WHAT INFANTS TRACK WHEN THEY TRACK MULTIPLE OBJECTS

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ABSTRACT OF THE DISSERTATION

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Many studies have found that infants in the first year of life use continuous amount, rather than discrete number, to represent small sets of objects. Using a looking-time paradigm, we show that twelve-month-olds use discrete quantity representations even when continuous quantity information is available, while nine-month-olds are just beginning to attend to discrete quantity. In the first study, twelve-month-old infants were required to track the changing locations of objects and sets of objects on a trial-by-trial basis. Infants were surprised to see both one and three objects when two were expected, despite the total surface area of the sets remaining constant. A second study found that twelve-month-old infants tracked the locations of a singleton and a pair and were surprised when the sets unexpectedly swapped positions. In a third study using the same methodology as the first, nine-month-old infants detected changes from two to three objects, but fail to detect changes from two to one. A fourth study investigated whether twelve-month-old objects can track sets adding up to more than three objects. Twelve-month-olds infants used shape information to individuate across pairs and track a total of four objects. Infants who were familiarized to two distinct pairs (for a total of four objects) looked longer at an outcome of only two objects, while infants who were familiarized to two mixed pairs (for what appeared to be a total of two objects) did not look longer. Finally, twelve-month-old infants were tested on their ability to represent sets of two and three, for a total of five objects. Pilot data suggest that infants can do so. These studies suggest that by twelve months of age, infants can reason about discrete quantity in addition to tracking continuous quantity. We propose that even young infants may have access to mechanisms of innate number, and represent at least small numbers using integer concepts.

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This dissertation is dedicated to my parents, finally!

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Chapter One - Introduction

According to traditional Piagetian views of infant development, babies could not track even one object as it passed out of view (Piaget, 1955). For them, the world was considered to be literally "out of sight, out of mind." However, we know now that infants can track even multiple objects through occlusion (Baillargeon, 1986, 1987; Spelke, 1990). How do they accomplish this feat? Do babies use discrete or continuous quantity information to form representations of these objects? Recent research has shown that not only do infants apparently individuate objects and discriminate between different numerical outcomes, they also seem to perform arithmetic computations, suggesting that they possess high-level concepts of number. However, many of the studies providing evidence for these capabilities have been assailed as failing to sufficiently rule out alternative interpretations for their data. Specifically, infants may be responding on the basis of continuous variables, such as area or perimeter, rather than on the basis of discrete variables, such as number. Alternatively, even if infants do possess the ability to track discrete properties of sets of objects, this does not entail that they possess concepts of number. Rather, the ability to track discrete number may simply be served by a limited-capacity attentional mechanism. What is the true nature of infants' early numerical competence?

A growing body of research has traced continuity between animal and human quantitative abilities, suggesting that number is an innate, evolutionarily-specified endowment. Specifically, human adults, like rats and pigeons, seem to represent number using a mental mechanism which can be characterized as an accumulator (Meck & Church, 1983;

Gallistel and Gelman, 1992; Cordes, Gallistel, Gelman, & Whalen, 2001). The accumulator is amodal and represents quantity (both discrete and continuous) using continuous mental magnitudes, which by nature are imprecise and noisy. As the magnitudes grow larger, the variability around the magnitudes increases. As a result of this increase in variability, human ability to discriminate between two numbers exhibits both size and distance effects consistent with Weber's law. In other words, the discrimination of two magnitudes depends on their proportional difference, rather than the absolute difference between them. The question of whether infants perceive objects based on their continuous or discrete properties intersects with and informs the debate over whether number is innate. If infants fail to represent objects as discrete individuals and instead attend only to their continuous properties, this supports a more empirical view of the infant's concept of number. According to such accounts, infants develop or extract discrete representations from continuous ones, which are apprehended through sensory input (Mix, Huttenlocher, and Levine, 2002). However, if infants do individuate objects in the world, at a minimum they have a capacity to attend to discrete objects, either using the accumulator to non-verbally enumerate objects, or via an attentional mechanism for tracking objects akin to one found in human adults (Pylyshyn and Storm, 1988; Trick and Pylyshyn, 1994).

Many studies have found that infants demonstrate sensitivity to discrete numerosity in multiple modalities, but the interpretation of these findings remains controversial. The bulk of these studies have looked at whether infants visually detect numerical equivalence of objects in sets. Four-month-old infants who are habituated to sets of two or three dots dishabituate when shown a novel numerosity (Starkey and Cooper, 1980); even newborns make this discrimination (Antell and Keating, 1983). 10 to 12-month-old infants succeed at comparing two and three when presented with arrays of both homogeneous and heterogeneous objects (Strauss and Curtis, 1981). Converging evidence from a reaching task shows that infants in this age correctly select a larger number of crackers when presented with comparisons of 1 vs. 2, 1 vs. 3, and 2 vs. 3 crackers (Feigenson, Carey and Hauser, 2002). This ability also extends beyond objects. 5-month-olds habituated to either two groups of objects or four groups of objects look longer at a novel number of groups, even though the total number of items remains constant (Wynn, Bloom, and Chiang, 2002). Six-month-olds dishabituate to novel numbers of visual events, such as jumps (Wynn, 1996). Seven-month-old infants even cross-modally match equivalent sets of two and three, preferring to look at a display that shows the same number of objects as sounds heard (Starkey, Spelke and Gelman, 1983). Infants also seem to enumerate auditory stimuli, such as syllables, at four days (Bijeljac-Babic, Bertoncini, & Mehler, 1993), and tones, at seven months (vanMarle and Wynn, 2003). Even very young babies clearly demonstrate some sensitivity to discrete number.

However, this ability seems to be limited to small numbers, as infants fail to discriminate between sets of four and six (Starkey and Cooper, 1980; Antell and Keating, 1983) and four and five (Strauss and Curtis, 1981). More surprisingly, infants choose randomly when presented with a comparison of one cracker versus four crackers, even though they correctly choose three crackers over two; the global set size is the same for both comparisons (Feigenson, Carey and Hauser, 2002). However, they do correctly choose four crackers over one cracker when both sets are in plain view, and four crackers over no crackers in occlusion, suggesting that they have some limited ability to reason about sets of four, even in occlusion (Feigenson and Carey, 2003). Interestingly, these failures do not extend to the large number range. Infants can discriminate between sets of 8 and 16 at 6 months (a ratio of 1:2) and between sets of 8 and 12 by 9 months (a ratio of 2:3) for visual and auditory stimuli (Xu & Spelke, 2000; Lipton and Spelke, 2003; Xu, 2003). Six-month-olds can even discriminate between four and eight jumps, although they fail to discriminate between two and four jumps. By nine months, infants discriminate between sequences of four jumps and six jumps (Wood and Spelke, 2005). These findings (with the exception of Wood and Spelke's (2005) six-month-olds' failure on 2:4 jumps) are consistent with the Weber fraction signature demonstrated by the accumulator. Furthermore, they indicate that sensitivity to large number comparisons increases over development. Why, then, do infants fail at small number comparisons with a decidedly favorable ratio, such as 1 vs. 4, when they make much finer distinctions between large numbers? The question of why infants demonstrate different patterns of behavior when discriminating small and large numbers deserves further consideration and will be addressed later.

However, nearly all of the studies finding evidence that infants are sensitive to discrete variables are subject to the same criticism, namely, that these studies necessarily confound continuous variables, such as area and perimeter, with number. In the real world, changes in discrete quantity invariably co-occur with changes in continuous quantity. Adding a cracker to an existing set of crackers always increases the total amount of cracker stuff; taking a cracker away from a set of crackers always results in less cracker stuff. If infants simply track a continuous amount of stuff, they do not even need to individuate objects, let alone possess any numerical competency. And indeed, when continuous variables are controlled, infants fail to respond to discrete quantity. Clearfield and Mix (1999) attempted to replicate Starkey, Spelke and Gelman (1990) while controlling for continuous quantity – specifically, total perimeter. They found that infants failed to detect a change in number when perimeter was held constant, but looked longer at changes in perimeter when number was held constant. Infants show the same pattern of results for changes in area (Clearfield and Mix, 2001). In light of these results, the claims that infants have sophisticated and complex number concepts must be reexamined. Instead, Mix, Huttenlocher and Levine (2002) argue that infants may be equipped only with the ability to monitor continuous quantities, such as area or perimeter, and through experience, such as applying counting routines, eventually derive or extract ever more precise concepts of number. Is there any evidence that infants represent discrete number?

