even infants younger than 9 months are sensitive to this discrimination (Starkey & Cooper, 1980). To control for area in our design, we created two sets of each array – one with a total surface area that was twice as large as the second set. By 6-months, infants can detect a 1:2 ratio in area (Brannon, Lutz, & Cordes, 2006), and may use continuous extent (i.e., total surface area) in their number discrimination (Clearfield & Mix, 1999; Clearfield & Mix, 2001). To decrease infants' use of total surface area here, during habituation, we showed infants both small and large area displays.

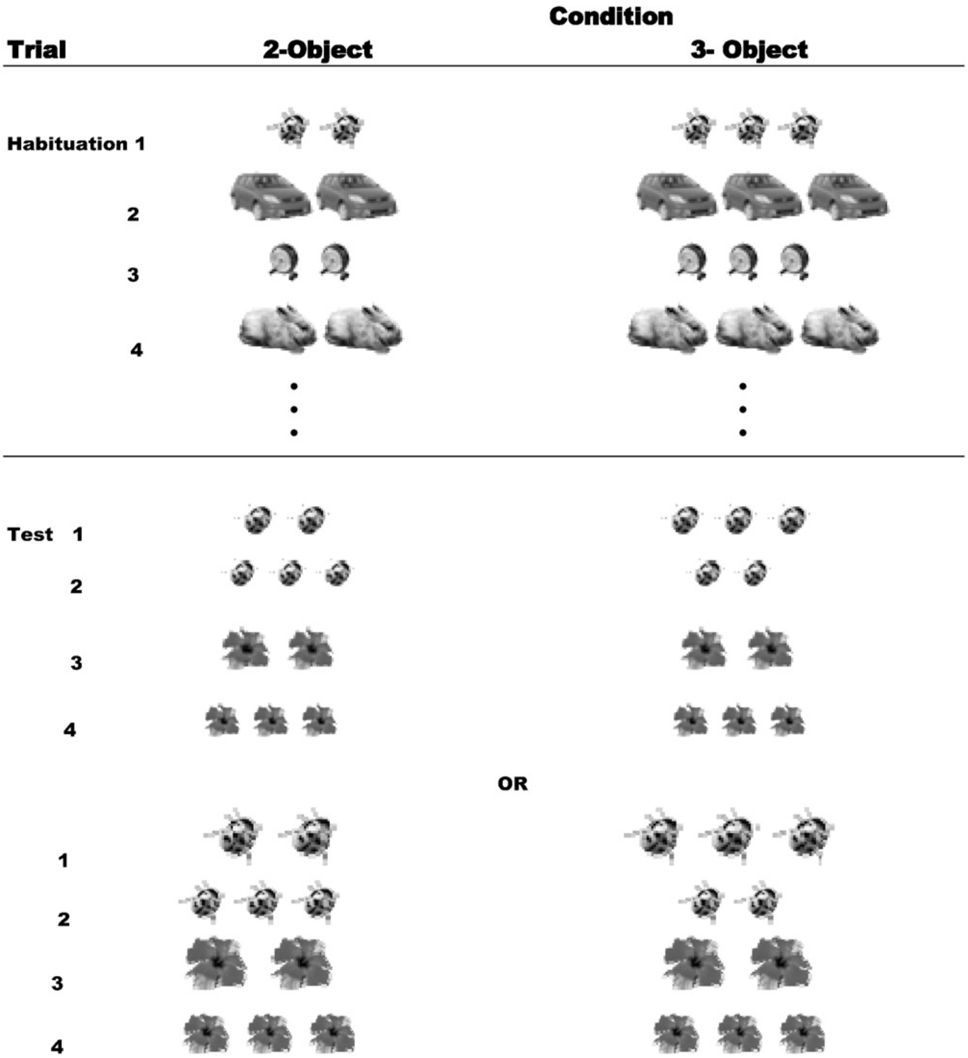

Fig. 1. Design of the study.

