The Dissertation Committee for Caitlin Christine Brez certifies that this is the approved version of the following dissertation:

Infant Number Perception: A Developmental Approach

Committee:

Leslie B. Cohen, Supervisor

Jacqueline D. Woolley

W. Todd Maddox

Rebecca Bigler

Eugenia Costa-Giomi

Infant Number Perception: A Developmental Approach

by

Caitlin Christine Brez, B.A.; M.A.

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Dedication

This dissertation is dedicated to my family for their love and support.

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Infant Number Perception: A Developmental Approach

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Caitlin Christine Brez, Ph.D.
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Supervisor: Leslie B. Cohen

Infant number perception is a topic that has been studied for many years, but many questions remain regarding what cues infants use to make these discriminations, when and how these abilities develop, and what systems are responsible for infants' number processing. In the domain of small number perception (quantities less than four), researchers have studied the effects of continuous extent on infants' number discrimination (Clearfield & Mix, 1999; 2001). While evidence exists that infants can use continuous extent to make discriminations, it is not clear how much influence continuous extent has on infants' behavior in these tasks. Another issue that has not been thoroughly addressed is the role of featural information in number discrimination. Few studies exist in which featural information is manipulated so that this issue can be addressed. The current study was designed to address these issues as well as to study infant number discrimination from a developmental perspective across several ages. Infants, aged 9-, 11-, and 13-months, completed a categorization task in which they were habituated to pictures of objects (*e.g*. bowl, tree, shoe) in *either* groups of two or groups of three. They saw four different sets of objects throughout habituation. In the test phase, infants saw *both* new and old objects in *both* groups of two and three. The 9-month-olds discriminated number independent of whether the object was familiar or novel. In contrast, the 11-month-olds appeared to discriminate between the familiar and novel objects. And, the 13-month-olds exhibited a combination of these two patterns; they discriminated between the familiar and novel object when the number of objects was familiar, but not when the number of objects was novel. These data suggest that number is an easily abstracted construct and that early number representations do not contain any featural information. As infants get older, they begin to incorporate featural information into their representations, but they do so in a step-wise fashion, as demonstrated by the 13-month-olds. Therefore, featural information does not appear to be important for small number discrimination at early ages, but infants do begin to integrate featural information as they develop.

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Chapter 1: Literature Review

Review of Discrimination Studies

The development of number perception and numerical ability are topics that have intrigued psychologists for many years. Strauss and Curtis (1983) began their book chapter with a quote by Harl Douglass who published one of the first articles on number development in the Journal of Experimental Psychology (Douglass, 1925). Douglass raised an important issue regarding how we determine what evidence to use in order to establish numerical abilities in humans. Strauss and Curtis introduced the quote by explaining that Douglass' question is one that is a current and important issue in the field. Despite the 25 years of studies that have been published since Strauss and Curtis' chapter, this issue has yet to be resolved and will certainly be one that surfaces throughout this paper. Douglass studied number abilities in children, but the issue seems even more relevant for the study of infant number perception because of the difficulty in assessing infants' perceptual and cognitive abilities. Therefore, it only seems fitting to once again quote Douglass and pose yet again, the age-old question of how we determine numerical abilities in infants and children. Douglass (1925) states:

> What then is the standard by which we shall judge possession of a concept?...Is it necessary that a child recognize a group of four objects, let us say dots on a piece of paper, before he may be said to 'know' four?...Must we insist that the 'knowing' of four depends upon perceiving four without counting? or adding? Does a child really 'know' four until he is able to assemble a group of four objects, to select four from a large number? Must he be able to distinguish four from three, from five, and all other numbers? Can he be said to have a 'true' concept of four if he is not aware of all its properties, *e.g.*, that it is half of eight or a third of twelve, that it is twice two and the sum of three and one, and that it is the difference between ten and six and between five and nine?...Can a child be

> said to possess the concept of the number four until he can identify tactile, auditory, kinaesthetic, or gustatory experiences of four in all the possible variations and situations? It is clear that there is no limit which may be set to the extension or perfection of a concept. It is never complete, and the bounds of its development are limitless (pg. 444-445).

Douglass' issue is clearly important, and it will continue to surface throughout this paper. However, it is first necessary to address how number studies have been conducted and review the findings on this topic to date.

As Douglass (1925) wrote, there are many ways to assess numerical abilities in infants and children, and researchers have used a variety of techniques. Douglass used three tasks to assess numerical skills in children. First, he asked them to estimate the number of dots on a piece of paper without counting. In his second task, children were asked to match cards with dots on them to the correct number (again without counting). And, in his third task, the experimenter held a collection of marbles in his hand and the child had to again estimate how many marbles there were. Douglass' tasks were all based on numerical estimation as a means of assessing underlying numerical abilities.

Another task often used with children is Piaget's number conservation task (Flavell, 1963). Piaget, one of the pioneers of cognitive development, was interested in studying the basic numerical abilities of children which he termed "number readiness" (Flavell, 1963, pg. 310). Therefore, he wanted to understand how children responded when he pitted various other factors, such as perceptual change, against number. For example, he would show a child two rows of balls of equal number. They would be arranged in perfect correspondence so that each ball sat directly across from its corresponding ball in the other row. He would then stretch one row out such that the balls were spaced further apart and therefore the row length was longer (although it was still the same number of balls). He would ask the child which row had more balls. A child with conservation of number would say that both rows still contained the same number of items while the child who had yet to develop this concept would say that the row that covered more perceptual space had more balls. Piaget also used this same principle to study other related issues such as conservation of quantity, space, and time (Flavell, 1963).

While 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 1980's (Strauss & Curtis, 1981 and Starkey & Cooper, 1980). The field has advanced since then and we are closer to understanding how infants may process number and how that ability develops. However, many issues and questions have yet to be addressed. This review of the literature discusses the major findings to date as well as highlights the gaps in this research (see Tables 1 and 2 for a summary of the infant discrimination studies).

The early infant discrimination studies were simple both in their design and in the stimuli that they utilized (see Strauss & Curtis, 1981; Starkey & Cooper, 1980; and Treiber & Wilcox, 1984). Using a habituation design, Starkey and Cooper (1980) found that 5.5-month-old infants could indeed discriminate two from three items. They used simple arrays of dots that varied in their length, density, and position. As is standard for most discrimination studies, infants were habituated to *either* two-dot arrays *or* three-dot arrays. In the test trials, infants saw *both* two-dot and three-dot arrays. If infants dishabituated to the novel number of dots, researchers claimed that this was evidence that they could discriminate two from three. In Starkey and Cooper's (1980) study, 5.5-month-old infants dishabituated to the novel number of dots suggesting that 5.5-month-olds can discriminate two dots from three. However, these infants were unable to discriminate between four and five dots.

Strauss and Curtis (1981) expanded on this early finding with 5.5-month-olds by testing older infants, with more complex stimuli, and testing multiple pairs of quantities. They found that 10-12-month-old infants are able to discriminate numerosities when the quantities are less than four. In this study, infants were habituated to sets of either homogenous or heterogeneous items. In the homogenous condition, infants always saw the same item throughout the habituation and test trials. In the heterogeneous condition, infants were habituated to the same number of items, but the items themselves would vary across each presentation (*i.e.,* two ducks, two houses, etc). The researchers found that infants could discriminate two versus three items, but not four versus five regardless of homogeneity. Interestingly, for the three versus four condition, there was an interaction such that female infants could discriminate the quantities in the homogeneous condition and males could discriminate the numerosities in the heterogeneous condition. It is unclear, however, if this interaction is a robust finding as this gender and homogeneity/heterogeneity interaction does not appear in later studies (Starkey, Spelke, & Gelman, 1983, 1990; Wynn, 1995, 1996; and Antell & Keating, 1983). However, the finding that infants can discriminate numerosities less than four does appear to be a reliable result (see Starkey & Cooper, 1980).

Several other researchers have found that infants can discriminate small numbers of objects (less than four) and can do so at many different ages (Starkey, Spelke & Gelman, 1983; Antell & Keating, 1983, Mack, 2006; and Feigenson, Carey, & Hauser, 2002; see Table 1). There are even some data to support that newborns may be able to discriminate number (Antell & Keating, 1983). Starkey, Spelke, and Gelman (1983, 1990) found evidence for discrimination with 7-month-olds in a two versus three discrimination. Furthermore, in this study, infants could match the number of drumbeats heard to the number of items on the monitor, suggesting that infants are able to perceive numerosity and match it across modalities. This finding suggests that infants' ability to process number is general and abstract enough to allow infants to transfer that knowledge to a second domain. They are not simply matching visual displays (Wynn, 1995) as they might be doing in most visual habituation tasks. However, two studies cast doubt upon these results (Moore, Benenson, Reznick, Peterson, & Kagan, 1987 and Mix, Cohen Levine, & Huttenlocher, 1997). Moore et al. (1987) found that infants' looking behavior was significantly different depending on the number of drumbeats; however, they found that infants looked longer at the noncorresponding display (*i.e.,* the visual display does not match the number of auditory tones) which is the opposite of Starkey, Spelke, and Gelman's finding. Moore et al. used a slightly different procedure, but this does not seem to account for the discrepant results. Mix, Cohen Levine, and Huttenlocher (1997) used a procedure more similar to that of the original Starkey, Spelke, and Gelman study, but also found that infants looked longer at the noncorresponding displays, thus replicating Moore et al.'s study. Furthermore, Mix, Cohen Levine, and Huttenlocher performed a second study in which they randomly varied the rate and duration of the drumbeats. In this case, they no longer found significant differences in infants' looking behavior between the two displays. Therefore, the evidence for cross-modal number perception from these studies is far from conclusive.

Despite the conflicting results from the intermodal matching studies, evidence for number discrimination does exist outside of the visual domain. Wynn (1995, 1996) has found evidence for number perception using sequences of action rather than visual stimuli. She found that infants (6-months) could discriminate numerosity within sequences of actions (*i.e.,* a puppet jumping). Infants were habituated to a puppet jumping either two or three times on a stage. Wynn controlled for both duration and tempo of the jumps. Again, these infants were able to discriminate between two and three jumps. This is further evidence of infants' number discrimination in yet another modality.

One interesting conclusion that can be made from all of these studies is that infants can discriminate number when the number of items to be discriminated is less than four. Most of the studies comparing discrimination with one versus two or two versus three items support this claim (Feigenson, Carey, & Spelke, 2002; Feigenson, Carey, & Hauser, 2002; Starkey & Cooper, 1980; Mack, 2006; and Starkey, Spelke, & Gelman, 1983). This result has been found with infants as young as newborns through 14.5-month-olds. However, with numbers greater than four (like four versus five or four versus six), infants generally fail to discriminate (Mack, 2006; Starkey & Cooper, 1980; and Feigenson, Carey, & Hauser, 2002; see Tables 1 and 2).

What happens with discrimination in the "gray" area (*i.e.,* discriminations that straddle this dividing line of four items)? The results are mixed when it comes to discrimination of numbers that cross this line. For example, two studies found positive results (*i.e.,* infants can discriminate) when comparing two versus four items (Wynn, Bloom, & Chiang, 2002 and Mack, 2006). However, four different studies found that infants cannot discriminate two versus four items (Wood & Spelke, 2005; Xu, 2003; Feigenson, Carey, & Hauser, 2002; and Feigenson & Carey, 2003). The pattern is similar for a three versus six discrimination. Mack (2006) found that infants could discriminate three versus six dots; yet Feigenson, Carey, and Hauser (2002) found that neither 10-month- nor 12-month-old infants could make this discrimination. Additionally, in the Feigenson et al. study, the stimuli were graham crackers that the infant could reach for and grab. It is possible that the infants may have been motivated by the food to reach for the greater amount; yet, infants still did not reliably pick one quantity over the other.

This result that infants can discriminate numbers less than four more easily than numbers greater than four is interesting because it aligns well with studies of adults' subitizing (Trick & Pylyshyn, 1994 and Peterson & Simon, 2000). Subitizing is the process in which enumeration is rapid and occurs in parallel for items less than four. However, with quantities greater than four, enumeration may occur by counting which is a serial process that requires more time. Additionally, the slope of the reaction time curve for enumeration shows a distinct pattern in that it barely increases for quantities up to four and then there is an inflection at four items where the slope increases sharply in a linear fashion as the number of items to be enumerated increases. Perhaps infants have a similar subitizing process such that it is relatively easy for them to enumerate and distinguish between small quantities that do not require counting. Counting may be a process that requires verbal skills (Gallistel & Gelman, 2005), which these younger infants do not yet possess.

Based on these earlier studies, it is easy to conclude that infants are able to discriminate numerosities when the number of items is small (*i.e.,* less than four), but not when the number of items is large. However, some researchers have argued that infants' inability to discriminate large numbers is not based on the numerosities themselves, but on the ratio between the numbers (Xu and Spelke, 2000; Brannon, Lutz, & Cordes, 2006; and McCrink & Wynn, 2007). Xu and Spelke (2000) conducted a study in which they habituated 6-month-old infants to displays of either 8 or 16 dots varying in spatial size and density. Infants were then tested on both the familiar and novel numerosities. When the ratio was large enough (1:2), infants were able to discriminate between the large numerosities. However, when they reduced the ratio to 2:3 (same as Starkey & Cooper [1980] in which 5.5-month-olds could easily discriminate), infants were no longer able to discriminate the numerosities. They argued that infants' number perception follows Weber's law and that at quantities larger than four, numerosities must differ by a great enough ratio for infants to detect a difference. Weber's Law states that it is not the absolute difference between two items that is important for discrimination, but rather the proportional difference that is crucial (vanMarle & Wynn, 2006).

This sensitivity to Weber's Law has also been found in area discrimination. Brannon, Lutz, and Cordes (2006) habituated 6-month-old infants to either small or large faces of Elmo. In the test phase, infants saw the Elmo face either enlarged or reduced by a ratio of 2:3, 1:2, 1:3, or 1:4. They found that infants were able to discriminate the change in area in all of the conditions except 2:3. This result suggests that infants require at least a 1:2 ratio before they can discriminate a dimension such as area. This corresponds to the findings with large number perception (Xu & Spelke, 2000 and Wood & Spelke, 2005). There are several studies, mostly by Spelke, Xu, and colleagues which suggest that infants require 1:2 ratio to discriminate number when the number of items is greater than four (Wood & Spelke, 2005; Xu & Spelke, 2000; and Xu 2003; see Table 2). Xu and Spelke (2000) conducted an experiment with 6-month-olds using stimuli that consisted of dots. They found that 6-month-olds could discriminate between 8 and 16 dots (1:2 ratio), but not 8 and 12 dots (2:3 ratio). Additional evidence for this limit based on overall number and ratio comes from Wood and Spelke's (2005) study. They tested number discrimination for action sequences (*i.e.,* puppet jumping) rather than visual stimuli. They were able to demonstrate that at 6-months, infants can discriminate four jumps from eight jumps. However, 6-month-olds were unable to discriminate two jumps from four jumps in their study. The ratio between the two discriminations is the same; however with other variables such as jump rate and duration controlled, infants were unable to make the discrimination with the smaller numbers. Wood and Spelke also tested 6-month-olds on a discrimination of four versus six jumps (2:3 ratio) and again found infants unable to successfully discriminate based upon number. Finally, they tested 9-month-olds on the four versus six-jump discrimination and found that 9-month-olds were able to make the discrimination based upon number. Their results suggest that the ratio necessary for infants to discriminate numbers decreases as infants develop. Additional support for this developmental trend comes from Xu & Arriaga (2007) who found that 10-month-olds could discriminate between 8 and 12 items (a 2:3 ratio). Together, these studies provide further support for the distinction between processing smaller numbers (less than four) and larger numbers. The distinction that is made is that infants can easily discriminate smaller numbers, but that with larger numbers, the ratio must be at least 1:2 before infants can make the discrimination. However, the necessary ratio does seem to decrease as infants develop suggesting that they can make finer discriminations with larger numbers the older they get.