Few studies to date have shown unambiguously that infants represent small sets of objects as discrete entities – that is, infants respond based on discrete number when continuous variables are controlled. To further complicate the issue, it is very difficult to control for changes in number, area and perimeter simultaneously, particularly for smaller sets (but see Chapter 5). Studies investigating infants' numerical competency using large numbers of texture elements, such as dots on a screen or squares on pieces of paper, can control not only for total area and perimeter, but also for variables such as luminance and density, and are therefore immune to criticisms based on continuous extent (Xu & Spelke, 2000; Lipton & Spelke, 2003; Xu, 2003). Only three studies looking at the small number range have found unassailable evidence for discrete number, rather than continuous quantity. Of these, only two studies showed that infants responded on the basis of discrete representations when they could have responded on the basis of continuous ones. Brannon, Abbott and Lutz (2004) found that six-month-old infants could detect a two-fold change in number when area was held constant, but not a two-fold change in area when number was held constant. A second set of studies used a reaching paradigm to investigate discrete number representations. Infants aged 12 to 14 months were shown items being introduced sequentially into a box and then encouraged to search for the objects. Infants represent up to three hidden objects, even when objects retrieved are larger than the objects that were concealed (Feigenson and Carey, 2003). However, they failed when four objects were hidden. For numbers up to three, infants tracked how many objects came out of the box, not a total amount of stuff. In this case, infants could have responded on the basis of either discrete or continuous representations but chose discrete. Perhaps the size of the individual objects is irrelevant in a reaching paradigm, though this explanation seems unlikely to gain support from any camp, given the weight that is placed on the role continuous extent in infant object representations.

A third study eliminated continuous variables as a possible dimension of interest altogether. Feigenson (2005) eliminated continuous extent as a dimension of consideration altogether by always varying the total area and perimeter of the habituation and test arrays. Seven-month-old infants were habituated to either one or two objects that differed in both color and texture both within and between displays. In the one-object habituation condition, the object had a total of two colors and two textures, to provide an equivalent control to the two-object condition. Infants in this study detected a change in numerosity when shown a novel numerical outcome. These results contrasted with those from an earlier study, which found that infants did not notice changes in number when objects differed only in color (Feigenson, Carey and Spelke, 2002). When infants cannot use continuous quantity information to represent objects, they do seem to respond on the basis of discrete variables, suggesting that they can attend to this information under certain circumstances. Feigenson (2005) suggested that featural heterogeneity blocks summing of continuous quantity across objects and forces the infants to rely on alternate sources of information, but this explanation does not account for why infants in the one-object habituation condition detect a number change when both texture and color differ, but not when only color changes. A more likely interpretation of the data is that heterogeneity encourages infants to consider objects as distinct individuals, alerting them to the fact that number is a salient property of the display.

However, even if infants do use discrete number to discriminate between sets of objects, infants may not necessarily possess truly numerical concepts. Instead, infants may succeed by using an attention-based object-tracking system such as one demonstrated by adults (Pylyshyn and Storm, 1988; Trick and Pylyshyn, 1994). This system tracks items by assigning a mental finger, also known as an object index or object file (henceforth OF), that points to each object or collection of objects (such as a flock of birds) to be tracked. Adults can keep track of up to four objects at a time, but this system may be limited to three objects in infants (Leslie, Xu, Tremoulet and Scholl, 1998; Scholl and Leslie, 1999). By nature, this finger is agnostic about the objects it points out (Leslie et al., 1998; Scholl and Leslie, 1999; Pylyshyn, 2004). Information about these objects is stored in a separate object representation (OR), which is bound to the OF. What property information goes into these ORs and when it is used remains largely undefined. OFs are only implicitly numerical; in other words, without counting, one cannot know how many objects are indexed. Because of this, the object indexing account is equally compatible with both discrete and continuous accounts of infants' quantity representations. If infants represent objects only by their continuous quantities, object indexing may be a possible explanation for why they also seem to sometimes respond based on discrete variables. If infants do represent objects discretely, indexing may complement non-verbal counting, or may serve as the mechanism by which infants track sets of objects in the small number range. The latter possibility seems unlikely given that infants appear to enumerate non-objects, such as events (Wynn, 1996; Wood and Spelke, 2005) and sounds (Bijeljac-Babic et al., 1993; vanMarle and Wynn, 2003), though these may be discriminated on the basis of continuous variables such as duration, tempo, etc. Wood and Spelke (2005) suggest that infants may form "event files", parallel representations similar to object files, which pick out transitory events in the world rather than enduring objects; however, no empirical evidence to defend this claim has been offered.

More convincing evidence for true numerical competence in infants comes from studies of arithmetic. Infants do demonstrate some capacity for performing arithmetic computations even at a very young age, though, like studies of numerical equivalence, the results are open to multiple interpretations. Five-month-old infants, when shown displays of simple addition and subtraction problems, looked longer at unexpected and impossible outcomes of 1+1=1 and 2-1=2 (Wynn, 1992; also Simon, Hespos and Rochat, 1995). Infants even perform these computations across the large number range. McCrink and Wynn (2004) found that nine-month-old infants look longer at outcomes of 5+5=5 and 10-5=10. Intriguingly, infants even add across sensory modalities. Kobayashi, Hiraki, Mugitani, and Hasegawa (2004) trained five-month-old infants to associate a tone with the introduction of an object and found that infants looked longer at one object + one tone = three objects and one object + two tones = two objects than at expected outcomes.

While studies showing evidence for infant arithmetic are more convincing proof of true numerical competency than studies showing discrimination of sets, these studies are still subject to criticisms based on failure to control continuous extent. In fact, Feigenson, Carey and Spelke (2002) replicated Wynn's task using controlled stimuli, showing infants one small doll + one small doll = one large doll (with the same total area as the two small dolls together). They failed to find longer looking times for the numerically unexpected outcome with an expected continuous extent. Studies of infant arithmetic are subject to an additional criticism, that infants may prefer familiar displays over novel ones. Cohen and Marks (2002) found that a preference for familiar numerical outcomes, rather than sensitivity to numerosity, might have driven infants' looking time. In other words, infants in Wynn's study looked longer at an unexpected outcome of 1+1=1 not because they expected to see 2 dolls, but because they preferred to look at the display to which they had been familiarized. McCrink and Wynn (2004) controlled for continuous quantity by always varying the continuous extent of the elements in their study, but failed to control for familiarity. They argue that by 9 months of age, infants begin to demonstrate a novelty preference, rather than a familiarity preference, and so their study cannot be criticized on the basis of familiarity. For advocates of familiarity, this argument may be less than convincing. Kobayashi et al. (2004) controlled for familiarity by showing infants both of the possible numerical outcomes. They also controlled for continuous quantities because infants always saw the same initial display but never saw the "objects" being added. Instead, they had to infer this information from auditory cues. However, an alternative interpretation of the results is that infants do not use number to form a correct expectation, but instead use object tracking. Hearing a tone may be enough to open a new object file for an expected object. Infants' expectations may be based on whether their open object indexes match the display, rather than number. A more rigorous test of infant numerical competency would have to investigate infants' ability to do arithmetic on numbers larger than can be tracked by the object indexing system in controlled conditions. Success would indicate that infants can perform arithmetic computations on the small as well as the large number range, and that representations of both number ranges are subserved by the same system.

Infants do seem to represent the discrete properties of objects when continuous variables are controlled, both for studies looking at equivalence of sets and studies of arithmetic. Further, infants' ability to represent continuous quantity may not be as robust as claimed. Brannon, Abbott and Lutz (2004) compared six-month-old infants' ability to discriminate between outcomes differing in discrete or continuous quantity. They found, as expected, that six-month-old babies, when familiarized to displays of constant number but with large variations in area (up to a five-fold change) were able to discriminate 8 elements from 16 elements, but failed to notice an equivalent two-fold change in total area when familiarized to displays of constant area with large variations in number (again, up to a five-fold change). Brannon, Lutz and Cordes (2006) found that six-month-old infants could discriminate between successive presentations of Elmo faces varying in size for ratios of 1:2, 1:3 and 1:4, but failed for ratios of 2:3.