A closed circuit television camera was mounted below the monitor and connected to a DVD recorder, which was used to record the sessions. HabitX (Cohen, Atkinson, & Chaput, 2000) was used to present the stimuli and record infants' looking.

1.3. Procedure

Infants were seated on a parent's lap in front of the stimulus display monitor, and parents were instructed to close their eyes. The basic procedure and design was nearly identical to that used in Brez and Colombo (2012). Infants were randomly assigned to one of two numerosity conditions. Infants in the *two-object* condition were habituated to arrays of 2 items, and infants in the *three-object* condition were habituated to arrays of 3 items (see Fig. 1). Regardless of numerosity, infants saw four different object types; on each trial only one kind of object was presented, and each object was presented once in each block of four trials. Presentation order within a block was determined using a Latin square. Habituation trials continued until the looking time on any block of successive four trials was 50% of their looking on the first block of four trials (we used a "sliding window", so block 1 was trials 1 through 4, block 2 was trials 2 through 5, and so on; the minimum number of trials was 5), or until 20 trials had been completed. All trials were infant controlled; the stimulus remained visible on each trial until the infant looked away for one second (after accumulating at least one second of looking) or until 30 s had elapsed. If one second of looking was not recorded, the trial was repeated, and did not count toward the habituation criterion.

After the habituation phase, each infant was presented with four test trials (see Fig. 1). The first trial was the *Familiar Number-Familiar Object* test; on this trial the particular object in the array was familiar (one of the four presented during habituation), and the array had the same number of objects as during habituation (two or three). This first test trial served as a clean test of habituation independent of the trials used to meet the habituation criterion. Because infants can have both

Table 1
Mean looking time (s) for 9-, 11-and 13-month-old infants by test area.

Test area	Mean	Standard deviation	*n*
9-month			
Small	4.46	2.22	14
Big	3.99	1.65	14
11-month			
Small	4.72	1.87	13
Big	5.68	2.06	13
13-month			
Small	7.43	3.06	15
Big	4.55	.97	14

familiarity and novelty preferences, it is crucial in a habituation task to insure that infants have habituated in order to make conclusions in the test phase based on preferences for novelty (Oakes, 2010).

The next three trials were the (a) *Novel Number-Familiar Object* test, in which one of the four objects presented during habituation was in an array with a different number of objects (e.g., two if the habituation arrays had three items, and three if the habituation arrays had two items), (b) *Familiar Number-Novel Objects* test, in which the array contained the same number of items, but a new object that was not seen during habituation; and (c) *Novel Number-Novel Objects* test, in which both the number of objects and the objects themselves were different from the habituation arrays. The order of these three test trials was counterbalanced using a Latin square.

With regard to the area of the objects in the test trials, half of the infants viewed test trials in which *all* of the objects were of the smaller area regardless of the number of objects, and the other half of the infants saw objects of the larger area. Thus the test events did not vary in area and area was familiar for all infants in all conditions because they were habituated to examples of both small and large areas.

The experiment began with the attention-getter (looming green circle accompanied by a ringing sound) playing on the monitor. Once the infant fixated the monitor, the attention-getter was turned off and the habituation trials began. The attention-getter reappeared between each trial to redirect the infant's attention to the monitor, and the trials began when the infant fixated the monitor. An observer, seated out-of-sight in an adjacent room recorded looking time on each trial by pressing keys on a computer. A second observer re-coded the recording for the sessions for 26 9-month-old infants, 25 11-month-old infants, and 28 13-month-old infants. The correlation between the two coders for the duration of looking on each trial were high, $r = .98$ (9-months), $r = .96$ (11-months), and $r = .98$ (13-months).