One issue that arises from studies of infant number discrimination is whether infants are truly discriminating number or whether these findings result from the use of other confounding variables such as item size, density, contour length, and overall area (see Clearfield & Mix, 1999 and Feigenson, Carey, & Hauser, 2002). The results on this issue appear to be mixed (see Tables 1 and 2). For small number discrimination, there are several studies that show that infants can still discriminate number even with some of these variables controlled. For example, Starkey and Cooper (1980) intentionally varied the length and density of the displays (rows of dots) and found that 7-month-old infants were still able to discriminate two versus three dots. The exact same procedure was used in the Antell and Keating (1983) study in which they found that newborns could discriminate two versus three items. Strauss and Curtis (1981) varied the size and position of the objects in their displays and again found that infants could discriminate two versus three, but not four versus five items.

However, several studies suggest the opposite – that infants may be relying on these extra cues to make the discriminations instead of number. For example, Feigenson, Carey, and Hauser (2002) allowed infants to choose between one versus two crackers. Ten- and 12-month-old infants reliably chose the greater quantity. However, once they controlled for the surface area (*i.e.,* total amount of cracker), there was no difference in infants' choices between one and two crackers. Results from looking time studies also corroborate this finding. Clearfield and Mix (1999) tested to see whether infants used contour length to aid in number discrimination. Contour length is the sum of the perimeters of all objects in the display. They habituated 7-month-old infants to displays of either two or three squares that varied in contour length. During the test phase, infants saw displays that kept number familiar while changing the contour length and saw displays that kept contour length the same and changing the number of items. They found that infants dishabituated to the change in contour length, but not the change in number. This suggests that infants are using contour length when making discriminations of number. Furthermore, Clearfield and Mix (2001) replicated their study and extended the findings to changes in area as well. In this study, they habituated 6-month-old infants to displays of either two or three items. For half the infants, area and number changed in the test, but contour length remained constant across both habituation and test. Just like their previous study, the test trials pitted area change against number change such that one test trial contained a change in area while holding number constant and the second test trial contained a change in number while holding area constant. Alternatively, infants tested in the contour length condition had habituation trials and test trials where contour length and number varied (as in their 1999 study), but area remained constant across both habituation and test. Clearfield and Mix found that infants dishabituated to a change in area and a change in contour length, but never dishabituated to a change in number. This provides further support for the argument that infants may be relying on other cues when making number discriminations. Finally, Feigenson, Carey, and Spelke (2002) replicated Clearfield and Mix's (2001) findings that infants would dishabituate to a change in area, but not number (Feigenson et al. used 7-month-olds as opposed to 6-month-olds). They conducted several additional studies in which they varied area changes across habitation and test and were unable to replicate the previous findings with these new manipulations. For example, in Experiment 2, they kept the change in area constant across test trials although the area changed from habituation. Again, infants did not dishabituate to the change in number; however, they did not dishabituate to the change in area either. The researchers suggested that the reason that infants did not dishabituate to the change in area in this experiment was that the change in area in the test trial was relatively small compared to the area in the habituation trials, and therefore, not great enough to elicit a change in infants' looking behavior. However, this does call into question some of the earlier studies that found that other continuous extent variables such as contour length and area are salient to infants and will lead to dishabituation. Generally, the results are mixed as to how these extraneous variables are influencing infants' behavior in small number discrimination tasks. It seems clear that infants can discriminate number, and they may be aided in that discrimination by confounding variables, but the extent to which these variables play a role is still an open question. This is one issue that the present study sought to address.

The issue of the role of extraneous variables on large number discrimination is slightly more understood (Wood & Spelke, 2005; Xu & Spelke, 2000; Xu & Arriaga, 2007; and Xu, 2003; see Table 2). Xu and Spelke (2000) used dots for their study and the dots were controlled for brightness, contour length, density, dot size, and display size. They found that 6-month-olds discriminated between 8 and 16 dots (1:2 ratio), but not 8 and 12 dots (2:3 ratio). They concluded that regardless of extraneous variables infants can discriminate based upon number, but only if the ratio between the displays is great enough (1:2 ratio) as discussed earlier. Wood and Spelke (2005) found similar results except that they tested number discrimination for action sequences (*i.e.,* puppet jumping) rather than visual stimuli. In their study, they controlled for sequence duration, jump duration, jump interval, jump speed, and jump height. They were able to demonstrate that, at 6-months, infants can discriminate four jumps from eight jumps. However, 6-month-olds were unable to discriminate two jumps from four jumps in their study. The ratio between the two discriminations is the same; however with other variables such as jump rate and duration controlled, infants were unable to make the discrimination with the smaller numbers. Wood and Spelke also tested 6-month-olds on a discrimination of four versus six jumps (2:3 ratio) and again found infants were unable to successfully discriminate based upon number (extraneous variables were controlled for). Finally, they tested 9-month-olds on the four versus six-jump discrimination and found that 9-month-olds were able to make the discrimination based upon number. Converging evidence also comes from Xu and Arriaga (2007). As discussed earlier, they tested 10-month-olds' discrimination of 8 versus 12 (2:3) and 8 versus 10 dots (4:5). They controlled for area, density of the dots, brightness, dot size as well as display size. Again, they found that 10-month-olds could make the 2:3 ratio discrimination, but not the 4:5 discrimination. This finding matches those of other large number discrimination studies that claim that by 9 months, infants are able to make discriminations when the ratio is as small as 2:3. These three studies collectively suggest that with large number discrimination, the key to infants' success is the ratio between the numbers rather than extraneous variables that may aid in the discrimination. It seems relatively clear that the ratio is the determining factor in these studies because several different extraneous variables were controlled for in these studies, and yet infants could still successfully discriminate the large numbers, *if* the ratio between the numbers was sufficiently large enough. Perhaps with large numbers that vary at least by a factor of two, infants do not need external cues to help them discriminate number, but with smaller numbers or those that vary by a ratio less than two, those external cues become important for discriminating numerosities.

REVIEW OF THEORIES OF NUMBER PERCEPTION

As demonstrated in the previous section, a distinction exists between how infants process small (less than four) and large numbers. But what accounts for this distinction? Currently, one main theory exists to explain how infants process small numbers and a different theory exists for large number perception (see Figure 1; Xu, 2003 and Feigenson, Carey, & Hauser, 2002). The processing of small numbers seems to rely on an object-tracking system (Feigenson, Carey, & Hauser, 2002 and Xu, 2003). Evidence for this system has been found in infants, adults, and rhesus macaques (Feigenson, Carey, & Hauser, 2002; Carey, 1998; Kahneman, Treisman, & Gibbs, 1992; and Trick & Pylyshyn, 1994). Because of the various fields using this theory, it has been referred to by a variety of names (*e.g*. FINST mechanism with adults [fingers of instantiation]). In the infant literature, the theory is most commonly referred to as the object-tracking or object-files model; therefore, both of these terms will be used synonymously throughout the remainder of this paper. This theory states that infants (and adults) assign tokens to each item that needs to be enumerated. However, the number of available object-files or tokens is limited to three or four items which explains why infants can easily discriminate numbers less than four. Thus, one limitation of this system is that the number of items that can be enumerated by infants reaches a maximum of three (see Figure 1), but a benefit is that the system is precise (*i.e.,* it can enumerate the exact quantity). While it appears that the object-files system can represent individual items, it is still unclear whether or not it can enumerate entire sets of items. Early evidence seemed to suggest that that the object-files could not enumerate sets (Xu, 2003); however recent research questions this claim (Feigenson & Halberda, 2004). Feigenson and Halberda (2004) used a manual search task in which 14.5-month-old infants were shown either two or four balls and then watched as the experimenter placed the balls into a box. Infants were able to reach into the box and pull out a ball, but the others were intentionally withheld. A 10-second measurement period ("more remaining" period) followed in which infants were allowed to reach towards the box for the remaining balls, but could not actually pull them out (the experimenter withheld them). Assuming that infants can represent the number of balls in the box, they should reach for the box and try to remove the remaining balls. Infants were then allowed to remove the final balls and another 10-second measurement period followed ("box empty" period). It was assumed that infants would not reach for the box in this case because there were no more balls in the box. The experimenters recorded how often infants reached towards the box during the two measurement periods. Infants were able to represent the balls in the two-ball condition. However, they could only represent the four balls when they were grouped as two sets of two. When the experimenters initially presented the balls to the infants, they either placed them all in a row on top of the box and put them in the box one at a time or they grouped them with two balls on each side of the box and placed them in two at a time. When the balls were spatiotemporally grouped as two sets of two, infants were then able to represent the four balls. The researchers concluded that infants might be grouping, or chunking, the items into two sets (Feigenson & Halberda, 2004). This study demonstrates the possibility that the object-files system may be able to represent sets of objects.

The most widely discussed theory explaining infants' enumeration of large numbers is the analog magnitude model (see Figure 1; Feigenson & Carey, 2003; vanMarle & Wynn, 2006; Xu, 2003; and Feigenson, Carey, & Hauser, 2002). This model is derived from the accumulator model (Meck & Church, 1983) used to describe counting and timing processes in animals. According to the accumulator model, nonverbal counting results from a mental accumulator that keeps track of all items until counting is finished. The accumulator stores impulses based on the input it receives. For each object that an infant (or adult) encounters, a gate is opened which allows a burst to enter the accumulator. Once the infant has scanned all of the items, a readout is provided which corresponds to the number of items perceived. This readout can then be stored in memory for later use. One key property of this model is that the magnitudes that are enumerated have some variability that increases as the number of items to be enumerated increases (Cordes, Gelman, Gallistel, & Whalen, 2001 and Meck & Church, 1983). Therefore, the greater the quantity to be enumerated, the more variability that may exist with the magnitude that is stored. Sometimes this model is referred to as a number estimation system which accurately portrays this variability. This variability may explain why infants' discrimination of large numbers follows Weber's Law. Instead of keeping track of each individual item as in the object-files system, this number estimation system is exactly that – an estimation of the quantities. Therefore, infants need a relatively large ratio between the quantities (1:2 until 9 months of age) in order to discriminate them. Unlike the object-files system, this analog magnitude model has been found in many different species including primates and rats (Xu, 2003 and Cordes et al., 2001). It appears to have no limit, treats large numbers as sets, and, as demonstrated by the studies with infants, follows Weber's Law (Xu, 2003).

PARALLELS WITH ADULT COGNITION

The data from the infant studies reviewed earlier support these two theories and the distinctions between the theories. Additionally, these theories are also used to account for data with adults (Trick & Pylyshyn, 1994 and Cordes et al., 2001). As mentioned earlier, the distinction between processing small and large numbers with infants mirrors subitizing and enumeration with adults (Trick & Pylyshyn, 1994; Peterson

& Simon, 2000; and Basak & Verhaeghen, 2003). Adults can rapidly enumerate numbers less than 3-4 (the exact limit is unclear), but process numbers larger than that in a slower, serial manner. Trick and Pylyshyn (1994) argue that the FINST mechanism (analogous to the object-files model) underlies adults' subitizing. They believe that subitizing is a pre-attentive, limited-capacity, parallel process that results as a side effect of visual perception. This theory could explain why we observe such accurate enumeration (as evidenced by discrimination) in infants for items less than four. Visual perception is functioning at birth, although not at an adult level (Slater & Johnson, 1998). Indeed, infants' visual system is close to adult-like ability by 6 months of age (Slater & Johnson, 1998). If this object-files system is a carry-over from basic vision, then it is reasonable to assume that infants would have this system in place early in development. This highlights another benefit of the object-files system – its general, cognitive function. Unlike the accumulator model whose sole purpose is to track and represent number estimates, the object-files system is domain general and can be used to individuate items in the visual field, store information in working memory, track property information for each item, and therefore numerically represent items. From a developmental and evolutionary perspective, a domain-general system, such as the object-files system, is efficient for infants to have early in development because it accomplishes tasks in multiple domains.

Despite the fact that the object-files system is domain general, evidence demonstrates that adults also use analog magnitudes to enumerate items (Cordes et al, 2001). From a developmental perspective, this is intriguing because it suggests that the bases for adult enumeration are in place in infancy. Infants' discrimination of large numbers seems to undergo improvement over the first year of life (it has not been tested beyond 10 months), but at least the basic mechanisms are in place.

REVIEW OF CRITERIA FOR DETERMINING NUMBER REPRESENTATION IN INFANTS

Thus far, research shows that infants are capable of discriminating both small and large numbers and researchers have explained how infants may succeed at these discriminations. However, we need to take a step back and consider the larger picture of whether or not infants are actually enumerating items; that is, are infants actually processing and understanding the numerical properties of the items in front of them? This brings us back to Douglass' (1925) concern about how we decide what to accept as evidence of numerical abilities. Is it sufficient to demonstrate discrimination? Is it more convincing when the underlying processes match those observed in adults? Douglass suggested several types of evidence that can be used to infer numerical understanding. One was recognition. One can infer from these discrimination tasks that infants can indeed recognize a particular set of items, for example two dots. In fact, discrimination was another of Douglass' methods for inferring numerical understanding and there is abundant evidence that infants can do this. Douglass also suggests that perhaps understanding number requires perceiving number without counting or adding. Clearly, infants can accomplish this as counting is generally considered a verbal process (Strauss & Curtis, 1983) and infants do not begin producing words until 12-13 months of age (Fenson et al., 1994). Douglass asserts that perhaps we cannot make conclusions about numerical competency until infants or children can demonstrate that they can perform operations on numbers. The question of infants' ability to add and subtract is a widely debated issue that continues into the present day.