Infants also do not show great accuracy when asked to track substances that can be measured only by continuous properties, such as sand or liquid. In fact, only one study points to infant competence in this domain. Gao, Huttenlocher and Levine (2000) familiarized infants to half a cup of pink liquid being poured into another container containing a quarter of a cup of pink liquid, and found that infants looked longer when shown a result of a quarter cup of liquid than the correct outcome of three-quarters of a cup, a 1:3 ratio. However, infants do not look longer at an incorrect outcome when the substances are piles of sand. In fact, even when a cup of sand is poured behind a screen next to and distinct from another pile of sand, infants do not look longer when only the original pile is shown, suggesting that their ability to reason about continuous substances is very different from their ability to reason about discrete entities (Huntley-Fenner, Carey and Solimando, 2002). 10- to 12-month-old infants also appear not to represent amount of food very precisely, choosing the larger quantity of Cheerios only when the two amounts differ by a ratio of at least 1:4 (vanMarle, in preparation). At this age, infants’ ability to quantify food substances also seems to rely largely on perimeter and density cues, as their ability to distinguish between discrete representations diminishes with changes to these variables in a display. When these cues are removed, infants perform only at chance.

Infants show no greater precision in their representations of continuous extent than in their representations of discrete number. In fact, their ability to discriminate between two different continuous extents seems to be governed by exactly the same Weber fractions as their ability to discriminate between discrete numbers (Brannon et al., 2006). If so, then it is unclear how discrete number concepts could have their origins in continuous quantity representations, as Mix et al. claim (2002). According to their theory, humans start with approximate numerical concepts based on representations of continuous amount, and through experience converge on ever more precise representations of number. However, it appears that even for very young infants, representations of continuous amount and number seem to develop in parallel. Children clearly do not have to learn to ignore continuous amount as a property of a set of objects in favor of discrete number. In fact, under certain circumstances, they may not even encode continuous amount as a relevant dimension of a set of objects (Feigenson and Halberda, 2004; Brannon et al., 2006).

In addition, studies of whether infants are able to retain accurate representations of the continuous properties of sets of objects through occlusion events yields mixed results. While Brannon and her colleagues found that infants could succeed in discriminating between the continuous extent of visual elements in large ratios, none of their studies involved occlusion (Brannon et al., 2004; 2006). vanMarle's (in press) results suggest that even at 12 months of age, representations of continuous quantity, sensitive as they are to visual cues such as density, may be subject to more variability than representations of discrete quantity. Feigenson and her colleagues found that infants tested in different reaching paradigms often ignored continuous quantity, for example, when choosing between a quantity of one and four crackers (Feigenson, Carey, and Hauser, 2002), or when searching for a number of toys hidden in a box (Feigenson and Halberda, 2004) It is therefore an open question whether infants' relatively noisy representations of continuous amount are robust enough to survive occlusion events.

The case for continuous extent as the sole basis on which infants compare objects has been considerably weakened by new experimental evidence, and has given fresh impetus to the question of whether infants do detect and track discrete quantity. But how much competence this ability to discretize reflects still remains controversial. Do infants actually have number concepts, meaning that they can non-verbally count (Brannon, 1992; Gallistel and Gelman, 1992; Simon, Hespos and Rochat, 1995; Wynn, 1992; Xu and Spelke, 2000; Leslie, Gallistel, and Gelman, in press)? Or is their ability non-numerical in nature, and simply subserved by a limited capacity attentional mechanism (Leslie, Xu, Tremoulet, and Scholl, 1998; Scholl and Leslie, 1999; Uller, Carey, Huntley-Fenner & Klatt, 1999)? The two accounts are not mutually exclusive and it is quite likely that infants may use both systems.

Recently, however, the relationship between the two systems has been further complicated by the proposal that infants represent different parts of the number range with each mechanism. Specifically, infants may use non-verbal counting via the accumulator solely for large numbers while representing the small number range through indexing or otherwise individuating small sets (Carey, 2001; Carey, 2004; Feigenson, Dehaene and Spelke, 2004; Feigenson and Carey, 2005; LeCorre and Carey, in press). Such a discontinuity may account for a wide range of results showing that infants' representations of large numbers appear to obey Weber's law (Xu & Spelke, 2000; Lipton and Spelke, 2003; Xu, 2003), but studies looking at whether their small number representations do so as well have found mixed results. Many studies have found infants repeatedly fail when required to represent individual sets larger than four (Starkey and Cooper, 1980; Strauss and Curtis, 1981; Antell and Keating, 1983; Feigenson and Carey, 2003; Feigenson and Halberda, 2004). This set size limitation is usually attributed to the inability of the infants' object indexing system to track more than three objects concurrently. A disconnect between the small and large number range is also seen in children's understanding of count terms, suggesting that the discontinuity exhibited by infants may extend into development. Children learning English seem to laboriously learn the referents for one, two, and three, but after acquiring *four*, they appear to grasp the idea of all numbers larger than four as well (Wynn, 1992b; Wynn and Bloom, 1997). The data do appear to favor the hypothesis that there is some difference in the systems infants use to operate over the small and large number ranges. However, an apparent discontinuity does not necessarily entail two distinct systems of representation of number. The fact that infants can make comparisons across the small and number ranges (from 2 to 8) suggests that these two systems are not incommensurable after all (Cordes, Lutz and Brannon, 2007).

Indeed, while object indexing is compatible with non-verbal counting, it cannot replace counting. Neither object files nor object representations can provide the basis for small number concepts; both are only implicitly numerical. In order to enumerate the number of assigned indexes, one must already be able to count. The object indexing system may be the source of the set size limitation, not because it provides an absolute limit on how many objects can be individuated, but because it may interact with representations of number in such a way that it prevents infants from demonstrating true competence. It is possible that exceeding the number of available object indexes results in a failure to enter a representation into memory. However, one of the puzzling features of the set size limitation is that it is not hard and fast. Feigenson and Halberda (2004) found that 14-month-old infants search for four objects when searching for objects hidden sequentially as a group of two and a group of two. "Chunking" the objects in this manner results in success nearly 10 months earlier than when the objects were introduced simultaneously into the box.

The set size limitation also applies only to individual sets, not to the overall number of objects. When asked to compare a total of five crackers, infants succeed on comparisons when shown two vs. three, but perform only at chance at one vs. four, even though they are asked to compare the same total number of crackers (Feigenson and Carey, 2003). What explains this particular pattern of success and failure? Infants cannot simply be individuating each object using attentional indexes – they would be unable to track any quantity greater than three, and would fail on both comparisons. They cannot be chunking object files, because they are merely attentional indexes and cannot be concatenated. If infants succeed in comparing these two sets, they must be doing so on the basis of the information stored in the ORs. Feigenson and Halberda (2004) remain agnostic about whether these chunked representations are based on continuous or discrete quantity. However, their results indicate that infants cannot simply be responding on the basis of total continuous extent. But if infants can only represent small numbers by using object indexes, how do they compare sets of objects without resorting to counting or concepts of number?

These criticisms have led Carey and her colleagues to revise their theories to rely less heavily on object indexing as the source of infants' small number representations. They now posit a core numerical representation system, "parallel individuation," which gives infants the ability to store representations of at least two sets of objects in working or long-term memory (Feigenson and Carey, 2003; 2005; LeCorre and Carey, in press). In such systems memory, not attention, determines the limits of infants' representations. Exactly how infants represent elements within the set has not been established (essentially, how specific the ORs for each element are), but "each individual is represented by a unique mental symbol." In essence, sets appear to be summaries or lists of these mental tokens. Set limitations indicate that items are represented discretely - each can hold only up to three or perhaps four individuals (Feigenson, Carey and Hauser, 2002; Feigenson and Carey, 2003; Ross-Sheehy, Oakes and Luck, 2003). In addition, these sets cannot be added to without destroying the existing representation (Feigenson, 2005). Like object-indexing, parallel individuation is only implicitly numerical. The system contains no symbols for number, such as those represented by the analog magnitudes, but infants are able to evaluate objects on the basis of *numerical identity*, i.e. whether the object they saw is the same as one they saw earlier (Xu and Carey, 1996), and can compare the sizes of represented sets by one-to-one correspondence (Feigenson and Carey, 2005). This system attempts to explain how infants can simultaneously represent at least two sets with a total of more than three objects without resorting to counting.