2. Results

We evaluated infants' looking during the *Familiar Number-Familiar Object* test trial to ensure that the infants included in the final analyses actually habituated. We excluded four outliers (three 11-month-olds and one 13-month-old) who met the habituation criterion, but who looked longer than two standard deviations from the mean. In addition, this ANOVA revealed an unexpected significant interaction between test area and age, $F(2,62) = 3.19$, $p = .048$, $\eta_p^2 = .093$ (see Table 1 for a breakdown of the means and standard deviations). This effect was due to 13-month-olds' preference for the small test items, $t(27) = 3.36$, $p = .002$ and the presence of no preference in either the 9- or 11-month-olds. As this effect did not interact with test trial, it is not considered in the explication of the analyses described below.

The overall analysis of all ages revealed a main effect of age, $F(2, 62) = 5.27$, $p = .008$, $\eta_p^2 = .145$, as older infants looked longer at test trials in general than younger infants, and a main effect of test trial, as infants looked significantly longer at the *Familiar Number-Novel Object* test trial than at the *Familiar Number-Familiar Object* test trial, $F(3, 186) = 3.11$, $p = .028$, $\eta_p^2 = .048$. These two overall main effects, however, were qualified by a significant interaction between test trial and age, $F(6, 185) = 2.15$, $p = .049$, $\eta_p^2 = .065$, as infants' responding to the test events varied across ages. To probe this interaction, we conducted 2×2 ANOVAs on the test trials with number (familiar or novel) and object (familiar or novel) as within-subject factors for each age separately.

Analyses of the 9-month-olds' data revealed only a significant main effect for the number of objects, $F(1,27) = 4.28$, $p = .048$, $\eta_p^2 = .106$, indicating that 9-month-old infants discriminated two objects from three objects irrespective of whether items in the test arrays are familiar or novel (see Fig. 2). They looked longer on the trials with a novel number of objects ($M = 4.60$ s, $SD = 2.45$) than with a familiar number ($M = 3.82$ s, $SD = 1.90$). The presence of just this main effect suggests processing of quantity in isolation, ignoring object identity.

In contrast, 11-month-olds' data revealed only a significant main effect of object type, $F(1,25) = 4.93$, $p = .036$, $\eta^2{}_p = .138$. These infants looked longer at the novel objects ($M = 6.02$ seconds, $SD = 3.32$) than at the familiar objects ($M = 4.38$ seconds, $SD = 2.00$). Thus, while 9-month-old infants discriminated number collapsed across objects, 11-month-olds the identity of objects in the array, apparently ignoring number. Again, the presence of just this main effect suggests processing of stimulus content in isolation, ignoring the property of quantity.

Finally, the analysis of the 13-month-old infants revealed no main effects of number or object, but did yield a significant *interaction* between object and number, $F(1,28) = 7.40$, $p = .01$, $\eta^2{}_p = .209$. Here, 13-month-old infants' discrimination of

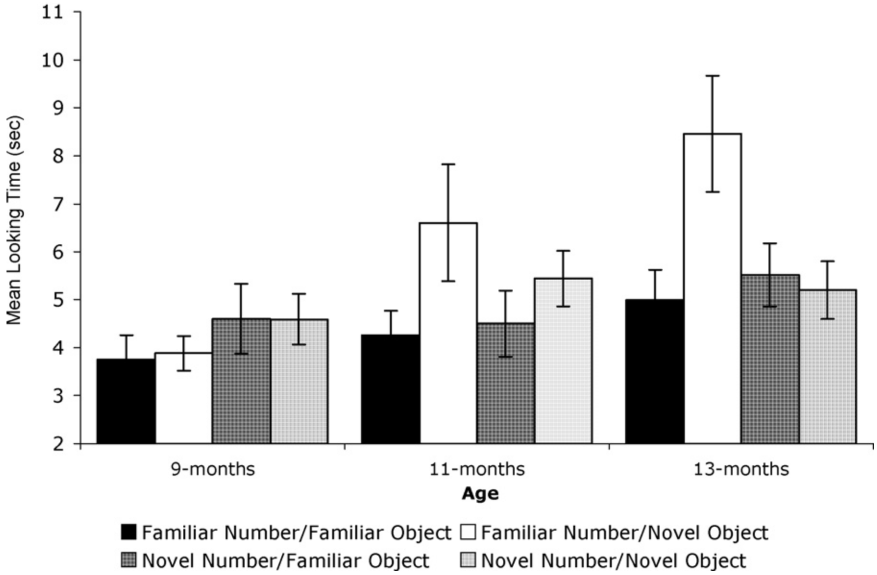

Fig. 2. Mean looking time (s) for each test trial by age. Error bars correspond to one standard error.