Wynn (1992) first made the suggestion that infants could add and subtract after conducting a violation-of-expectation study with 5-month-olds. In her study, infants were familiarized to either an addition or subtraction event. In the addition event, one doll was placed on a stage in front of the infant. A screen was raised, obstructing the infant's view of the stage. Next, a second doll was placed on the stage behind the screen. When the screen was lowered, the infant either saw two dolls on the stage (possible event) or one doll on the stage (impossible event). The subtraction event followed the same basic procedure, except that the trial began with two dolls on the stage and one doll was removed. Again, when the screen was lowered at the end of the trial, either one doll (now the possible event) or two dolls (impossible event) were on the stage. Wynn found that in both the addition and subtraction events, 5-month-old infants looked longer at the impossible events (Wynn, 1992). This corresponds with the predictions of a violation-of-expectation paradigm; infants should look longer at the result that is unexpected. This finding has been replicated using cross-modal stimuli (Kobayashi, Hiraki, Mugitani, & Hasegawa, 2004) and supported with brain data (event-related potentials; Berger, Tzur, & Posner, 2006). Wynn makes strong claims from this study that infants must have an innate representation of number; and beyond just representing numerical quantities, they also have the ability to make mathematical transformations over the quantities (Wynn, 1992).

Despite the attention these findings received both in academia and in the public's eye, Wynn's (1992) study has been criticized for several reasons. First, several researchers have suggested that Wynn's findings can be explained by a simpler, perceptual explanation (Cohen & Marks, 2002; Clearfield & Westfahl, 2006; and Moore & Cocas, 2006). These researchers have evidence that infants respond to the test trials based upon familiarity with the stimuli which happens to coincide with the impossibility of the event in Wynn's design. Cohen and Marks (2002) proposed a dual-process model to explain Wynn's findings. In their model, infants should respond to stimuli based upon a combination of two processes. One process is a familiarity bias; infants tend to look longer at a familiar stimulus early in familiarization before they have had time to habituate. In Wynn's study, infants only saw six familiarization trials, so it is reasonable to expect infants to show a familiarity bias especially due to the complex nature of the stimuli (multi-step events involving several different components including the hand moving in and out and the screen raising and lowering). The second process of the dual-process model is the tendency for infants to look at the larger set of items when given a choice. Again, Cohen and Marks conducted several studies which support this theory.

Further evidence for the role of familiarity comes from Clearfield and Westfahl (2006) who conducted a study in which they gave infants several familiarization trials prior to the test trials. These familiarization trials were of either the impossible or possible outcome. When familiarized to the impossible outcome, infants looked longer during the test at the possible outcome (the opposite of Wynn [1992]). And, when the infants were first familiarized to the possible outcome, they then looked longer at the impossible event in the test. These findings suggest that familiarity can bias infants' looking behavior towards the familiar stimuli at least in these addition- and subtraction-type events. This is strong evidence to counter Wynn's conclusions that infants can perform mathematical transformations.

Another criticism of Wynn's (1992) study is that she makes grandiose claims about infants' abilities from her data (Cohen & Marks, 2002; Cohen, 2002; Carey, 2002; Mix, 2002). As shown above, there are multiple interpretations of how infants are performing this task, and as scientists and developmentalists, we should be cautious of over-attributing skills and abilities to infants. However, the debate over whether these studies show numerical competence or a simpler perceptual bias continues in the present day.

As Douglass (1925) pointed out, this issue of what to accept as evidence for numerical competency is very complex and could be limitless. Every individual can have his or her own notion or expectation for sufficient evidence. Carey (1998) makes a reasonable suggestion that there should be two criteria for judging human's capacity to represent number. The first criterion is that humans can discriminate items based solely upon number and not variables of continuous extent such as area, volume, and contour length. The second criterion is that humans can demonstrate that these quantities have numerical meaning (Carey, 1998). One way to show that quantities have numerical meaning is to demonstrate that they have serial order. Carey's criteria require that evidence goes beyond simple discrimination and shows a higher level of processing and understanding of number. Infant studies have demonstrated discrimination (Strauss &

Curtis, 1981; Starkey & Cooper, 1980; and Treiber & Wilcox, 1983), although whether that discrimination is possible without continuous extent variables remains unanswered (see above discussion). Infant studies also have shown that infants are able to process and understand numerical differences in ordinality (Brannon, 2002 and Suanda, Tompson, & Brannon, *in press*).

Ordinality is the ability to process and understand the relationships between numbers, more specifically greater-than and less-than relationships. Elizabeth Brannon has led the field in studying how infants process ordinal information. In her 2002 paper, she discussed a series of experiments that show that ordinal knowledge develops between 9 and 11 months of age. In this study, she habituated infants to a sequence of squares that either increased in number or decreased in number. For example, in the ascending condition infants saw two squares, then four squares, and then eight squares. This sequence was repeated multiple times throughout habituation. During the test phase, infants saw either a familiar sequence (3, 6, 12 squares) or a novel sequence (12, 6, 3 squares). It should be noted that the actual numerosities themselves were novel during the test phase, although the overall ordinality was either familiar or novel. Additionally, Brannon used sequences that increased by a ratio of two in accord with Weber's Law. Brannon found that 11-month-old infants dishabituated to the change in ordinality, but there was no difference in looking time for the 9-month-olds. To rule out any confounding variables that may be aiding in 11-month-olds' processing of ordinality, Brannon ran a second study in which the size, surface area, and density of the shapes were all controlled. Again, she found that 11-month-olds successfully discriminated the sequences based on ordinal information, but 9-month-olds did not show any difference in their looking times to the familiar and novel displays. Finally, Brannon conducted a control study to determine if 9-month-olds' failure in the previous studies was due to the lack of the ability to compare rapidly changing displays. She habituated 9-month-old infants to a single square that changed size throughout the trial (*i.e.,* small square, medium square, large square). This pattern was repeated multiple times during habituation. During the test trials, infants were shown the familiar pattern (small, medium, large) or the novel pattern (large, medium, small) and infants were able to discriminate these two sequences. Therefore, 9-month-olds seem to be able to detect ordinal changes in size, but not number (Brannon, 2002).

In another set of studies, Brannon and her associates (Suanda, Tompson, & Brannon, *in press*) tried several different manipulations to better understand why 11-month-olds can process number, but 9-month-olds cannot. In their first experiment, they simply replicated Brannon's (2002) study and found that 11-month-olds were sensitive to displays that changed in ordinality, but 9-month-olds did not notice the difference. One possible explanation for the success of 11-month-olds is that they are simply paying attention to the very first item presented in each trial. If they were, one would expect the same pattern of results. For example, a baby in the ascending condition would always see two items on the screen at the beginning of each habituation trial and then during the test trials it was either 3 or 12 items. Because of the large change in numerosity from 2 items to 12, one would predict that infants should look longer at the sequence beginning with 12 items (*i.e.,* descending or novel display). Therefore, in the second experiment, Suanda, Tompson, and Brannon changed the test trials so that every trial began with eight items (8, 16, 32 for ascending and 8, 4, 2 for descending). The 11-month-olds dishabituated to the change in ordinality even when the first item on screen was equated across conditions which suggests that 11-month-olds are not simply discriminating based upon the first image they see, but rather seem to be incorporating information from across the entire trial to understand ordinality.

Yet it is still not clear why 9-month-olds cannot understand ordinal relationships. Suanda, Tompson, and Brannon (*in press*) tried to answer this question with a couple of control studies. In one of these studies, they gave 9-month-olds longer exposure to the individual numerosities (2- and 3-second durations instead of 1-second durations). However, this did not change the results; 9-month-olds still did not respond differently to the familiar or novel displays. They also tested to see whether 9-month-old infants could detect a change in displays in which either the object size or total area increased. In the experiment where the object size varied, the number of items remained constant throughout habituation. In the experiment where total area changed, the number of items on the screen varied randomly (neither increasing or decreasing). In both cases, 9-month-olds did not detect a change in either element size or total area. This results calls into question a previous finding by Brannon (2002) in which 9-month-old infants did notice a change in a single item that either increased or decreased in size. The previous study was a little simpler than this more recent finding because in the first report, it was a single square changing (as opposed to multiple squares in this second experiment). Secondly, element size and area were confounded such that infants had both cues to rely on. And thirdly, because it was a single square centered on the monitor, it could have appeared to the infant as a single item either looming forward or withdrawing backward (Suanda, Tompson, & Brannon, *in press*). This is certainly a simpler and more obvious phenomenon for the infant to attend to rather than picking up on changes in element size or area. However, Brannon and colleagues were finally able to get 9-month-old infants to succeed at an ordinal discrimination task when there were multiple cues present. In their final experiment, Suanda, Tompson, and Brannon (in press), habituated infants to ascending or descending displays, but in contrast to earlier studies, element size and total area were correlated with the change in numerosity. In this case, 9-month-olds now successfully discriminated between the familiar and novel sequences. This result suggests that 9-month-old infants may be able to discriminate sequences based upon ordinality, but only when multiple cues are available. As the authors noted, it is interesting that 6-month-old infants can discriminate a 1:2 change in number (Xu & Spelke, 2000), yet even three months later, infants are unable to discriminate ordinal relationships that vary by a 1:2 ratio. According to Carey's (1998) proposition, infants are not able to truly represent number until 11 months of age when they can discriminate items based upon ordinality.

THE NATIVIST-CONSTRUCTIVIST DEBATE

Assuming that infants do have numerical discrimination and possibly ordinality, the next logical step from a developmental approach is to determine where these abilities come from and how they develop. The nature/nurture debate is a central issue in the number perception field as it is throughout all of development. It is an ongoing debate that will continue to be discussed in the future, but it is important to discuss various views on this issue. One of the strongest supporters of the nativist approach is Karen Wynn (1995; 1996) who believes that infants are born with a system for numerical knowledge. In fact, Wynn goes as far as to claim that infants have innate systems for not only representing different numbers, but also procedures for manipulating numbers (Wynn, 1992; 1995). She argues that this number representation system is domain general and applies to several different perceptual abilities. For example, infants can discriminate different numbers of jumps (Wood & Spelke, 2005) as well as match visual stimuli with the correct number of auditory tones (Starkey, Spelke, & Gelman, 1983; 1990). Wynn argues that discrimination does not rely on perceptual properties, but on the number of items. Generally, it is difficult to find solid support for a nativist approach as infant abilities can also usually be explained by a learning or constructivist approach (Cohen, Chaput, & Cashon, 2002). However, the idea of number discrimination being domain general is one that is supported by the literature (*i.e.,* object-files system) and one that can be supported from both a nativist and constructivist position.

In contrast to Wynn, several researchers have argued that infants' success in number discrimination tasks can be accomplished without having any numerical representation system (Simon, 1997; Strauss & Curtis, 1983, and Clearfield & Mix, 1999; 2000). Clearfield and colleagues (see Clearfield & Mix, 1999; 2001) posit that infants may not even need any representation of number to make these distinctions; rather, they use overall amount, which they refer to as spatial extent (Clearfield & Mix, 2001). By comparing continuous quantities such as area, volume, and contour length, infants can make distinctions between varying numerosities. Interestingly, Piaget's early number studies evolved from his studies of conservation of quantity, such as area (Flavell, 1963). He believed that representations of number, quantity and space were all inter-related and developed in unity. Thus, this theory has some grounding in Piagetian concepts. Clearfield and Mix, along with others, have data to support their theory (Clearfield & Mix, 1999; 2001 and Feigenson, Carey, & Spelke, 2002). In their own studies, Clearfield and Mix found that infants responded to changes in contour length and area over changes in number. Additionally, Feigenson et al. (2002) found similar patterns with area such that infants were sensitive to changes in area when area was pitted against a change in numerosity. Thus, it could be possible that infants can successfully complete these tasks without a number representation system. However, evidence from cross-modal studies (Starkey, Spelke, & Gelman, 1983; 1990) offers a challenge to this theory, as it is more difficult to understand the concept of spatial extent with auditory tones. While the duration of the tones could be summed to create some notion of "larger quantity", it seems a more difficult explanation to make for auditory stimuli than visual stimuli. Additional evidence against this theory comes from Wynn, Bloom, and Chiang (2002). They studied 5-month-olds' discrimination of moving sets of objects. Infants were habituated to either two sets of three dots or four sets of three dots. They controlled for contour length, surface area, brightness, and density of the sets. Additionally, the sets were in constant motion to reduce the possibility that infants may be grouping the objects to make enumeration easier. They found that infants could discriminate the sets and stated that this supports their position that infants have a true numerical representation of the items that they are discriminating (Wynn, Bloom, & Chiang, 2002). While there are limitations with this study (*e.g.,* they span the small/large number distinction making it difficult to determine how infants may be completing the task), it does argue against the spatial extent hypothesis because even with several spatial extent variables, such as area and density, controlled, infants were still able to discriminate moving sets of objects which is a relatively complex discrimination task. However, the evidence is not conclusive one way or the other; infants may be relying on correlated variables to aid in discrimination until they are able to form a strong representation of number. This is an interesting theory and certainly one that needs to be considered when conducting any study dealing with number perception.

Similar to Clearfield and Mix (1999; 2001), Simon (1997; 1998) has argued for a "non-numerical" account (Simon, 1997; pg. 350) of infant number perception. He contrasts his theory to Wynn's (1995) view that there is an innate numerical representation system. Instead, Simon claims that the system that engages in number tasks is one that evolved to address non-numerical issues. Simon takes a very constructivist approach in that he believes infants are born with the ability to perceive, individuate (*i.e.,* discriminate), represent, store, and reason about the world around them. With these skills, an infant can begin to understand and learn about the environment. These same skills can be used to discriminate numbers in a habituation task and make judgments regarding items in an addition task. Simon has even developed a computational model, INFANT, (Simon, 1998) to account for the data in the addition and subtraction tasks. His model begins with the same four competencies he believes infants are born with – memory, individuation/discrimination, abstract representation, and physical reasoning. INFANT is a non-numerical model and accurately matches the results of his replication of the original Wynn (1992) addition and subtraction tasks.

Simon's theory (1997; 1998) is one of domain-generality; the basic principles that underlie infants' ability to process and discriminate number are the same skills which infants use in a variety of other tasks. Simon is not alone on this issue; various evidence to support this theory has already been discussed. For example, studies have shown that infants can discriminate number across different modalities (Wood & Spelke, 2005; Starkey, Spelke, & Gelman, 1983; and Wynn, Bloom, & Chiang, 2002). While far from conclusive, these studies do suggest that the ability to comprehend the numerical properties of stimuli is general in that it is not exclusively tied to visual objects and can be matched across modalities. More convincingly, support for the object-files system proposes that this system could have evolved from basic visual abilities and is now used to facilitate visual perception, individuation, number discrimination, and working or short-term memory (Feigenson, Carey, & Hauser, 2002 and Trick & Pylyshyn, 1994).