However, it is not clear how infants make the transition from these one-to-one comparisons to judgments on the basis of numerical concepts, or how infants go from these small sets to larger number representations. Carey and her colleagues propose that three core endowments do the work. The first is the ability to represent large numbers as mental magnitudes, the accumulator mechanism (Meck & Church, 1983; Gallistel and Gelman, 1992). Secondly, infants represent the existence of small discrete sets using parallel individuation; these sets are represented on the level of the individual. They also have access to yet another core system of numerical knowledge, “set-based quantification,” which allows children to form summary representations of the sets picked out by parallel individuation, and which provides the meanings of natural language quantifiers, the morphemes denoting sets (such as “a” and plural “-s”), and in languages that feature such terms, markers for concepts such as “dual” and “trial” (Corbett, 2000). Infants who grow up speaking languages with these morphemes first map between these terms and the small sets which they can individuate in parallel, and from there induce concepts of small integers (up to the limit of three). Infants further come to understand that sets of two are one item larger than sets of one, and sets of three are one larger than sets of two, and from this realization induce the successor function, which allows them to map into even larger integers, assuming the count terms for such concepts are available in one's language – if not, these larger numbers are never learned. LeCorre and Carey (in press) call this integration process "enriched parallel individuation".

This process of "bootstrapping" into specific small number concepts and from there into larger number concepts via quantifiers and the count list (Carey, 2004; Feigenson and Carey, 2005) suggests a relationship between language and numerical competence, a relationship apparently supported by data from Carey and her colleagues. Infants will search for one, two, and three objects hidden in a box, but when four objects are hidden, they fail to search longer than for one object (Feigenson and Carey, 2003). Infants begin to pass this task at around 24 months of age; this ability is highly correlated with acquisition of the plural marker *–s* (Barner, Thalwitz, Wood and Carey, in press) and varies cross-linguistically, although non-human primates also make the singular/plural distinction, suggesting that this ability cannot be linguistically-determined (Barner, Wood, Hauser and Carey, under review). Infants learning languages with redundant linguistic cues for plurality pass this task earlier than English learners (Kouider, Halberda, Wood and Carey, 2006). In addition, studies from adult speakers of languages with impoverished count list inventories have found that adults in these cultures show less precision in their mathematical abilities than do individuals speaking languages with terms for large numbers (Dehaene, 1999; Gordon, 2004), though these conclusions have been challenged (Gelman and Gallistel, 2004). Once infants have established the correspondence between the count list items “one”, “two”, “three”, and “four”, and the relationship between those concepts, they are then able to induce the counting principles which allow them to learn terms for even larger integers and map them correctly to the appropriate numerical representation, most importantly, the counting principles.

However, Rips, Asmuth and Bloomfield (2005) argue that using language to “bootstrap” into an infinite system of number concepts does not work without specifying a more restricted definition of the concept “next number word”. Simply learning a count list could not give you the means to induce the successor function, because the count list, being meaningless, cannot specify whether the next item in the list is in fact a larger number (for instance, FIVE following FOUR) or simply the restarting of a cyclical system (such as SUNDAY following SATURDAY). Children learning a finite set of words for numbers can only distinguish between these options if he or she understands that the “next” word maps to the output of the successor function. Such a restricted definition of the “next number word”, however, implies an innate or at least prior understanding of the successor function, rendering bootstrapping unnecessary.

LeCorre and Carey’s (in press) argument still holds if one assumes that young children learning the count terms map them only to the limited and finite set of small numbers that they have mapped to their set representations. However, this limitation again raises the question of how children ultimately break out of these small number representations into larger numbers. Infants may start with a limited number of small number concepts, but they still at some point must deduce the larger integers on the number line, and Rips et al's (2005) criticism still holds for that process. Indeed, why are infants limited to the small number range for their set representations? The answer appears to have something to do with the capacity of working memory – one might think of attention as a funnel allowing only a certain number of items to fit into a slot. If the funnel overloads, then nothing gets placed into the slot, resulting in the failure to represent larger sets of four and greater (Feigenson, Carey and Hauser, 2002; Feigenson and Halberda, 2005). However, long-term memory should not be subject to such limitations. In addition, the capacity of working memory increases over time (Kaldy and Leslie, 2003, 2005; Leslie and Kaldy, in press; Ross-Sheehy et al., 2003), while nothing suggests that the set limitation must change along with it. Indeed the data from numerous studies reviewed earlier suggest this limit is already at three by the age of six months. If working memory dictates what can be placed into these set representations, then the set limitation must start at one for six-month-old infants and increase over time to three only by about 10 months of age. LeCorre and Carey do not offer this restriction and it is unclear whether any data support this claim. But if working memory constrains long-term memory then the issue of how six-month-old infants can form representations of sets up to three must be clarified while restricting older infants from representing still larger sets in long-term memory.

A further question is why it is necessary to posit three core endowments for number that carry out different but related functions, all in the name of avoiding assigning infants numerical competence. Assuming an innate understanding of number eliminates the need for at least two of Carey and her colleague's posited systems of numerical representation, namely, parallel individuation and set-based quantification, leaving only a core system that represents all numbers, large and small, using analog magnitudes (and perhaps represents small numbers up to three with integer concepts) (Leslie et al., in press). Under such a system, the acquisition of verbal counting does not require mapping from small sets to items in the count list, and from there the induction of counting principles. Rather, the counting principles (namely, one-to-one correspondence of items in the count list to items being counted, stability of the count list, and cardinality, the last term used in counting the set establishes the cardinal value of the set), as well as the successor function, come for free, and guide the acquisition of the verbal count list (Gelman and Gallistel, 1978; Leslie et al., in press).

Understanding what kind of information forms the basis of the representations infants use to track sets of objects in the world sheds light on what humans know about objects and number from an early age, and sets the tone for research investigating older children's numerical abilities. Is it more accurate to depict number learning as a developmentally protracted, culturally determined process of drawing connections between the environment and linguistic terms? If so, then the behavior of children before and after learning this mapping should be discontinuous, and qualitatively different. Or is knowing about number governed by evolutionarily advantageous systems that allow us to recognize and exploit numerical information in the environment? If that is the case, then the behavior of infants, young children, older children, and adults should exhibit strong continuity. Establishing the nature of infants' numerical competence provides us with certain assumptions regarding these questions, and has far-reaching implications for the fields of cognitive science, developmental psychology, mathematics, and education.

What do we know about infants and how they perceive the world? Infants clearly track the continuous properties of sets, though this ability may not be as robust as originally believed. And although the evidence is not conclusive, infants may track discrete quantities as well. This ability may be subserved by an attention-based object-indexing system, or it may reflect true numerical competency. If infants represent both kinds of property information about objects, the question of the nature of their object representations must be reformulated. If infants track both discrete and continuous quantity information, what kind of information is stored in their object representations? Do infants tailor their behavior to the task at hand and utilize different systems of representation when appropriate? For instance, when choosing amount of food, it is more sensible to rely on continuous extent than number; one large cracker is preferable to two small crackers. Studies of infant arithmetic make changes in discrete numerosity very salient, and may access counting. When infants are asked to track objects through occlusion, they may do so by indexing the objects. The set of studies described here investigate the nature of infants' small number representations. Can infants track discrete quantity for small numbers when continuous variables are controlled? If so, what mechanisms underlie this ability? Do infants non-verbally count, do they simply index objects, or do they form set representations?

Chapter Two

Experiments 1 and 2: 12-month-olds' discrete number representations

Background

Do infants track objects through occlusion based on discrete or continuous quantity information? To investigate, we used Kaldy and Leslie's (2003) two-screen methodology. This paradigm was originally used to investigate whether infants use color and shape information to identify and individuate objects. In their study, nine-month-old infants were familiarized to two sequentially-presented shapes, a red disk and a blue triangle, which were introduced and then moved to the sides of the stage. The shapes switched sides on alternate familiarization trials in order to prevent infants from associating a shape to a particular location. During test trials, two screens were brought down and the two shapes introduced in the same way as during the familiarization trials. They were then moved behind the screens and the screens lifted to reveal either the expected outcome, or one of three unexpected outcomes – shape change (a red triangle in the red disk location and a blue disk instead of a blue triangle), color change (a blue disk in the red disk location, a blue disk instead of a blue triangle), or shape and color change (the expected objects swapped sides). In order to succeed at tracking, infants had to attend to objects based on their features and their location. They found that at nine months, infants used shape information to identify the objects, but ignored color information.