objects depended on the familiarity of the number. These infants dishabituated only to the *Familiar Number-Novel Object* stimulus, $t(28) = -2.56$, $p = .016$, but did not dishabituate to the *Novel Number-Familiar Object* stimulus, $t(28) = -.67$, $p = .51$, or the *Novel Number-Novel Object* stimulus, $t(28) = -.24$, $p = .81$. Thus, 13-month-olds discriminated new objects only when the objects appeared in the context of a familiar quantity. Infants did not dishabituate to the *Novel Number-Novel Object* trial, which was the most dissimilar to the habituation phase, and this may suggest that infants became overwhelmed when both the featural and numerical information changed. However, the presence of this interaction suggests that infants at this age were engaged in processing of both properties simultaneously.

3. Discussion

Using a task that assessed infants' simultaneous processing of both object identity and object quantity, we sought to examine whether and at what age infants integrated these properties of stimulus arrays. The results were relatively clear-cut: 9-month-olds processed the number of objects in the array independent of the non-numerical featural information, 11-month-olds processed object features independent of number, and only at 13 months of age did infants provide evidence of integrating processing of both properties of the arrays. This developmental trajectory, in which infants only begin to integrate the featural and numerical information at later ages, is consistent with models of emergent higher-order cognitive function in the second year (Banich, 2009; Colombo & Cheatham, 2006; Colombo et al., 2012; Garon, Bryson, & Smith, 2008; Oakes, Kannass, & Shaddy, 2002) in which the integration of basic cognitive processes results in the formation of more broadly constructed semantic networks that represent multiple properties. It is worth noting that this finding parallels recent reports of changes in the performance of older infants on categorization tasks (Oakes & Madole, 2000) where information acquired later in the second year readily spreads across concepts (e.g., form and function) and is connected to a number of other cognitive processes, especially word learning (e.g., Booth & Waxman, 2002a, 2002b; Booth & Waxman, 2006)

Finally, this study may be viewed as providing important new evidence of the relative priority or salience of infants' processing of both object identity and quantity under conditions when they are assessed simultaneously; this issue has rarely been addressed in the infant number literature. The current findings suggest that such salience is quite dynamic in the face of the rapid cognitive change occurring spanning the first birthday. Data from 9-month-olds suggest that number is more salient property early on. The response of 11 month-olds is interesting; at face value it may be taken as attention only to object identity but in fact, during habituation on the task used here, number was held constant and object identity was changing. The results here may suggest merely that 11-month-olds may have been attending to the more dynamic aspect of the displays (i.e., they were attracted to and preferentially processed object identity because it was an aspect of the displays that was constantly changing). Furthermore, while area was controlled for in this study, other variables of continuous extent, such as brightness, varied naturally and these could possibly influence infants' behavior in this task. These possibilities can be tested in future research where the habituation conditions are reversed and other variables of continuous extent are manipulated. Irrespective of the responses of the earlier two groups, the more mature pattern showing evidence of processing both object and quantitative properties in the arrays appears to emerge during the beginning of the second year.

The coordination and integration of cognitive processes for the facilitation of higher-order processes is an important cognitive ability as it leads to the development of executive function and other critical cognitive abilities. This study demonstrates one domain in which this ability is advantageous–namely, for number discrimination. This study also highlights the importance of taking a developmental approach to addressing this issue because it is an ability that develops over time.

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