Simon (1997) also asserts that all of the number tasks published up to the point of his publication can be completed successfully with a same/different discrimination. He states that even in Wynn's (1992) addition and subtraction study, infants can maintain a representation of the number of items on the screen and simply discriminate between what is stored in memory and what is displayed in the test trials. This does not require that an infant can perform mathematical transformations on the stimuli. He also states that evidence in support of Wynn's theory would consist of showing that infants can understand ordinal relations between numbers. We now have data to support infants' processing of ordinal relations (Brannon, 2002 and Suanda, Tompson, & Brannon, *in press*); however these data do not support Wynn's nativist approach. These findings indicate that infants cannot process ordinal relationships between numbers until 11 months of age. If numerical representation is an innate process as Wynn suggests, and is present by 4 or 5 months of age, then infants younger than 11 months should demonstrate this ability.

The constructivist approach applied to number perception

In contrast to Wynn's (1992; 1995) nativist approach, the constructivist approach to development can account for several of these number discrimination findings (Simon 1997; 1998). Cohen's constructivist model (Cohen, Chaput, & Cashon, 2002 and Cohen & Cashon, 2006) is very similar to Simon's non-numerical account; however Cohen's model adds a hierarchical component that Simon's model lacks. According to Cohen's model, infants have an innate system for processing low-level perceptual information such as shape and color. They also have the ability to process the relations between these features. This theory is constructivist in that infants can put these lower-level attributes together to form higher-level units which can then become the building blocks for even more complex relationships. Thus, infants' abilities build upon themselves in a hierarchical manner. However, one key aspect of this model that also differs from Simon's model is that infants still have access to those lower-level units and may revert back to processing information at a lower level should the system get overloaded. A good example of this comes from the work that Cohen and Cashon (2004) have done with infant face processing. They showed that at 3 months of age, infants process faces featurally for both inverted and upright faces. By 4 months of age, infants shift to processing adults' faces holistically for both upright and inverted faces. And by 7 months, infants process faces as adults do (*i.e.,* holistically for upright faces and featurally for inverted faces). The interesting developmental finding is that at 6 months of age, infants revert back to processing faces featurally for both upright and inverted faces. This seems at first glance to be a step backward because 4-month-olds can process faces holistically. The constructivist model can explain this because it has been suggested that at around 6 months infants spend more time sitting up and may begin to pay more attention to upright faces. As their information-processing system gets overloaded and they try to put this information together, they must revert back to processing faces featurally and then begin to form new relationships between the different features, particularly with upright faces, so that by 7 months, they are back to processing upright faces in a more adult-like holistic manner (Cashon & Cohen, 2004).

This constructivist approach also can be applied to number perception and may begin to explain the pattern of results that is emerging. For example, the findings on infants' processing of ordinal relations seem to fit nicely with this theory. The ability to understand ordinal relations is a constructive process such that infants must first be able to discriminate the numerosities (*i.e.,* realize that two is different from four which is different from eight). The next step is the ability to tie those numerosities together and process the relations among them. According to the constructivist approach, there should be a delay between when infants can discriminate those numerosities and when they can process the ordinality; and indeed such a delay is demonstrated. Recall that infants' discrimination of large numbers follows Weber's Law such that 6-month-old infants can discriminate numbers if there is a 1:2 ratio between the numbers (Wood & Spelke, 2005). But, it is not until 11 months of age that infants can notice a change in the ordinality of displays of items (Brannon, 2002). Several interesting predictions can be made regarding infants' behavior in these tasks across ages; yet the research has not been done to support these predictions. For example, we know that as infants get older, their ability to discriminate smaller ratios improves (Wood & Spelke, 2005 and Xu & Spelke, 2000). By 9 months of age, infants can discriminate a 2:3 ratio between quantities. According to the constructivist theory, another delay should exist between when infants can discriminate smaller ratios and when they can process ordinality with these smaller ratios. Therefore, even though 11-month-olds can discriminate ordinality with a 1:2 ratio, they presumably should not be able to process ordinality for a 2:3 ratio (*i.e.,* overloading the system), but later in development (perhaps around 14-15 months) they should be able to process the ordinality with these smaller ratios. Thus, they are building upon their experience and previous knowledge to perform increasingly complex tasks. This developmental finding would support Cohen's constructivist approach (Cohen, Chaput, & Cashon, 2002 and Cohen & Cashon, 2006).

It is possible that infants' discrimination of small numbers may also follow this hierarchical pattern, although the data thus far does not allow a firm conclusion to be made. It is possible that young infants do not yet have the numerical representations to make these discriminations based solely on numerical quantity. However, with the help of these salient perceptual features that covary with number, they are able to make successful discriminations between two and three items. Again, the data are mixed on whether or not infants are relying on these confounded factors to facilitate discrimination (see Tables 1 and 2), but the current study was designed to address this issue. As infants gain more experience and begin to put together the relationships between area and size and number, they should be able to represent number independently of area although they may still be at an intermediate stage where "number" does not contain numerical properties. For example, infants may be able to notice that an image of two cars is different from an image of three cars without knowing anything about "twoness" or "threeness". This interpretation would fit with an object-files approach or Simon's (1997) non-numerical theory because the infant can individuate and store two items and three items and make a simple same/different comparison to realize that the two images are different, but again have no concept of the numerical properties of the images. Finally, infants should be able to abstract out the number of items in each image. Thus, infants' discrimination of small numbers may follow an information-processing model of infant cognition, and the current study was designed to address this possibility.

PURPOSE AND DESIGN OF THE CURRENT STUDY

The study of infant number discrimination is a somewhat "messy" field. While research on this topic has been conducted for the past 40 years, many issues have yet to be addressed. Certainly progress is being made to find a cohesive description of the development that takes place in the first two years of life, yet more can be done. It seems clear that a distinction exists between processing small and large numbers. And while there is strong evidence to suggest that two distinct systems are responsible, no consensus has been reached on this topic. There are still some who assert that an analog magnitude model can explain performance on all number tasks (Cordes, Gelman, Gallistel, & Whalen, 2001). Another issue that has yet to be resolved is the role that extraneous variables, such as area, have in these tasks. Finally, the debate over what type of number representation infants possess and when and how that develops are all issues that have no clear answer. These final topics are also ones that are difficult to address empirically and will probably be debated for years to come. In addition to these issues, another concern is the lack of unity in the literature. Several reasons exist to explain the lack of cohesion in the findings to date. One reason is that there is huge variation in the types of studies being conducted. The stimuli being used in these studies vary from simple arrays of dots (Starkey & Cooper, 1980) to complex groupings of dots (Wynn, Bloom, & Chiang, 2000) to puppet jumps (Wynn, 1996). It is well known that the complexity of the stimuli can greatly influence infants' habituation and looking behavior in a task (Berlyne, 1958 and Cohen, 1976). Additionally, different researchers vary in how tightly they control extraneous variables such as area, brightness, and contour length. As with any topic in development, multiple ages are being studied from newborns (Antell & Keating, 1983) to 14.5-month-olds (Feigenson & Carey, 2003). Obviously, multiple ages need to be studied in order to understand the developmental changes or processes that may be occurring. However, the problem with the number discrimination literature is that there is little consistency between the studies being done at various ages. While some researchers have used the same procedure and stimuli at multiple ages (see Feigenson, Carey, & Hauser, 2002), most studies have only tested a single age group. The goal of any developmental study is to address differences across ages in order to determine how certain processes are developing over time. A second goal is not only to note the differences across ages, but also to understand the mechanisms of change. One way to accomplish this is to test infants (or children) using the same procedure at different ages. In this manner, direct comparisons can be made across ages that make it easier to make claims regarding what develops over time. However, one limitation of this approach is that certain methods may not be appropriate for different ages. For example, habituation is generally not possible with infants over the age of 18 months. Infants at this age are now mobile and do not want to sit still making it difficult to get them through a habituation study. Additionally, they also have better motor and language skills which means it is possible to use other methods, such as selective touching, pointing, or simple verbal tasks to assess their cognitive and perceptual abilities (Cohen & Cashon, 2006; Markman, Wasow, & Hansen, 2003; and Mareschal & Tan, 2007).

In the infant number discrimination literature, the majority of the studies have used habituation, which makes comparisons easier, but one problem is that the specifics of the methods, stimuli, and even assumptions about which stimuli should be preferred, vary widely across studies. The second problem, as noted above, is that most of the studies have not successfully shown development across ages. Therefore, the current study addressed some of these limitations in the literature. First, and foremost, the current study was a developmental study in that it specifically studied three different age groups (9-, 11-, and 13-month-olds) using the same procedure and stimuli. This allows direct comparisons to be made across ages. While infants at all ages should be able to make these simple discriminations, the patterns of results across each age should address possible mechanisms of change. For example, infants at the youngest age (9-months) may not discriminate the stimuli based upon number, but rather using continuous extent (area in this study). However, it was predicted that by 13 months of age, infants would be able to discriminate the stimuli based upon differences in numerical quantity. Again, this developmental approach allows predictions such as these to be tested.

A second issue that the current study addressed is the function that continuous extent has in number processing. As suggested earlier, younger infants may not have the representation to discriminate based upon discrete number, but they may be able to use continuous quantities, like area, contour length or density. This is related to the concern of how tightly controlled researchers make their studies. Generally, I favor tight control over studies; however, when it comes to number discrimination, it is almost impossible to control for every confounding variable that could possibly aid in infants' discrimination. Furthermore, if you do control for all of these variables, the design and stimuli become so complex that it no longer appears to be a number discrimination task, but rather a very complicated categorization task in which an infant must somehow abstract that number is changing amongst all of these other variables. Therefore, the current study only took into account one continuous variable (area). Area is very salient feature (Slater & Johnson, 1998) and infants can easily detect a 1:2 change in area (Brannon, Lutz, & Cordes, 2006 and Linn, Hans, & Kagan, 1978), thus area is a good choice for studying continuous extent in infants. Furthermore, most of the other studies on continuous extent have manipulated area (Clearfield & Mix, 2001; Feigenson, Carey, & Spelke, 2003; and Cordes & Brannon, 2008). This provides some literature to which we can compare the findings of the current study. By manipulating area in the current study, this should allow specific conclusions to be made regarding how area may be influencing infants' behavior in number discrimination tasks. If area is important to how infants process these stimuli and changes between numbers, then future studies can systematically address how other continuous variables may also be influencing infants' behavior in these tasks.

The current study tested 9-, 11- and 13-month-old infants in a design adapted from Casasola and Cohen (2002). As shown in Figure 2, infants were habituated to four examples of either two objects or three objects (see Figure 3 for examples of the stimuli). The combined area of the objects was manipulated such that two of the exemplars had a small combined area and the other two had a larger combined area. The areas differed by a ratio of 1:2, which should be sufficient for infants of all ages to discriminate. Infants were then shown four test trials. One trial was a familiar number of familiar objects (*e.g.,* two bugs). The second was a novel number of familiar objects (*e.g.,* three bugs). The third trial was a familiar number of novel objects (*e.g.,* two flowers) and the final test trial was a novel number of novel objects (*e.g.,* three flowers). It was predicted that infants of different ages would show qualitatively different looking patterns across all four test trials depending on how they are processing number. Figure 4 details several possible patterns of looking behavior during the test trials. The youngest infants (9-month-olds) should respond in one of two ways. If they are simply responding to the change in area, they should not dishabituate to any of the test trials. They have seen both the small and large area throughout habituation, so the area in all four test trials should be familiar and their looking time should be low. Alternatively, it could be possible that these infants are not responding to area or number and will simply dishabituate to a change in the object. In this case, they should dishabituate to only the two trials in which the novel object is present. The 11-month-olds will hopefully begin to abstract out information beyond changes in area, but if they are also responding based on overall amount, their looking times will remain down to all four test trials. However, I predict that these infants will be able to notice a change in number in addition to a change in object (see "Number w/ Fam. Obj." in Figure 4). They should be able to detect a change in number and, similar to Casasola and Cohen (2002), they should be able to detect a change in number within a familiar context (*i.e*. familiar objects). Finally, the 13-month-olds should be able to abstract out numerosity and dishabituate to the two test trials in which the number of objects changes from habituation (see "Number w/Novel Obj." in Figure 4). These predictions assume that a change in featural information (*i.e.,* the objects) will be noticed prior to a change in the number of objects. While the data may not come out as cleanly as predicted, this study should still be able to provide valuable evidence regarding the processes underlying infant number perception and its development.

Table 1: Review of the studies on infants' discrimination of small numbers
(*NB = newborn)

Quantities	Age (mon)	Discriminate	Stimuli	Variables controlled	Study	Notes
1 v. 2	7	yes	Lego animals	size	Feigenson, Carey, & Spelke, 2002	
	7	no	Lego animals	surface area	Feigenson, Carey, & Spelke, 2002	infants dishabituate to novel area; not number and not equal area; not when area varies during habituation
	10	yes	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"; discriminate only when area was not controlled
	10	no	graham crackers	surface area	Feigenson, Carey, & Hauser, 2002	studied choice of "more"; discriminate only when area was not controlled
	12	yes	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"; discriminate only when area was not controlled
	12	no	graham crackers	surface area	Feigenson, Carey, & Hauser, 2002	studied choice of "more"; discriminate only when area was not controlled
	14.5	yes	balls		Feigenson & Carey, 2003	
2 v. 3	*NB	yes	dots	length & density	Antell & Keating, 1983	
	5.5	yes	dots	length, density, & dot position	Starkey & Cooper, 1980	
	6	yes	jumps	varied tempo & duration	Wynn, 1996	
	6	no	configurations of squares	contour length & area	Clearfield & Mix, 2001	infants dishabituate to either area or contour length, but not number
	6	no	squares	contour length	Clearfield & Mix, 2001	infants dishabituate to novel contour length, not number
	7	yes	dots	varied position	Mack, 2006	
	7	no	squares	contour length	Clearfield & Mix, 1999	infants dishabituate to novel contour length, not number
	7	yes	household items	position, objects, & auditory duration	Starkey, Spelke, & Gelman, 1983, 1990	heterogeneous items, matched with auditory stimuli
	7	no	Lego animals	area (only during habituation)	Feigenson, Carey, & Spelke, 2002	
	10	yes	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"
	11	yes	household items	size & position	Strauss & Curtis, 1981	both heterogeneous and homogenous conditions
	12	yes	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"
	14.5	yes	balls		Feigenson & Carey, 2003	
2 v. 4	5	yes	groups of dots		Wynn, Bloom, & Chiang, 2002	clusters of constantly moving stimuli
	6	no	jumps	sequence duration, jump duration, jump rate, jump interval, & extent of motion	Wood & Spelke, 2005	
	6	no	3D discs	area & contour length	Xu, 2003	discs were black and white
	7	yes	dots	varied position	Mack, 2006	
	10	no	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"
	12	no	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"
	14.5	no	balls		Feigenson & Carey, 2003	
3 v. 4	7	yes	dots	varied position	Mack, 2006	
	10	no	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"
	11	yes/no	household items	size & position	Strauss & Curtis, 1981	gender/condition interaction; girls discriminate in homogenous cond., boys discriminate in heterogeneous cond.
	12	no	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"