A preliminary study (Lerner, 2003) was conducted in our lab to determine whether the two-screen methodology could appropriately be used for studies of number. Specifically, the study sought to confirm whether infants could track discrete number for two separate sets of one and one. Twelve-month-old infants were familiarized to two red-painted wooden discs with a radius of 2” (henceforth R2” discs). Infants saw one disc lowered to the center of the stage, tapped twice, and left for two seconds. The second disc was presented next to the first disc in the same way. The discs were then moved one at a time, in the order they were presented, to the opposite sides of the stage, tapped twice, and left there for 12 seconds. The familiarization trial ended when a yellow felt curtain was raised to occlude the stage. Infants saw a total of four familiarization trials; sidedness of first presentation varied across trials. On trials one and three, the first disc was presented to the infants’ left; on trials two and four, to the infants’ right.

The test trials differed from the familiarization trials only in that before the discs were presented, two screens covered in blue paper were lowered onto the stage in a position to hide the discs when moved to their final resting places on opposite sides of the stage. The discs were presented in the same way as in the familiarization trials, and then moved behind the screens. The screen hiding the last-placed disc was then removed, showing one of four possible outcomes in a between-subjects design. In the Control condition, infants saw the expected R2” disc. In the Unexpected Area and Number Change condition, infants saw two R2” discs, an outcome which differed in both expected number and expected total continuous extent. In the Number Change condition, infants saw two R1.41” discs, an outcome which differed in expected number, but which has the same total continuous extent as the R2” control disc. In the Unexpected Area Change condition, infants saw one R1.41" disc, the expected number, but with an unexpected total area.

On the first trial, infants looked longer at outcomes of two, but not to outcomes of one despite changes in area, perimeter, and diameter. These results suggested that infants could track discrete number for groups of one. They also confirmed that the two-screen methodology could be used for studies of number. We decided to extend the study to investigate whether infants could reliably track even larger numbers of objects. In the new study, infants were asked to track a group of one and a group of two for a total of three objects, three being the limit of distinct objects that infants can track concurrently (Scholl and Leslie, 1999).

The new study was designed to take advantage of the two-screen methodology by highlighting the discrete properties of objects. In order to track the objects successfully, the infants had to discriminate between the two sets and also attend to their location on a trial-by-trial basis. The study also sought to rule out confounds of continuous quantity, discrete number, and familiarity. Infants could track the sets either by discrete number or total continuous quantity; unlike studies that showed successful tracking by discrete number, we did not eliminate continuous quantity as a reliable source of information (Feigenson, 2005). The study's design eliminated the confound between changes in continuous extent and changes in discrete extent by showing infants outcomes that differed either in number or in area, but not both at the same time. We controlled for changes in perimeter by showing displays that changed in perimeter for all non-control groups. Our design also allowed us to rigorously test whether infants formed a familiar number preference or demonstrated a novelty preference. In the previous experiment, it is possible that infants formed a familiar number preference for the total number of objects to which they were familiarized, rather than showing a novelty preference for an unexpected numerical outcome. The new study eliminated this confound by showing two different unexpected number outcomes, only one of which was "familiar".

Method

Design

The design of Experiment 1 was based on the previous study, but instead of being presented with two R2" discs, infants instead saw three R1.41" discs. The discs were placed on the stage, one at a time, in a group of one and a group of two, with a space in between. The discs were then moved individually to the sides of the stage, the single disc to one side and the pair to the other side, where they rested for 12 seconds. Sidedness of the presentation of the two groups of discs alternated trial by trial for a total of four familiarization trials. Infants saw each group equally often on each side. Test trials were identical to familiarization trials except at the beginning of each test trial, two screens were introduced in a position to occlude the discs when placed in their final resting places at the sides of the stage. The discs were then presented as during the familiarization and then moved behind their respective screens. The screen occluding the pair was then lifted to reveal one of four outcomes. Figure 1 illustrates the design. The four possible outcomes are shown in Figure 1C.

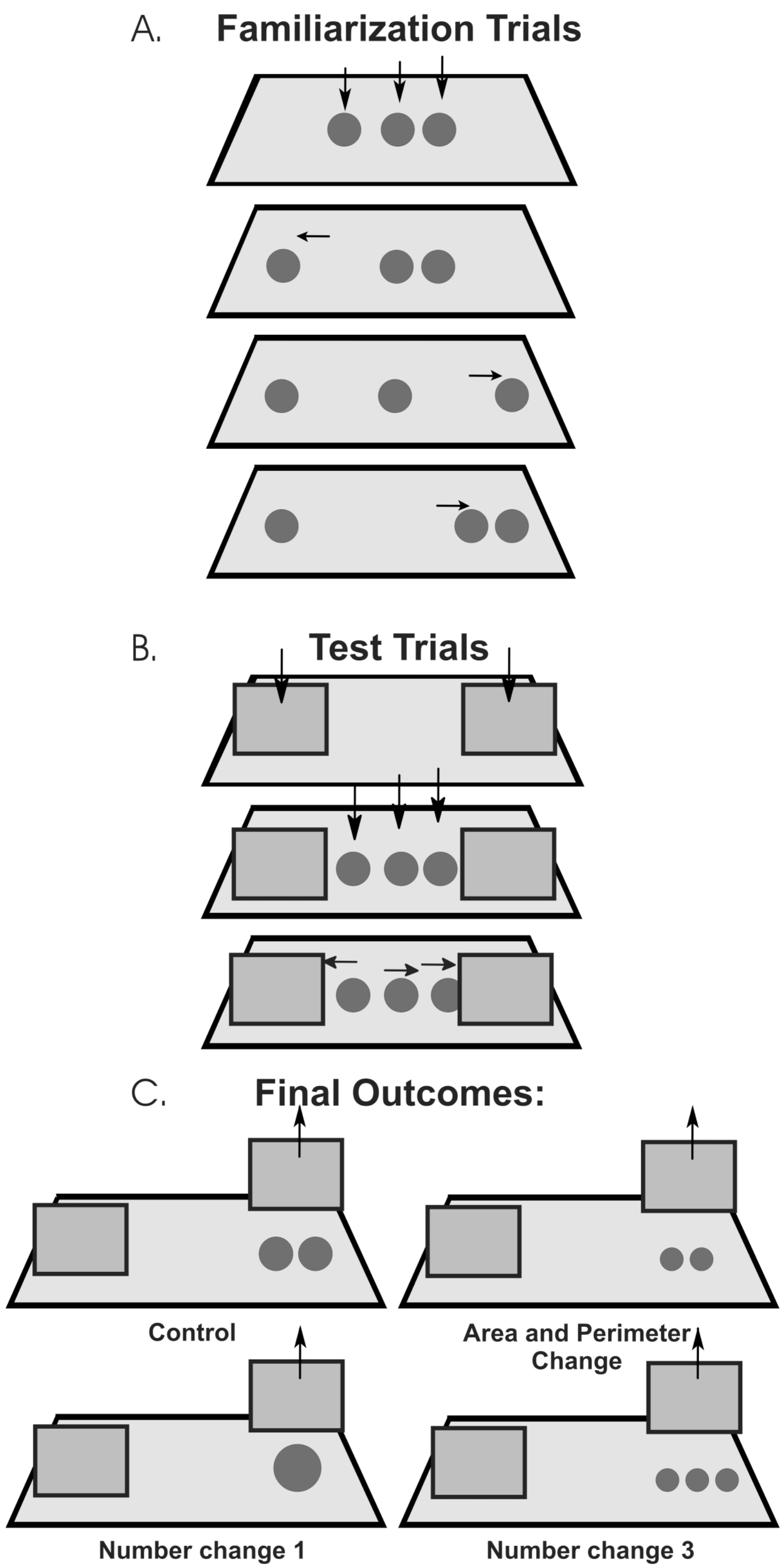

Figure 1. The design of Experiment 1.

Infants saw only one of four test outcomes in a between-subjects design. Two test outcomes presented the expected number of discs. In the Control outcome, the display consisted of the two expected R1.41” discs. In the Area and Perimeter Change outcome, infants saw a display containing two slightly smaller (R1.14”) discs. The expected number of discs was shown, but the total area decreased to about 66% of the expected total area, and the perimeter decreased to about 19% of the expected total perimeter. Two test outcomes showed infants an unexpected number of discs with the total expected area. In the Familiar Number Change condition, infants saw three R1.14” discs (the same discs as in the Area and Perimeter Change outcome) with the same total area as the two control discs and a 19% increase in perimeter. We considered three to be the familiar number because if infants were likely to form a familiarity preference, it would be for the total number of discs to which they were familiarized. The unexpected numerical outcome of three contrasted with the Unfamiliar Number Change condition, in which infants saw the unexpected numerical outcome of one large R2” disc, which had the same total area as the two control R1.41” discs and the three R1.14” discs. The perimeter of this R2” disc was about 70% of the total perimeter of the control discs (a 30% decrease). The total perimeter change in this condition was larger than in either of the other two non-control conditions. The changes in number, area and perimeter of each outcome are presented in Table 1.