Table 2: Review of the studies on infants' discrimination of large numbers (*NB = newborn)

Quantities	Age (mon)	Discriminate	Stimuli	Variables controlled	Study	Notes
3 v. 6	7	yes	dots	varied position	Mack, 2006	
	10	no	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"
	12	no	graham crackers		Feigenson, Carey, & Hauser, 2002	studied choice of "more"
4 v. 5	4	yes	dots	area, density, contour, contour density, & configuration	Trieber & Wilcox, 1984	
	7	no	dots	varied position	Mack, 2006	
	11	no	household items	size & position	Strauss & Curtis, 1981	both heterogeneous and homogenous conditions
4 v. 6	*NB	no	dots	length & density	Antell & Keating, 1983	
	5.5	no	dots	length, density, & dot position	Starkey & Cooper, 1980	
	6	no	jumps	sequence duration, jump duration, jump rate, jump interval, & extent of motion	Wood & Spelke, 2005	
	7	no	dots	varied position	Mack, 2006	
	9	yes	jumps	sequence duration, jump duration, jump rate, jump interval, & extent of motion	Wood & Spelke, 2005	
4 v. 8	6	yes	jumps	sequence duration, jump duration, jump rate, jump interval, & extent of motion	Wood & Spelke, 2005	
	6	yes	3D discs	area & contour length	Xu, 2003	discs were black and white
8 v. 16	6	yes	dots	size, position, brightness, contour length, density, & display size	Xu & Spelke, 2000	
8 v. 12	6	no	dots	size, position, brightness, contour length, density, & display size	Xu & Spelke, 2000	
	10	yes	dots	area, density, brightness, element size, & display size	Xu & Arriaga, 2007	
8 v. 10	10	no	Dots	area, density, brightness, element size, & display size	Xu & Arriaga, 2007	

Figure 1: Comparison of the object-files and analog magnitude models

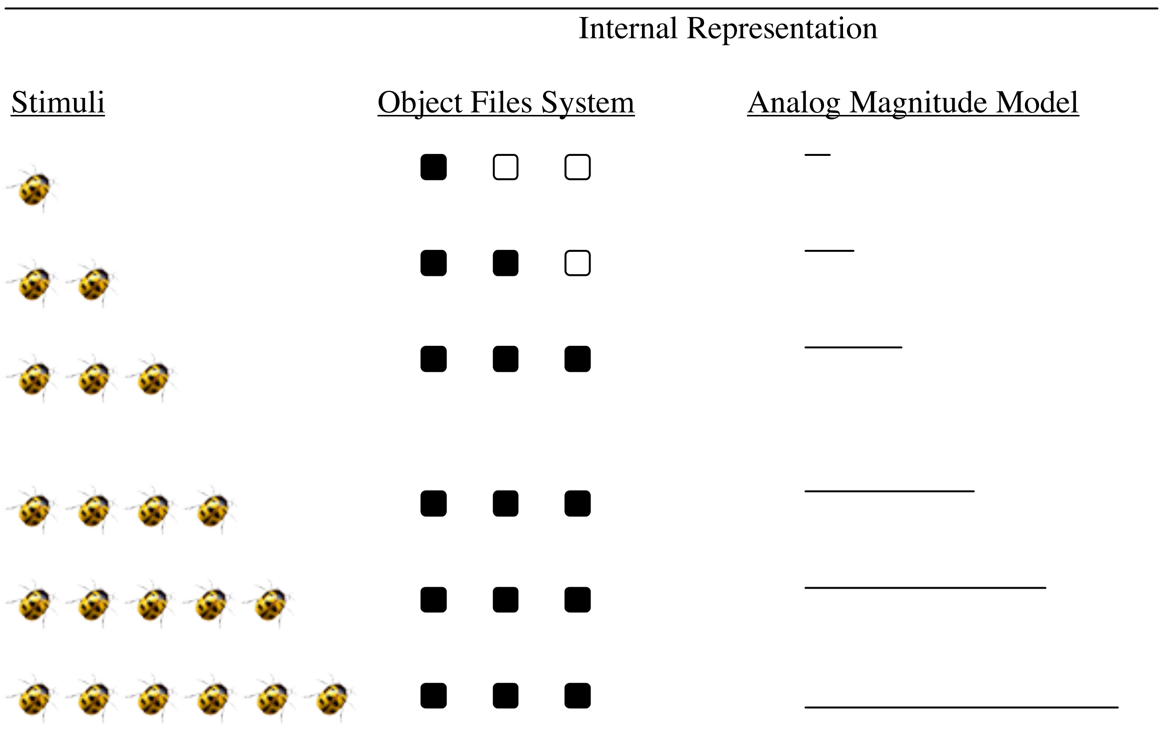


Figure 2: Overview of the design of the study

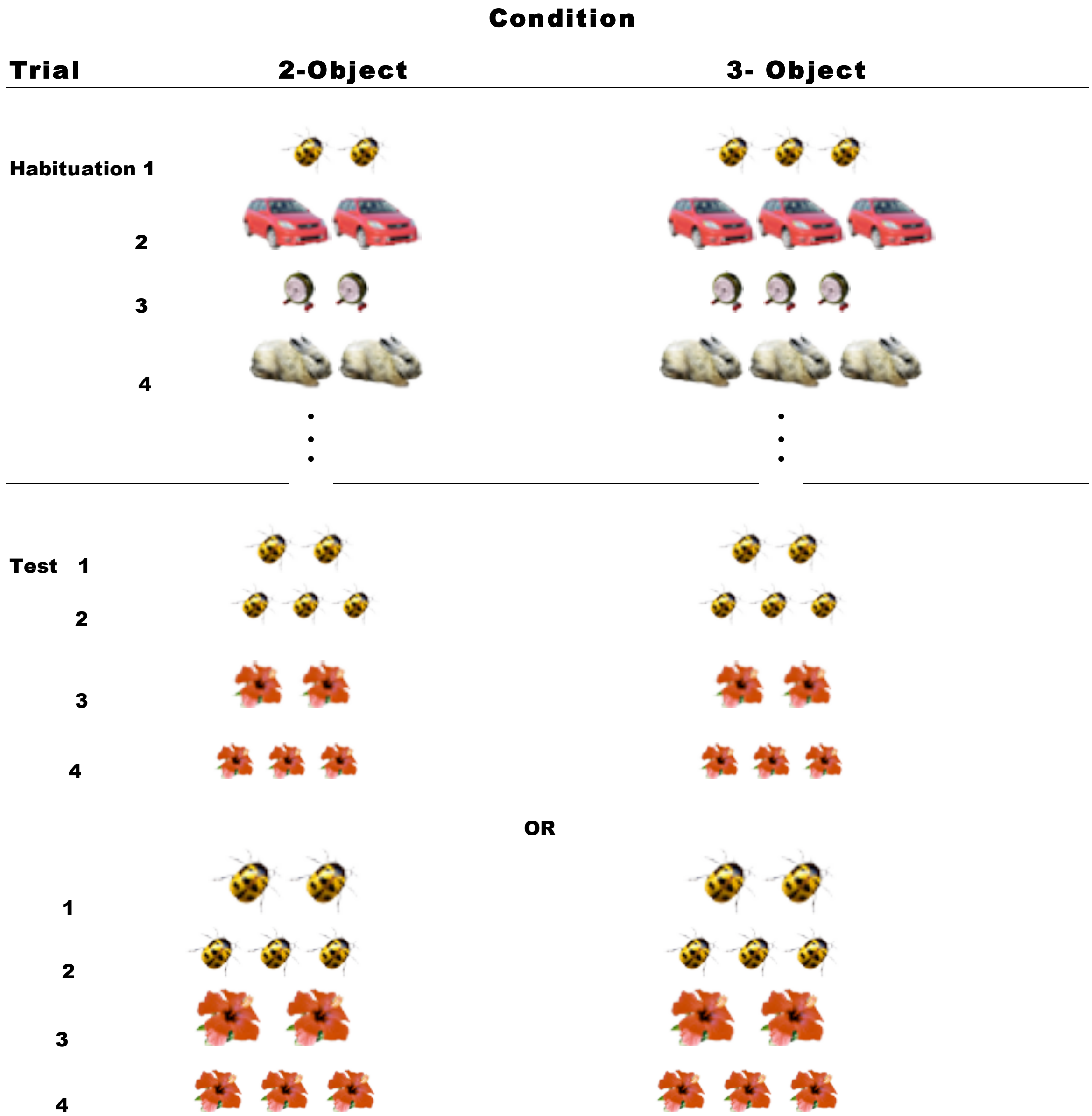
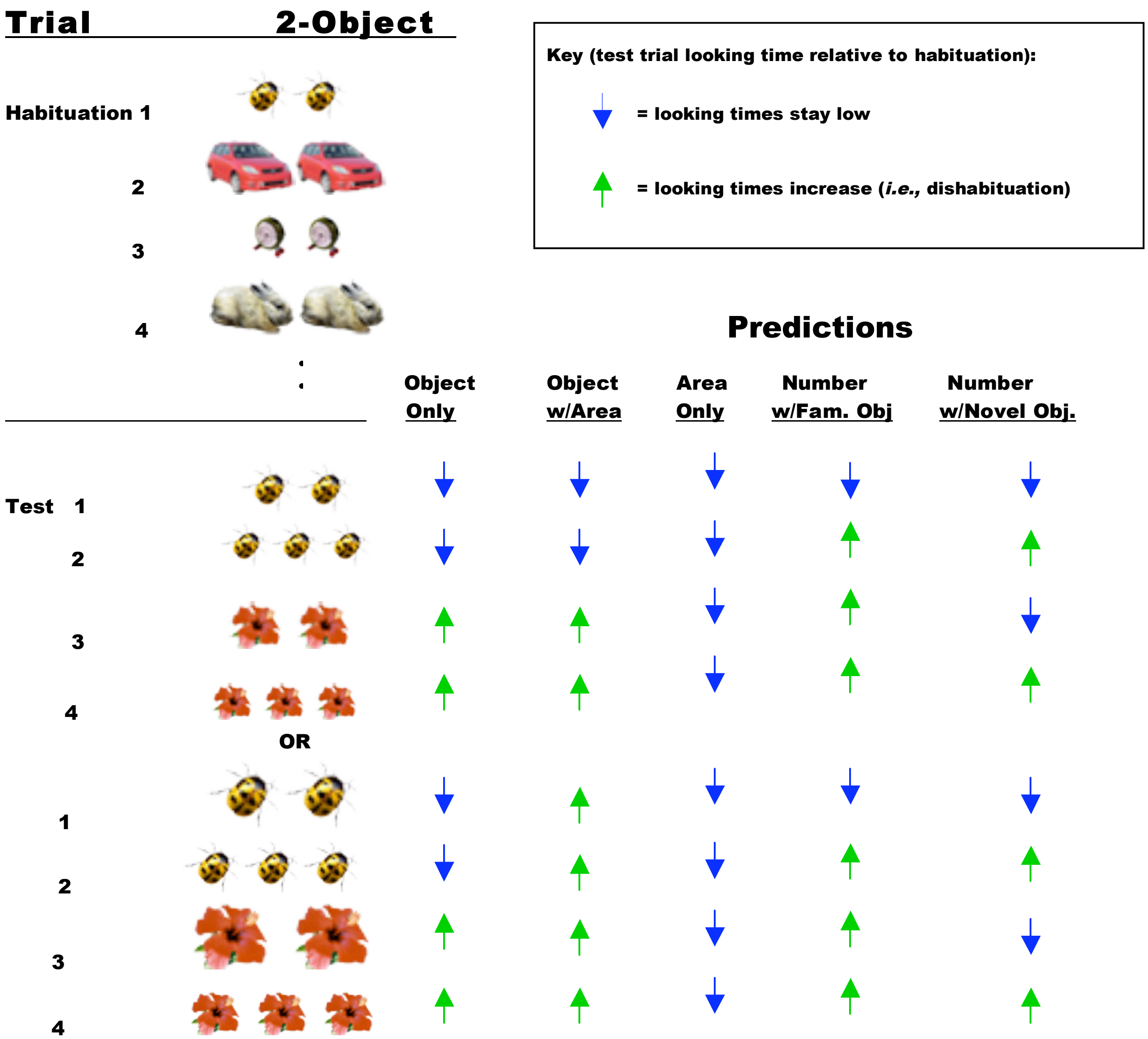


Figure 3: The stimuli for the study

Figure 4: Infants' predicted looking behavior during the test trials (relative to the habituation phase)



Chapter 2: Methods

Participants

Participants were 81 9-, 11-, and 13-month-old infants. They were all full-term and had no hearing or vision problems. There were 27 9-month-olds (*M* = 9.01 months, range: 8.57 – 9.46 months; 11 males, 16 females). An additional 22 9-month-olds participated, but were excluded for the following reasons: they did not habituate (*n* = 16) they were premature (*n* = 4), they became fussy (*n* = 1), or other (*n* = 1). There were 25 11-month-olds (*M* = 11.03 months, range: 10.57-11.49 months; 13 males, 12 females). An additional 19 11-month-olds participated, but were excluded for the following reasons: they did not habituate (*n* = 15), they were premature (*n* = 2), or they became fussy (*n* = 2). There were 29 13-month-olds (*M* = 13.22 months, range: 12.74-13.56 months; 12 males, 17 females). An additional 19 13-month-olds participated, but were excluded for the following reasons: they did not habituate (*n* = 14), they were premature (*n* = 1), they became fussy (*n* = 3), or other (*n* = 1). The majority of infants were Caucasian (77.3%), but 12% were Hispanic, 4% were Asian and the remaining 6.7% were classified as other. Most of the mothers and fathers had at least a four-year college degree (81.3% and 84.7%, respectively). Infants' and parents' names were obtained through birth records from the Texas 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.

STIMULI

The stimuli were presented on a 19" computer monitor. The attention-getter consisted of an expanding green circle on a black background accompanied by a ringing bell sound. The stimuli consisted of two-dimensional photographs of colored everyday objects as shown in Figure 3. The objects used for each infant were randomly determined. To create the sets of two or three items, the objects were placed next to each other in a linear fashion to create a row of either two or three objects (see Figure 2). Two copies of each set of objects (two or three items each) were created. One copy had a combined area of five square inches and the other had a combined area of 10 square inches.

APPARATUS

During the testing period, infants were seated in their parent's lap in a dimly lit room adjacent to the control room. The infants were seated directly in front of the monitor approximately 48" away. A closed circuit television camera was mounted below the monitor which allowed the experimenter seated in the control room to view the infants on a television monitor. All sessions were recorded on DVD. Each parent was instructed not to interact with their infant and to keep their eyes closed during the experiment to eliminate any subtle cues or interaction between infant and parent. If the parent did interfere with the experimental session, then those data were eliminated from the analyses ($n = 2$).

The experimenter presented the stimuli on a PowerMac G4 using the habituation software, HabitX (Cohen, Atkinson, & Chaput, 2000). Infants' looking behavior was recorded by keypress.

PROCEDURE

Infants and their parents came to the laboratory after being contacted and scheduled. Experimenters explained the study and procedure and answered any questions the parent(s) had. Informed consent was obtained for each participant. Infants and their parents were seated in the testing room as described above.

Each infant was habituated to the stimuli in one of two conditions (see Figure 2). In the 2-Object Condition, infants were habituated to four sets of two objects each. In the 3-Object Condition, infants were habituated to four sets of three objects. Again, the objects shown to each infant were randomly determined. The infants were shown a maximum of 20 habituation trials or enough trials for their looking time to reach the 50% criterion (determined by a sliding window of four trials). The trials were shown in blocks of four such that infants saw one example of each set of objects in every block. The order of the trials within each block was determined using a Latin square. The area varied across each block such that two of the objects were shown with the smaller area (5 square inches) and two were shown with the larger area (10 square inches). A single trial lasted for 30 seconds or until the infant looked away for one second. The infant was required to look for at least one second in order for a look to be counted as a trial; otherwise the same stimulus was repeated in the next trial.

After the habituation phase, each infant viewed four test trials (see Figure 2). One test trial (always the first trial) was a familiar object of the familiar number (either two or three depending on the habituation condition). The order of the last three test trials was determined using a Latin square. These three test trials included the novel number of the familiar object, the familiar number of a novel object, and the novel number of a novel object. With regards 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 (5 square inches) regardless of the number of objects. The other half of the infants saw objects of the larger area (10 square inches) throughout the test phase. This assures that the 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 playing on the monitor. Once the infants' attention was on the monitor, the experimenter began the first trial. The attention-getter continued to play in between each trial. A second observer watched and coded most infants' DVD for reliability purposes (9-months, $n = 27$; 11-months, $n = 22$; and 13-months, $n = 27$). The inter-rater reliabilities were as follows: $r = .98$ (9-months), $r = .96$ (11-months), and $r = .98$ (13-months).

Chapter 3: Results

OVERALL ANALYSES

Despite meeting the habituation criterion of a 50% drop in looking time, several infants looked much longer at the first test trial (always the familiar number/familiar object trial) than most infants which indicates that these infants probably did not actually habituate. Any infant whose looking time at the first test trial was more than 15.45 seconds which corresponds to two standard deviations above the mean for all ages (M = 5.39 seconds, SD = 5.03 seconds) was excluded from the data analyses (n = 4). The infants who were excluded had mean looking times of 29.9, 21.5, 21.1, and 19 seconds during the first test trial.

Figure 5 shows the mean looking time at each test trial for all three ages. It appears that there are developmental changes in how infants are responding to the stimuli. To test this observation, a mixed-design ANOVA was run with test condition as the within-subject factor (familiar number/familiar object, familiar number/novel object, novel number/familiar object, and novel number/novel object). The between-subject factors were age (9-, 11- and 13-months), gender, habituation condition (2 objects or 3 objects), and test area (small or big objects). Mauchly's test indicated that the assumption of sphericity was violated, χ^2 (5) = 14.70, p = .01; therefore, the degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = 1.00). There was a main effect of test condition, $F(3, 159) = 2.99$, p = .033, η^2_p = .053, indicating that infants responded differently throughout the test trials. Infants looked at the familiar number/familiar object test trial for 4.48 seconds (SD = 2.97) and at the familiar number/novel object test trial for 6.01 seconds (*SD* = 5.04). They spent 4.95 seconds (*SD* = 3.70) looking at the novel number/familiar object test trial and spent 5.25 seconds (*SD* = 3.08) looking at the novel number/novel object test trial. Additionally, there was a significant interaction between test condition and age, $F(6, 159) = 2.81$, $p = .013$, $\eta^2_p = .096$, demonstrating that developmental changes are occurring between 9- and 13-months of age (see Figure 5). The effects at each age will be discussed independently in the following sections (see Table 3 for a breakdown of the means and standard deviations at each age by trial type). Finally, there was a significant interaction between test trial and gender, $F(3, 159) = 2.73$, $p = .046$, $\eta^2_p = .049$. Males looked longer at the familiar number trials than females and within the familiar number trials, males looked longer at the novel object (see Figure 6). In contrast, females showed a preference for the novel objects over the familiar objects. All other within-subject effects were not significant ($p > .32$).

As for the between-subject effects, there was a main effect of age, $F(2, 53) = 3.40$, $p = .041$, $\eta^2_p = .114$. Looking times at the test trials increased with age. Nine-month-olds, overall, looked at the test trials for 4.40 seconds (*SD* = 2.05), 11-month-olds looked for 4.93 seconds (*SD* = 1.84), and 13-month-olds looked for 6.10 seconds (*SD* = 2.72) at the test trials. Unexpectedly, a marginally significant main effect of test area immerged, $F(1,53) = 3.89$, $p = .054$, $\eta^2_p = .068$. Infants preferred the small objects (*M* = 5.80, *SD* = 2.82) to the big objects (*M* = 4.53, *SD* = 1.55). All other tests were not significant ($p < .07$).

SEPARATE ANALYSES BY AGE

Nine-month data

Figure 7 displays the mean looking time towards each test trial for the 9-month-olds. To investigate whether 9-month-old infants discriminated either the number of objects or the objects themselves, a mixed-design ANOVA was calculated with the data from the 9-month-olds. Test trial condition (familiar number/familiar object, familiar number/novel object, novel number/familiar object, or novel number/novel object) was the within-subject factor and gender, habituation condition (2 objects or 3 objects) and test area (small or big objects) were the between-subject factors. None of the effects were significant ($p > .08$). However, a paired *t* test comparing the familiar number trials and the novel number trials revealed that 9-month-olds did discriminate the number of objects, $t(26) = -2.11$, $p = .044$. Nine-month-old infants were able to discriminate two objects from three objects regardless of the items themselves (see Table 3 for a break down of the means and standard deviations). Nine-month-old infants, however, showed no evidence of discriminating between the familiar and novel objects, $t(26) =. 07$, $p = .947$ (see Table 3).

Eleven-month data

As opposed to the 9-month-olds, 11-month-olds appeared to discriminate the test trials based on object type (familiar versus novel) rather than number (see Figure 8 and Table 3 for the means and standard deviations). The 11-month-olds did not discriminate the number of objects, $t(21) = -.21$, $p = .839$, but the difference in looking time between the familiar and novel objects was marginally significant, $t(21) = -2.06$, $p = .052$.

Eleven-month-olds looked longer at the novel objects (*M* = 5.59 seconds, *SD* = 2.65) than at the familiar objects (*M* = 4.28 seconds, *SD* = 2.04). This preference for the novel object was especially noticeable during the test trials with the novel number of objects, $t(21) = -2.30$, $p = .032$.

A mixed-design ANOVA was run with test trials as the within-subject factor and gender, habituation condition, and test area as the between-subject factors. There was a significant interaction between the test trials and habituation condition, $F(3, 42) = 2.86$, $p = .048$, $\eta^2_p = .170$ (see Table 4). Infants that were habituated to two objects looked longer at the familiar number/novel object test trial while those infants habituated to three objects preferred the novel number/novel object test trial. All other tests of within- and between-subject effects were not significant ($p > .07$).

Thirteen-month data

At the time of data collection, our lab was conducting a second study in addition to the current study with 13-month-olds investigating music perception. Infants in this study were habituated to short clips of music. Because of the difference in the stimuli (auditory versus visual), infants often participated in both studies at the time of testing. Nine of the 28 13-month-olds included in these analyses were tested in the music study prior to participating in the current study. Because of concerns with fatigue and possible carryover from participating in a different habituation study first, a mixed-design ANOVA was conducted to test for any effect of participation in the music study. Again, test condition (familiar number/familiar object, familiar number/novel object, novel number/familiar object, and novel number/novel object) was the within-subject factor and gender, habituation condition, test area, and music (participated in the music study first or not) were the between-subject factors. There was no significant effect of participating in the music study first, $F(1,15) = .11$, $p = .74$. Additionally, Independent samples *t* tests were run on all four test trials comparing the looking times of infants who ran in the music study first and those that did not and all tests were not significant ($p > .21$). Therefore, all subsequent analyses include the data from all infants.

Comparable to the analyses with the other age groups, the data for the 13-month-old infants were analyzed with a mixed-design ANOVA (test condition, within-subject; gender, habituation condition, and test area, between-subject). Mauchly's test indicated that the assumption of sphericity was violated, χ^2 (5) = 13.95, $p = .02$; therefore, the degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .99$). There was a significant effect of test condition, $F(2.97, 59.34) = 4.15$, $p = .010$, $\eta^2_p = .172$ (see Figure 5). Similar to the analysis with all age groups, 13-month-olds preferred the small test stimuli ($M = 7.43$ seconds, $SD = 3.06$) to the big objects ($M = 4.57$ seconds, $SD = 1.01$), $F(1,20) = 8.70$, $p = .008$. All other tests were not significant ($p > .09$).

As shown in Figure 9, 13-month-olds exhibited an interesting pattern of looking behavior during the test trials. They discriminated between the familiar and novel objects when the number of objects was familiar, $t(27) = -2.43$, $p = .022$, but they failed to discriminate between the objects when the number of objects was novel, $t(27) = .45$, $p = .658$. When comparing the overall differences between looking at familiar number and novel number trials, the results were marginally significant, $t(27) = 2.01$, $p = .055$.

Similarly, the differences between overall looking times towards the familiar and novel objects did not reach significance, $t(27) = -1.75$, $p = .091$.

Table 3: Mean looking time (sec) for 9-, 11-and 13-month-olds by test trial type

Test Trial Type	*Mean*	*Standard Deviation*	*n*
		9-month-olds	
Familiar Number	3.94	1.89	27
Novel Number	4.86	2.73	27
Familiar Object	4.42	2.88	27
Novel Object	4.38	2.15	27
		11-month-olds	
Familiar Number	4.85	2.50	22
Novel Number	5.01	2.62	22
Familiar Object	4.28	2.04	22
Novel Object	5.59	2.65	22
		13-month-olds	
Familiar Number	6.37	3.80	24
Novel Number	5.16	2.74	24
Familiar Object	4.63	2.00	24
Novel Object	6.90	4.47	24

Table 4: Mean looking time (sec) during the test trials for 11-month-old infants by habituation condition

Test Trial Type	*Mean*	*Standard Deviation*	*n*
		2-Object Condition	
Fam. Num./Fam. Obj.	4.24	3.34	12
Fam. Num./Nov. Obj.	6.89	5.06	12
Nov. Num./Fam. Obj.	4.18	3.39	12
Nov. Num./Nov. Obj.	4.88	2.19	12
		3-Object Condition	
Fam. Num./Fam. Obj.	4.50	1.98	10
Fam. Num./Nov. Obj.	3.49	1.65	10
Nov. Num./Fam. Obj.	4.19	3.21	10
Nov. Num./Nov. Obj.	5.83	3.00	10