Condition	Number Change	Area Change	Perimeter Change
Control	0	0	0
Area Change	0	-33%	-19%
NumCh1	-1	0	-30%
NumCh3	+1	0	+19%

Table 1. Number change, area change, and perimeter change for Experiment 1 test conditions.

Our outcomes were designed to control for confounds and make specific predictions about how infants tracked the presented sets based on measured looking times. If infants attend to discrete number and form a preference for novel displays, we predict longer looking in the two Number Change conditions. If infants track changes in area, we expect longer looking times only in the Area and Perimeter Change group. As it was impossible to simultaneously equate area and perimeter of the numerical outcomes, our outcomes were designed to allow us to take into account infants' reactions to changes of total perimeter. If infants react to changes in perimeter, we should see longer looking in all non-control groups. More specifically, they should look longest at the Unfamiliar Number Change outcome, which had the greatest change in perimeter. And if infants form a familiarity preference for the total number of objects to which they were familiarized, they would look longest at the Familiar Number Change group. However, it is possible that the infants instead formed a familiarity preference for one of the local sets that they tracked (either the group of one or the group of two). If so, then infants would demonstrate longer looking to either the outcome of one or the outcomes of two.

Materials

The familiarization stimuli consisted of three R1.41" wooden discs. The front of each disc was painted red, and concealed a small weighted wooden base, which allowed each disc to be presented upright and apparently balancing on its edge. The test stimuli consisted of one large R2" disc, and two or three R1.14" discs. These test discs were constructed in the same way as the familiarization discs. Two posterboard screens were also used in the study. These measured approximately 8" tall and 10" wide, and were covered by a 7"x9" blue paper rectangle centered on the front of each screen. Stimuli were presented on a posterboard stage measuring 40.5"W x 19.5"H x 19"D. Infants sat on their parents' laps facing the stage, which was placed 2.5 feet away and at about the infants' eye level. The floor of the stage was covered in blue paper; the back and sides were white. The back of the stage was covered in a lattice of interwoven strips of paper concealing two secret doors, through which surreptitious substitutions could be made. The stage was illuminated by two 40-watt lamps; the room was illuminated by a single dim halogen lamp. A noise machine ran during the experiment to cover up noises made by the experimenter and observers; a metronome beating once a second ensured consistent timing. During the experiment, the experimenter wore two elbow-length white gloves and a string of bells on the right wrist, which was shaken when moving objects around.

Procedure

Infants were first familiarized to three R1.41" discs presented on a posterboard stage. Infants saw the first disc individually lowered onto the center of the stage. As the experimenter lowered each disc, she shook her wrist to attract infants' attention to what was happening on stage. The disc was tapped twice, and then displayed for two seconds as measured by the metronome. A second disc was placed 3 inches away from the first disc, tapped twice, and left there for two seconds. The third disc was placed half an inch away from the second, tapped twice, and displayed for two seconds. The distance between discs created a natural visual grouping of one and two. After all three discs were introduced, each disc was moved individually (always shaken, in order to ring the bells on the experimenter's wrist) to the sides of the stage, maintaining the group of one and two. The group of one disc was always moved first. The discs rested in this final position for 12 seconds and the curtain was raised. Infants saw a total of four familiarizations. Sidedness of the group of one and the group of two varied across familiarizations, to prevent subjects from associating one side of the stage with a particular numerical outcome. On trials one and three, the group of one was placed to the infants' left; on trials two and four, to the infants' right.

At the beginning of all test trials, two screens covered in blue paper were simultaneously lowered onto the stage. The discs were then presented in the same way as during the familiarization trials. As the discs were moved to the sides of the stage, they were placed behind the screen. In trials of the non-control conditions, the experimenter, using the concealed doors, surreptitiously replaced the group of two discs with novel stimuli. In the Familiar Number Change condition, the discs were replaced by three R1.14" discs; in the Unfamiliar Number Change condition, by one R2" disc; in the Area and Perimeter Change condition, by two R1.14" discs. The experimenter then shook her wrist before the screen concealing the group of two discs to attract infants' attention to it, lifted the screen, and said, "Now" to cue a hidden observer to begin timing looking times to the display. The observer was always blind to the test condition. A trial was not considered valid unless the infant looked continuously at the display for at least two seconds. Trials ended when the infant looked away for two seconds. This presentation was repeated for a total of three test trials.

After the experiment was completed, all test trials were blindly rescored by at least one other observer. Original times were used in the data analysis unless the majority of rescorers agreed that the original times were incorrect. In such cases, the first rescore was typically chosen for inclusion in analysis. Rescorer percentage agreement averaged 88%.

Subjects

83 infants (40 girls, age 47-56 weeks, mean age 51 weeks) from the Central New Jersey area were recruited through direct mailing. An additional 39 infants were tested, but excluded from analyses due to fussiness/sleepiness (18), experimenter error (9), equipment failure (8), parental interference (3), and being a statistical outlier (1). Subjects were randomly assigned to one of four conditions, with 20 in the Control condition, 21 in the Area and Perimeter Change condition, 22 in the Unfamiliar Number Change condition, and 20 in the Familiar Number Change condition.

Results

Mean looking times on all three test trials were analyzed in a repeated measures ANOVA with factors Trials (3) x Condition (4). One infant was dropped from the analysis because the full three trials were not completed. There was no significant main effect of Trials and no significant interaction. There was a significant main effect of Condition ($F_{3,78} = 3.45$, $p = 0.02$, $\eta^2 = .117$). Post-hoc Dunnett's *t* for mean looking times averaged across the three test trials revealed that infants in the Unfamiliar Number Change (1) condition looked significantly longer than Control infants ($p = 0.02$). Infants in the Familiar Number Change (3) condition also looked significantly longer than Control infants ($p = 0.005$). Infants in the Area and Perimeter Change group, by contrast, did not look significantly longer than Controls despite changes in both area and contour ($p = 0.16$).

The same pattern of results was found when only first test trial looking times were analyzed. The infant who was dropped from the analyses of the overall mean looking times was included in these first test trial analyses. Again, a significant main effect of Condition was found ($F_{3,79} = 3.04$, $p = 0.03$, $\eta^2 = .104$). Post-hoc Dunnett's *t* revealed that infants in the Unfamiliar Number Change (1) group looked significantly longer than the Control group ($p = 0.03$). Infants in the Familiar Number Change (3) group also looked significantly longer than Controls ($p = 0.02$). Infants in the Area and Perimeter Change group did not look significantly longer than Controls despite changes in both area and contour ($p = 0.43$). Figure 2 shows mean first test trial looking times by condition.

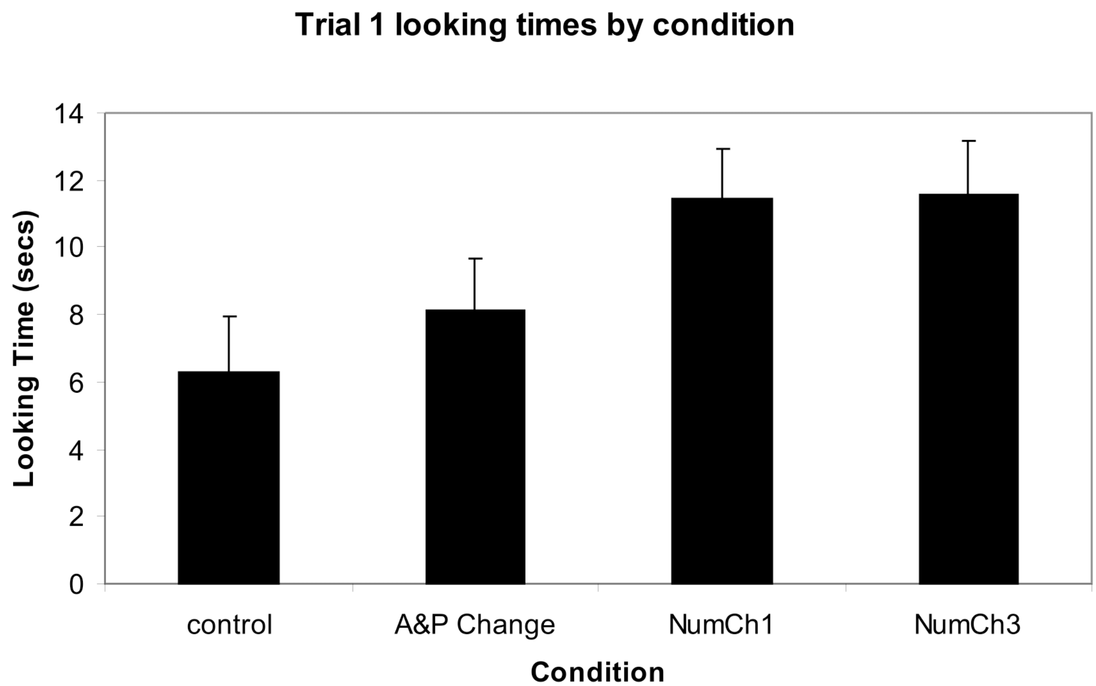

Figure 2. Experiment 1 mean Trial 1 looking times by condition

In planned comparisons, we found no difference in first trial looking to the Familiar and Unfamiliar Number Change conditions ($t_{40} = 0.3$, $p = 0.38$, one-tailed). We therefore collapsed data from these groups (mean 11.8 seconds) and compared them with first trial looking in the Area and Perimeter Change condition. Exploration of this data set indicated severe departures from normality. We therefore examined the data in two ways. First, we entered log transformed looking times into a t-test which showed longer looking in the Number Change condition ($t_{61} = 2.37$, $p = 0.021$, two-tailed). Second, we entered the raw looking times into a non-parametric analysis, which confirmed longer looking to Number Change (Mann-Whitney $U = 281.5$, $z = 2.33$, $p = 0.02$, two-tailed).

Discussion

Infants look longer at both unexpected number outcomes (2 to 1 and 2 to 3). This increase in looking cannot be attributed to changes in continuous extent; the area of the discs in both Number Change conditions equaled the area of the discs in the Control condition. Changes in perimeter also could not account for this result because perimeter changed in all three non-control conditions. In addition, the change in perimeter in the Area and Perimeter Change condition was equal to the change in perimeter in the Familiar Unexpected Number condition. If perimeter change drove longer looking times, infants should have looked equally long at these two conditions, but they did not. Infants also failed to respond on the basis of changes in average area, despite the fact that adults are quite good at estimating and tracking the average size of sets (Chong and Treisman, 2002). We found no similarities in looking times to the Area and Perimeter Change condition and the Familiar Number Change condition, despite the fact that the average disc area was the same in both.

However, it is possible, though unlikely, that the change in continuous quantity (-33%) that we presented was below the threshold that infants can detect, whereas we always showed at least a 50% change in discrete number. When Experiment 1 was designed, infants' competence at detecting changes in continuous quantity had not been established. However, readings of the continuous account of success on number tasks suggested that infants should be able to detect even very small changes in continuous quantity (Clearfield and Mix, 1999; 2001). We now know that at six months, infants can only detect changes in area that are quite large (1:2) and fail when shown a 2:3 change

(Brannon, Lutz and Cordes, 2006). 10-month-old infants should be able to detect a 2:3 change by 10 months (Libertus, Suanda and Brannon, in prep), but our 12-month-olds failed to do so for a 3:2 change. This inconsistency in results could be due to methodological differences. Perhaps three presentations were insufficient for them to detect a change, or the occlusion of the groups behind a screen prevented them from making a successful comparison. Whatever the reason, it is clear that infants should have been able to discriminate the presented changes in continuous quantity and could have used this information to track groups over successive presentations in occlusion, but did not. Another possibility is that this fraction holds only for increases in continuous quantity, not for decreases. However, there is no principled reason to believe that this is the case. We are confident that if presented with even larger changes in continuous quantity, infants could detect them even when pitted against number. However, our goal in this study was to show that infants could attend to and track based on discrete quantity, not to show that infants will detect changes in continuous quantity, which has already been firmly established. Under these circumstances, they do pay attention to discrete number.

The results of Experiment 1 also cannot be attributed to infants' forming a familiar number preference. Our results indicate that unexpected number outcomes were indeed unexpected, and are consistent with a novelty preference for unexpected outcomes. Infants did not appear to form a familiar number preference for the global set (three) or for either of the local sets (one or two). 12-month-old infants do not react to changes in number only on the level of familiarity.

However, one possibility that our design for Experiment 1 did not rule out is that infants simply looked longer when presented with completely novel groups. Perhaps infants did not track the locations of the group of one and the group of two at all, and were satisfied if they saw a group that looked similar to either of the groups to which they were familiarized. Although the Area and Perimeter Change display was novel, perhaps it was insufficiently discriminable from the Control display. Because we did not present infants with an outcome of one single R1.41" disc (i.e., showing them a familiar group not in its expected location), we cannot rule out this possibility. Under this interpretation, infants' looking longer at changes in number could simply be attributed to the infants "matching" the test group with one of the familiarization groups, and looking longer when they found a mismatch. Experiment 2 investigated whether infants actually tracked both groups, and if they formed specific expectations about each group's location.

Experiment 2

Background

Experiment 1 showed that babies looked at changes in discrete number, but did not establish that infants tracked both sets simultaneously or that they formed specific expectations about the location and contents of these sets. We did not add a condition to Experiment 1 in which infants saw an unexpected outcome of one R1.41" disc because such a condition could result in a confound. If we found that infants did look longer at this display, two interpretations would be equally likely – infants might have reacted to unexpected number, or they might have reacted to seeing a familiar group in an unexpected location. Instead, we imposed a more stringent test on whether infants simultaneously tracked both sets.

Design

In Experiment 2, we modified the design of Experiment 1 by removing both screens to show both sets of discs in test trials, rather than lifting just the screen hiding the last-hidden group. In the Control condition, infants saw the expected groups in their expected locations. In the Swap condition, the locations of the expected groups were swapped. Infants should be surprised to see the expected groups swap locations only if they have formed a specific expectation for both the number and location of the items behind the screens. If infants fail to track both groups simultaneously and simply react to seeing an unfamiliar group, they should not look longer at a swap in locations. This design also controls precisely for continuous quantity, as the total area and perimeter of the displays remain identical throughout and across conditions. The design is illustrated in Figure 3. The Control and Swap test conditions are illustrated in Figure 3C.

Apparatus

Same as Experiment 1.

Stimuli

Same as Experiment 1.