Figure 5: Mean looking time (sec) for each test trial by age

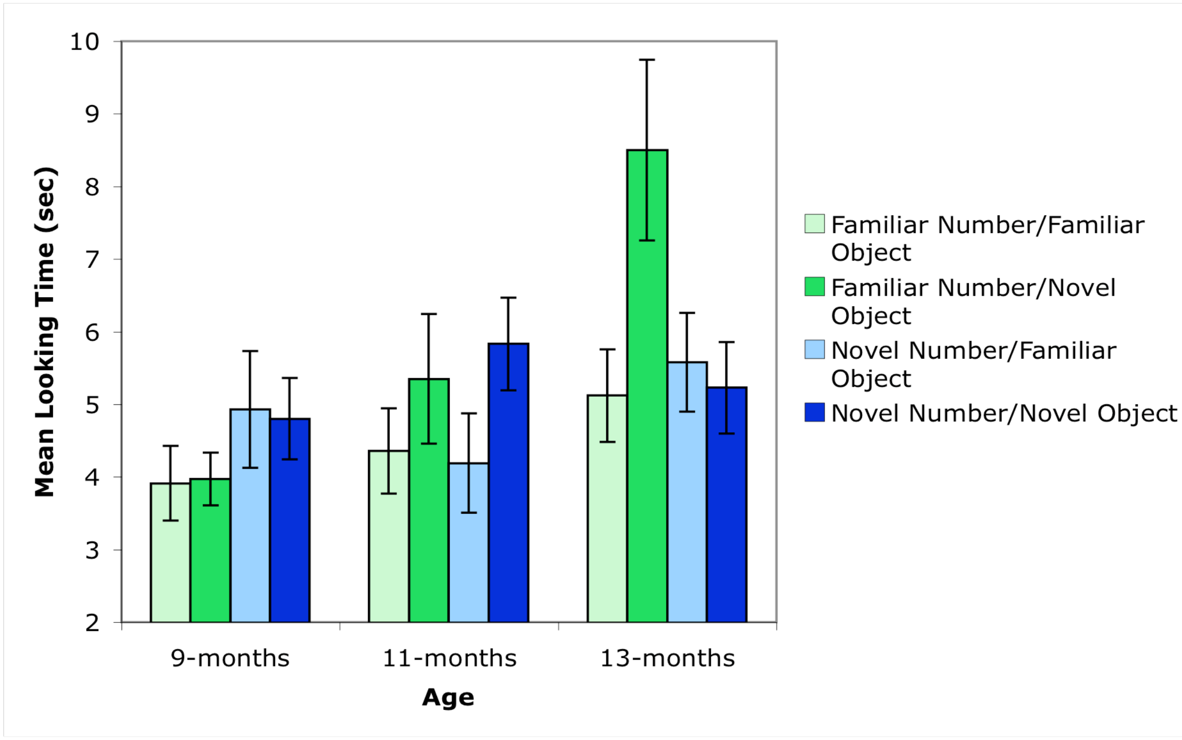


Figure 6: Mean looking time (sec) for each test trial by gender

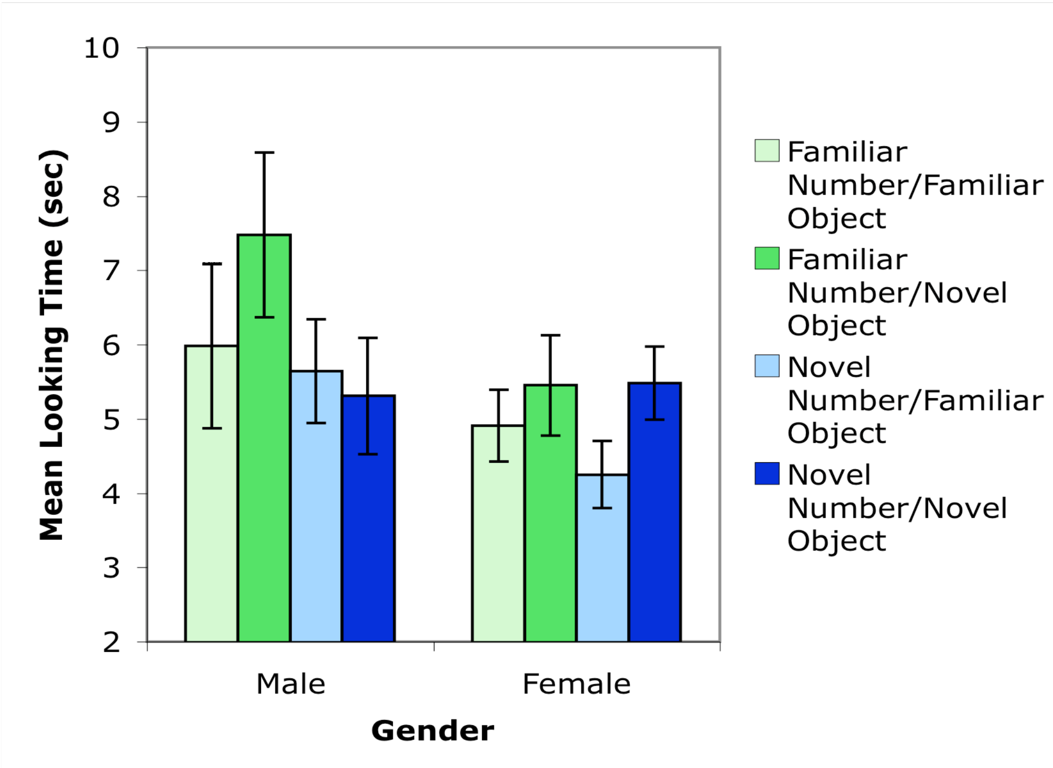


Figure 7: 9-month-olds' mean looking time (sec) during the test trials

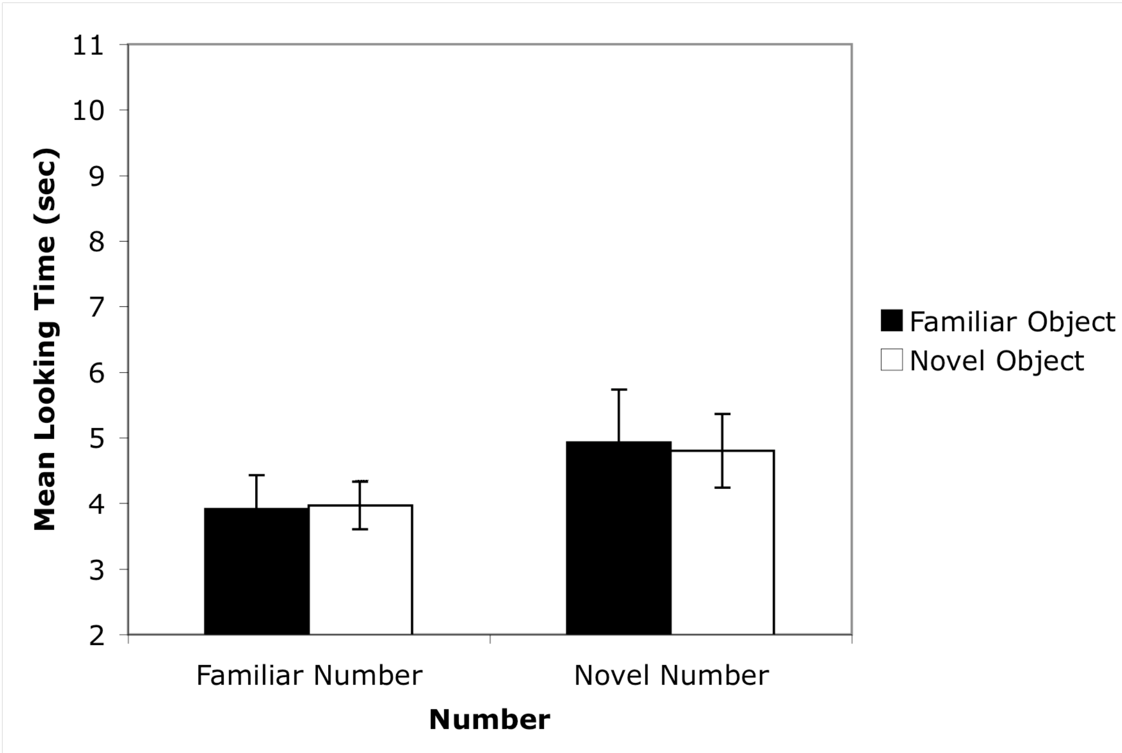
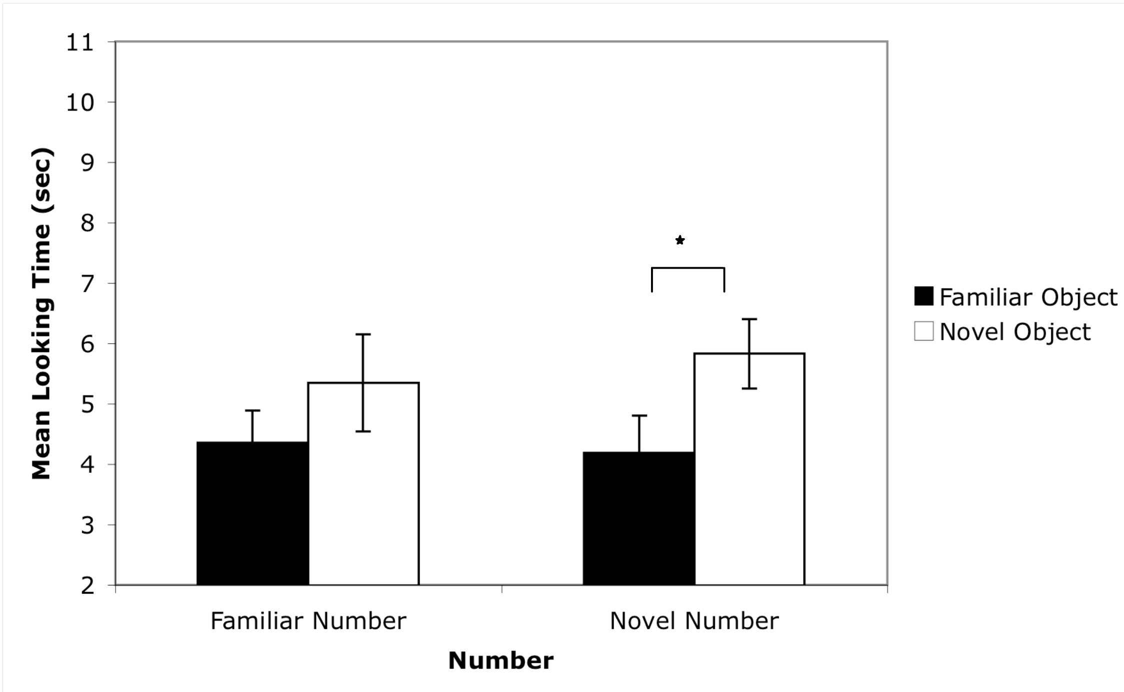
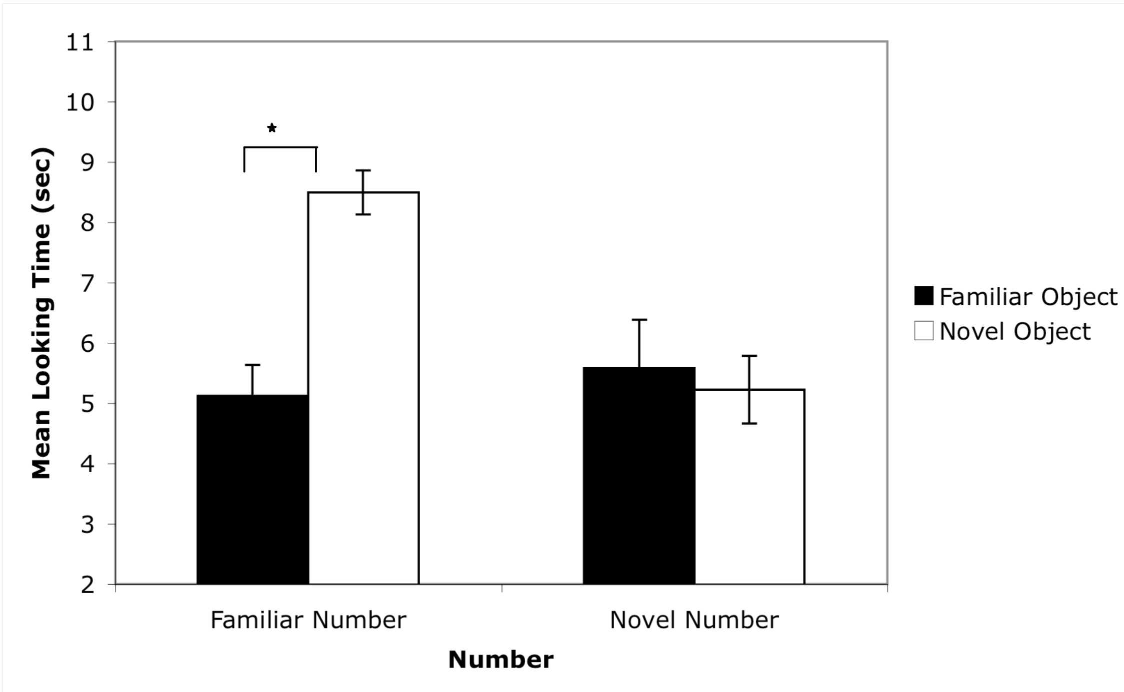


Figure 8: 11-month-olds' mean looking time (sec) during the test trials



* $p < .05$

Figure 9: 13-month-olds' mean looking time (sec) during the test trials



* $p < .05$

Chapter 4: Discussion

This study was designed to address how infants discriminate number and how this ability develops. It was predicted that the development of infants' number processing would support a constructivist model such that the youngest infants would begin by processing low-level featural information such as area or other characteristics of the objects and move towards processing number independent of these features. Interestingly, the data do support a constructivist model of development; however, not in the predicted direction. The data show that the youngest infants (9-month-olds) begin by processing the number of objects independent of the featural information and that it is not until later in development (11- and 13- months) that they begin to integrate featural information. These data are consistent with the object-files account of number perception for small numbers (see Feigenson & Carey, 2003 and Feigenson, Carey, & Hauser, 2002), but suggest that the representation of number changes over development.

Summary of the Results

Nine months

The 9-month-olds were able to abstract out the numerical information from a relatively complex categorization task. Similar to previous number studies (*e.g.*, Starkey & Cooper, 1980 and Xu & Arriaga, 2007), the displays that infants saw varied in numerous aspects despite number. For instance, infants saw objects of differing area, brightness, and density. In fact, the objects themselves changed; therefore other featural information such as color, shape, and texture differed as well. Despite all of this varying perceptual information, the 9-month-olds discriminated the test trials based upon changes in number alone; they did not respond to the change in object. This demonstrates that 9-month-old infants are able to categorize objects based upon number and suggests that numerical information is highly salient and discriminable for infants. Again, this is consistent with an object-files account which states that infants can enumerate number in a parallel process (Feigenson & Carey, 2003 and Feigenson, Carey, & Hauser, 2002). Object-files are limited in number (less than four), but provide an accurate and quick representation of the items being encoded. While this finding alone cannot address the question of whether or not infants are storing featural information along with the item stored in object-files, 9-month-olds did not appear to discriminate the objects nor did they show any effect of the object on their processing of number. This is the youngest demonstration of number categorization by infants. Strauss and Curtis (1981) conducted the only other study in which infants were habituated to a variety of differing objects, but they only tested 11-month-olds. Their study demonstrated that 11-month-olds could discriminate two from three objects, and the current study extends this finding to 9-month-olds.

Eleven months

The results from the 11-month-olds are less conclusive, but seem to suggest that at this age, infants are discriminating the stimuli based upon object type (see Figure 8). While the overall difference between infants' looking times towards the familiar and novel objects was marginally significant, the difference between infants' looking times towards the familiar and novel objects within the novel number condition was significant (see Figure 8). However, it is unclear whether the difference in the novel number condition is driving the overall preference for the novel object or whether 11-month-old infants are actually discriminating object type, and it just happened that the difference was great enough in the novel number condition to produce a significant result. One concern in interpreting these results is the smaller sample size of 11-month-olds. The sample began with 25 infants (less than the other ages), but three infants were eliminated from the final analyses due to a failure to truly habituate (recall that data from all infants looking longer than 15.45 seconds at the familiar number/familiar object test trial were discarded). Therefore, the final sample consisted of only 22 infants. Ideally, collecting data from several more 11-month-olds would allow for more conclusive interpretations regarding their behavior in this task.

At the very least, 11-month-olds appear to be using featural information to make discriminations of the objects. Yet, it is unclear how number may be playing a role in this discrimination. It is possible that 11-month-olds are trying to incorporate featural information into their representation of the number of objects, but are failing to do so. Or, they may simply be attending to featural information alone, ignoring the number of objects. Either way, the results of the current study fail to replicate the findings from Strauss and Curtis (1981). They found that 11-month-old infants could discriminate two objects from three objects in both their homogenous condition (similar to the current study) and in their heterogeneous condition (in which the objects within a set varied). Clearly featural information varied across exemplars in their study; and infants were still able to generalize the number of objects. One difference between the two studies is the age of the participants. Strauss and Curtis actually ran infants who ranged from 10- to

12- months of age. Whereas they allowed a one-month window around 11-months of age, we allow a two-week window for our participants. The greater variability in the age of the infants may account for differences in the results of the two studies. However, they varied size throughout the habituation and test whereas area was more tightly controlled in the current study. Given that area is an important cue which infants may be using to aid in number discrimination (Clearfield & Mix, 1999; 2001; and Feigenson, Carey, and Spelke, 2002), how experimenters manipulate area throughout the task can influence infants' processing of number. This could be another reason for the failure to replicate their study.

One interesting finding with the 11-month-olds is the interaction between the test trials and the habituation condition (see Table 4). Infants that were habituated to two objects looked longer at the familiar number/novel object test trial while those infants habituated to three objects preferred the novel number/novel object test trial. In both habituation conditions, infants spent more time looking at the novel object; the difference was whether the novel objects were grouped in the familiar number or novel number. This finding is generally consistent with the overall finding that 11-month-olds seem to be discriminating the objects. It is unexpected that the habituation condition would influence infants' looking behavior, as it should not bias infants' behavior during the test trials. It most likely is the result of chance because no other significant effects of habituation condition were found in any other age group. Furthermore, many studies have been conducted in which infants were habituated to either two or three objects and none of those studies report any effects of habituation condition (*e.g.*, Strauss & Curtis, 1981, Starkey & Cooper, 1980, and Clearfield & Mix, 2001). Collecting more data could confirm this possibility as well as running a replication study.

Thirteen months

In contrast to the 11-month-olds, the 13-month-olds are responding to the novel objects differentially across number trials and these results are more conclusive. Thirteen-month-old infants are able to discriminate the objects within the context of the familiar number, but not in the context of the novel number. This result is analogous to the Casasola and Cohen (2002) study in which they found that infants were able categorize simple spatial relationships with both familiar and novel objects, but for more complex spatial relationships, they were first able to categorize using familiar objects, but not novel objects. Similarly, infants appear to first be able to grasp the number of objects (9-months) and then are able to detect changes in the objects themselves (11-months). Once they can process each of these aspects of the task, they can then begin to process the relations between them (*i.e.,* tying the featural or object information with the number of items). However, this process of tying the relational information together also occurs in a hierarchical manner such that infants (13-months) can first process the featural information of the stimuli in a familiar context (*i.e.,* familiar number of objects), but not in a novel context (*i.e.,* novel number of objects). Evidence for this conclusion also comes from the overall increase in looking times across the three ages. Compared to the 9- and 11-month-olds, the 13-month-olds spent the most time looking at the test trials. This could suggest that they are trying to process both the featural and number information, and more time is required to process all of this information.

Similar to the results from the 11-month-olds, there was an unexpected finding with the 13-month-olds; specifically, the significant effect of test area on infants' looking behavior. The 13-month-old infants preferred the small test items to the big items. Infants saw objects during habituation of *both* the small (5 square inches) and large (10 square inches) combined area. During the test, infants saw all test stimuli of *either* the small *or* large combined area. This bias for the smaller items probably results from some perceptual tendency that makes the smaller items easier to perceive. For instance, because the objects were smaller, they were separated further from each other on the monitor. Nonetheless, it is unlikely that this result would replicate given that neither the 9-month-olds nor the 11-month-olds showed this same bias towards the smaller items.

THE ROLE OF FEATURAL INFORMATION

As discussed in the introduction, the role of featural information in infants' processing of number is one issue that has yet to be resolved in the infant number literature. Many of the classic number studies (*e.g*. Starkey & Cooper 1980) used black dots as the stimuli in which featural information was not very salient. More recent studies have used a variety of stimuli such as puppets (Wynn, 1996) and Legos (Feigenson, Carey, & Spelke, 2002) which contain more variable featural information like color, shape, and texture. However, discussion of what role these features may have in infants' representation is lacking. The Feigenson et al. (2002) study is one of the few to discuss this topic; and they suggest that some featural information is stored in object-files, but the only relevant feature in their study was area or volume (they used graham crackers as stimuli). Strauss and Curtis (1981) conducted the only other study similar to the current one in which the stimuli were colorful images of real objects and in which the objects changed throughout habituation and test. In their study, 11-month-old infants could discriminate the number of items regardless of whether the objects were the same within each set (*e.g*. two apples forming a set of two) or different within each set (*e.g*. one apple and one truck forming a set of two). Therefore, it is difficult to determine whether featural information is important because there was no difference in infants' behavior across both conditions. While they did find an interaction between the two conditions (homogeneous and heterogeneous stimuli) and gender, which could suggest a difference in how featural information is being processed, this interaction has not been replicated and therefore, any conclusions based upon this finding are tentative.

Xu and Carey (1996) reported an interesting study in which infants saw two objects move from behind a screen; one came from the left side and one from the right. They varied whether the objects coming out from each side were the same or different (*e.g*. two ducks or one duck and one truck). Infants were then tested on either a single item or a pair of items. Xu and Carey found that 10-month-olds did not use property information to determine the correct number of items, but 12-month-olds did. This finding suggests that sometime between 10- and 12-months of age infants are beginning to use property or featural information to distinguish objects. However, other studies suggest that infants may be able to use featural information to individuate objects depending on the nature of the stimuli (Bonatti, Frot, Zangl, & Mehler, 2002) or the design of the task (Wilcox & Baillargeon, 1998). Wilcox and Baillargeon found that even infants as young as 7.5 months can use featural information to individuate objects.

The results of the current study suggest that infants are not using featural information to help enumerate items until at least 11 months of age; but it is still possible that younger infants are able to store featural information, but may not use it to make discriminations between numerical quantities.

THE ROLE OF AREA

As Clearfield and Mix (1999) noted, infants sometimes rely on continuous extent to make discriminations of number. The current study was designed such that if infants were solely tracking area, then there would be no differences between their looking behavior across all four test trials. Being that infants did exhibit different looking patterns to each test trial across all three ages, this suggests that infants were not simply attending to area alone. It is unlikely that infants were using area to discriminate number because area did not systematically vary with each individual object or with each set of numbers (two objects or three objects). Furthermore, there were no significant effects of area aside from the main effect of area with the 13-month-olds. Thirteen-month-olds showed a general preference for the small test objects over the big test objects; but area did not interact with any of the other variables at any age in such a manner that would suggest that infants were relying on area to discriminate between the test trials.

Previously, Feigenson (2005) suggested that infants might use continuous extent differentially depending upon the context of the task. She found that infants use continuous extent when the objects being enumerated are identical, but use number when processing different objects. Strauss and Curtis (1981) showed that 11-month-olds can discriminate number for both homogeneous and heterogeneous stimuli, but they did not specifically control for contour length or area (it varied randomly across trials) leaving open the possibility that given the opportunity, infants would show a preference for a novel contour length or area in the test trials. A recent study (Kwon, Levine, Suriyakham, & Ehrlich, 2009) provides contradictory findings to the Feigenson study. They found that infants can represent both number and continuous extent for both homogeneous and heterogeneous arrays. Based on the literature as a whole, it appears likely that infants can and do use continuous extent when discriminating number (Clearfield & Mix, 1999; 2001; Feigenson, Carey, & Spelke, 2002; Feigenson, 2005; Kwon, Levine, Suriyakham, & Ehrlich, 2009; Cordes & Brannon, 2008a; and 2008b); but, they are able to discriminate number without using area as well. The current research provides evidence that infants do not have to use area and suggests that they are relying on an object-files system which early on may encode little, if any, featural information, including area.

Furthermore, the findings on this topic seem to differ depending on how continuous extent is controlled for or manipulated. For example, some studies randomly vary continuous extent such that it cannot be a reliable cue for discriminating number (*e.g*. Strauss & Curtis, 1981; Starkey & Cooper, 1980). In these instances, infants are able to discriminate number. However, other studies (Clearfield & Mix, 1999; 2001) specifically compare discrimination based upon continuous extent and discrimination based upon number. In these studies, infants discriminate the test trials based upon continuous extent and not number. The current study did not allow infants to display a preference for a change in area over a change in number. Therefore, it may not be surprising that infants did not use area alone, but instead could discriminate number. It would be interesting to alter the design such that infants are habituated to *either* small objects or large objects, and then tested on *both* small and large objects. In this case, it may be that given the same stimuli and same number discrimination task, infants may be more likely to use area and may discriminate between the area of the objects in the test trials in addition to or instead of discriminating number.

OBJECT-FILES OR ANALOG MAGNITUDE MODEL?

Results of the current study provide further support for the object-files model of infant number perception of small numbers. Infants in this study were able to discriminate pictures of objects based on number alone before they were able to discriminate the objects themselves. This suggests that number is a highly salient, easily abstracted construct (Feigenson, Carey, & Hauser, 2002). As discussed earlier, these findings also suggest that featural information is not incorporated into infants' object-files or representations of number until later in development. Analogous to adults' subitizing (Trick & Pylyshyn, 1994), infants are able to easily enumerate quantities less than four at 9-months of age. The older infants seem to have more difficulty enumerating the quantities as they begin to incorporate featural information. However, even the data from the 13-month-old provide evidence that they are able to enumerate the quantities because they are qualitatively behaving differently in the familiar number trials than in the novel number trials. This study cannot address the distinction between processing small and large numbers or the separate systems that support that distinction because only infants' processing of small numbers was tested. Future studies can use the same design with larger quantities to see if a distinction does exists and how featural information is used in making discriminations between larger quantities.

A CONSTRUCTIVIST APPROACH

The current study supports a constructivist approach to development because infants begin by processing the stimuli in terms of number and then build upon that ability by later encoding featural information and putting together the relations between number and features. The youngest infants (9-months) were able to discriminate number independent of the features. If infants have a limited number of object-files that allow them to quickly individuate and encode objects, then it is likely that this is a fairly basic task. The addition of encoding featural information may make the task more complex. Eleven-month-old infants seem to be encoding featural information, but it is not clear whether they are using that information to aid in the discrimination of number or if they are simply encoding featural information alone. It is possible that although they are capable of encoding numerical information, their processing system is overwhelmed and they can only attend to one aspect of the task, in this case features or the objects themselves. This argument aligns well with Cohen's constructivist model (Cohen, Chaput, & Cashon, 2002 and Cohen & Cashon, 2006) which suggests that when infants overload the system, they revert back to a simpler processing strategy. Again, it may be that encoding featural information is not necessarily a simpler way of processing the information, but just a different way of processing the task. Without testing infants younger than 9-months of age, it is difficult to assess whether processing number or processing object identity is the simpler or more basic strategy.

Once infants can process number and encode featural information, they can begin to process the relations between these. This is exactly what the 13-month-olds infants appear to be doing. Even this process of combining relations occurs in a hierarchical manner because infants are able to process the featural information when the number of objects is familiar, but not when the number of objects is novel. When trying to combine featural information with the number of objects, 13-month-olds have no problem doing so in a context that is familiar. But, when forced to generalize this number category, they can no longer bind the featural information and number. The next step in this constructivist process would be the ability to bind featural information to the number of objects regardless of whether the number of objects is familiar or novel. This ability could be demonstrated in a couple of ways. First, the pattern of looking across all four test trials could match that of the 9-month-olds; namely, that infants discriminate number regardless of object type. Again, it is possible that the younger infants are storing featural information along with the number of objects in object-files. But, if making the discrimination between number only relies on comparing the number of object-files filled, then the featural information is not necessary to successfully discriminate the numbers. An alternative pattern of results is that infants could show two main effects of number and object type, respectively, but not an interaction. They may discriminate number and also show a preference for the novel object in both conditions. This would demonstrate that infants are storing featural information and are making discriminations based upon number. While this too would not provide conclusive evidence that infants are binding the featural information and number, it would help to complete the constructivist course of development demonstrated in the current study and it would definitely confirm that infants are able to discriminate number and objects.

LINKS TO PREVIOUS RESEARCH

As shown in Table 1, many studies have shown that infants can discriminate two from three objects (see Table 1 for references). This finding has been found in newborns through 14.5-month-olds (Antell & Keating, 1983 and Feigenson & Carey, 2003), using stimuli that range from simple dots and squares to colorful objects and puppets (Starkey & Cooper, 1980; Strauss & Curtis, 1981; and Wynn, 1996). The results of the current study partially confirm these findings, but also suggest that infant number perception may be slightly more complicated than previously thought. Indeed, 9-month-olds are able to discriminate two from three objects rather easily corroborating these earlier findings that infants from early in development are likely to abstract number. Despite this indication that number is relatively easy to discriminate, the 11-month-olds in the current study were not able to discriminate number. This is inconsistent with previous studies that found that infants as young as 6- or 7-months can discriminate number, and this may be due to the nature of the stimuli. Many of these earlier studies with younger infants (6- and 7-month-olds) used simple stimuli such as dots (*e.g.* Starkey & Cooper, 1981), while the stimuli in the current study were colorful pictures of everyday objects. Additionally, the design was considerably more complicated because it was a category study of number, not just a simple discrimination task. Nonetheless, Starkey, Spelke, & Gelman (1983) used similar stimuli with 7-month-olds and found that they could match the number of drumbeats heard aurally to the number of objects viewed. Intermodal matching may be a more complex task than simple discrimination, but one important factor was not controlled for in this study – area. As discussed earlier, infants could certainly be using area to make the discrimination in this task. Furthermore, Moore, Benenson, Reznick, Peterson, and Kagan (1987) and Mix, Cohen Levine, and Huttenlocher (1997) all conducted studies which call into question the validity of Starkey, Spelke, and Gelman's results. The only other study to find number discrimination between two and three objects with complex stimuli is the categorization study by Strauss and Curtis (1981) which was not replicated.

GOALS OF THE STUDY REVISITED

As outlined in the introduction, I had three main goals for this study. First, this study was designed to be a developmental study in order to address infants' numerical abilities across ages. The other goals were to address the roles of continuous extent and featural information in infants' number discrimination, respectively. To differing extents, this study accomplished each of those goals. Unlike previous studies on infants' number discrimination, this study truly does describe the development of infants' number discrimination. Beginning at 9-months, infants are able to detect changes in number in a complex categorization task using pictures of real objects. As infants get older, they begin to incorporate featural information into their representations of number. While it is not conclusive that they are doing this at 11-months, they are definitely able to do so at 13-months. However, at 13-months, they are incorporating featural information in a step-wise manner as they are able to discriminate the objects when the number of objects is familiar, but not when the number of objects is novel.

The second goal of this experiment was to determine the role of continuous extent in infants' number discrimination. Both this study and previous studies demonstrate that infants can discriminate number without using area to make the discrimination. More research needs to be conducted specifically testing for other continuous extent variables such as contour length, brightness, or density, but it is clear that infants were not only attending to area in the current discrimination task, but were sensitive to the number of items.

Finally, this study suggests that featural information, such as color, shape, and texture is not important for early number representations (object-files), but throughout development, infants begin to incorporate featural information into these representations. It would be interesting to extend the age range to see how featural information is being used at earlier and later stages of development. While many questions still remain regarding how infants process number, this study helps to explain how infants are processing number and, more importantly, how this ability is developing throughout infancy.

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VITA

Caitlin Christine Brez attended Chagrin Falls High School, Chagrin Falls, Ohio. In 1999, she entered Wake Forest University in Winston-Salem, North Carolina. In 2001, she attended Wake Forest University's study abroad program in London, England. She received the degree of Bachelor of Arts in Psychology from Wake Forest University in May 2003. During the following year she was employed as a research coordinator at Case Western Reserve University in Cleveland, Ohio. In August 2004, she entered The Graduate School at The University of Texas and received a Masters of Arts in Psychology in 2006.

Permanent Address: 3111 Tom Green Street, # 104
Austin, TX 78705

This manuscript was typed by the author.