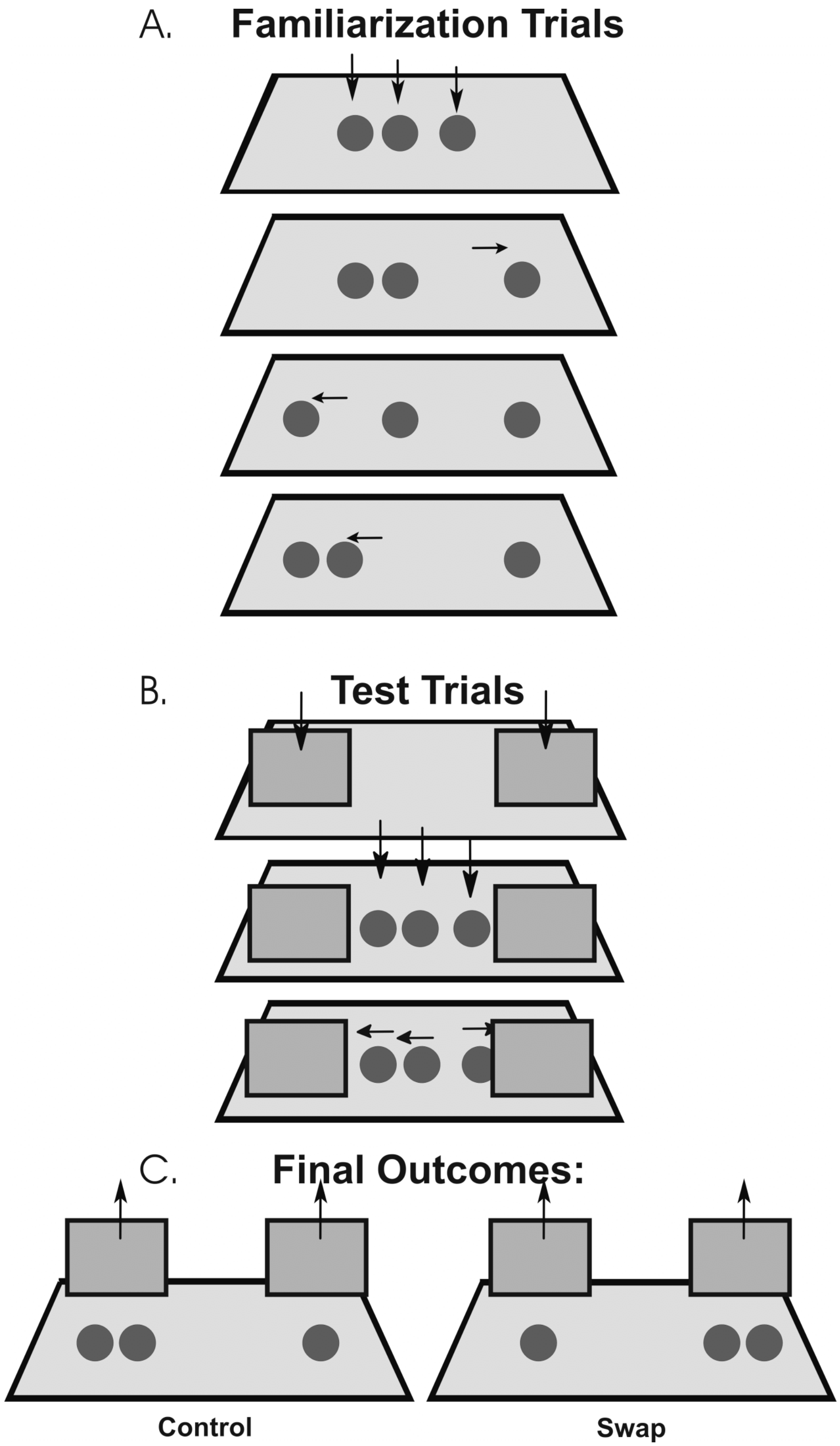

Figure 3. The design of Experiment 2.

Procedure

The familiarizations were the same as in Experiment 1; two test trials followed. Test trials were identical to those in Experiment 1, except that at the end of each test trial, both screens were removed simultaneously to reveal either the Control outcome or the Swap outcome. Infants saw only one outcome in a between-subjects design. Looking time to the display was recorded until the infant looked away for two seconds. Rescorer percentage agreement averaged 86%.

Subjects

24 infants (9 girls, 44 weeks to 57 weeks, mean age 51 weeks, s.d. 3.75 weeks) were tested, with 12 randomly assigned to each condition. A further four infants were excluded for fussing.

Results

Infants in the swap condition looked significantly longer than infants in the control condition (15.54s vs. 7.65s); ANOVA with Condition (2) x Trials (2) showed only a significant effect of Condition ($F_{1, 22} = 6.68$, $p = .017$, $\eta^2 = .23$). There were no other significant main effects or interactions. Figure 4 shows mean looking time results for Experiment 2.

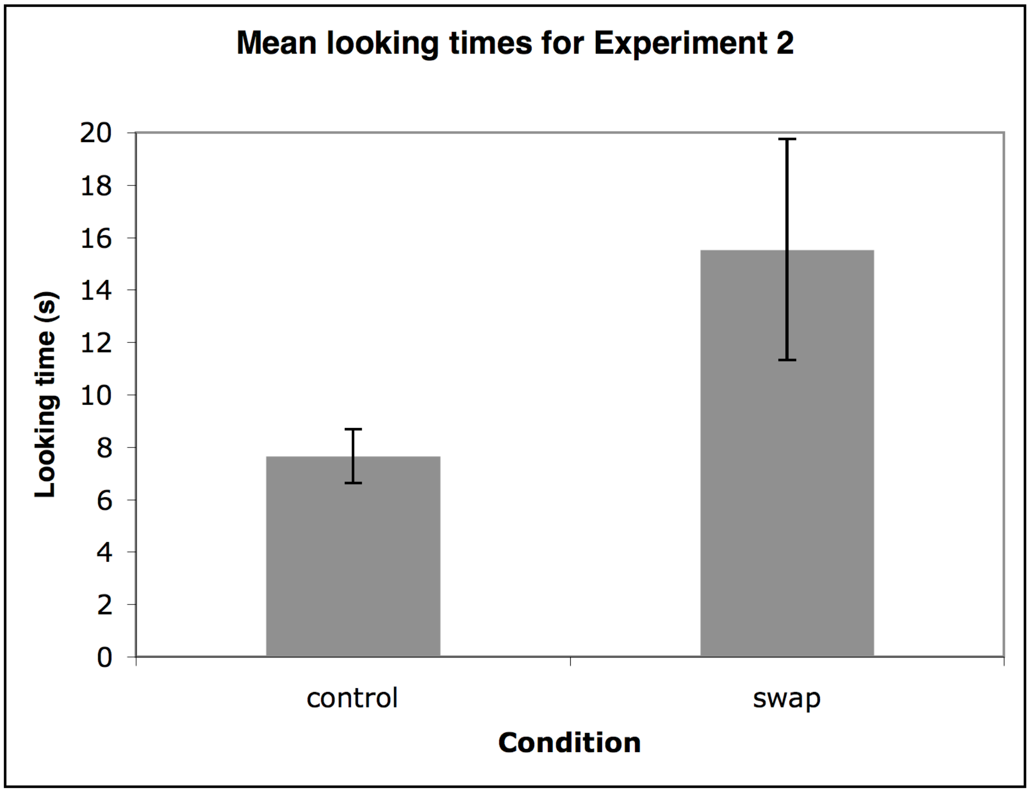

Figure 4. Mean looking times for Experiment 2 by condition.

<u>Discussion</u>

Experiment 2 confirmed that infants tested using the two-screen methodology do track sets on a trial-by-trial basis. Infants not only encoded the discrete numerosity of each set, they also used number to track the sets' locations, looking longer only when groups unexpectedly swapped sides. If infants did not simultaneously track both sets, but instead represented the occluded groups as simply "a group of one and a group of two" (or some other representation to that effect) and formed no specific expectations about where each should be, they would not have looked longer at a swap outcome. The results of Experiment 2 suggest that it is unlikely that infants in Experiment 1 simply looked longer when shown completely novel displays, as they also look longer when familiar groups appeared in unexpected locations.

<u>General Discussion</u>

The ability of infants to detect changes in the continuous variables of displays has been well established (Clearfield and Mix, 1999; 2001; Feigenson, Carey and Hauser, 2002; Feigenson, 2005). The results of Experiment 1 and 2 show that by the end of the first year of life, infants can also attend to and represent the discrete properties of occluded sets. They do so even when they could track sets based on continuous variables such as area and perimeter; they also do not form a familiarity preference for number. At twelve months, infants have access to both continuous and discrete representations and may use whichever is most appropriate to the task at hand. Experiment 3 extends our findings to even younger infants, nine-month-olds.

Because of the heterogeneity of the paradigms used and populations involved in number research, it can be difficult to reconcile the many conflicting results in the field. The studies most relevant to the work presented here utilize the graham cracker task developed by Feigenson, Carey and Hauser (2002). As in our studies, Feigenson and her colleagues tested 10- and 12-month-old infants on their ability to track two occluded sets (in their case, a quantity of graham crackers hidden in two pots). Our study utilized looking time at wooden disks as the dependent variable; Feigenson and her colleagues gave babies one trial to crawl to their preferred location to select a quantity of crackers. As discussed in Chapter 1, infants in Feigenson's study chose pots on the basis of continuous quantity (with one exception), while we found evidence that they attended to discrete number. What accounts for the discrepancy in these results? It seems likely that infants foraging for food would seek to maximize the amount of food given to them as a reward, explaining why they always chose based on continuous quantity even when it conflicted with discrete number (i.e. one very large cracker vs. 2 very small ones). However, Feigenson et al's (2002) results do not mean that infants fail to attend to discrete number – just that they are not foolish scavengers. Choosing a smaller amount of food simply because it is contained in a larger number of discrete items makes little ecological sense. Perhaps, also, infants attend to total amount over discrete number because they understand that numerosity can be altered, for example in breaking events. Number therefore does not provide a reliable cue to total amount (Cheries, Mitroff, Wynn and Scholl, in press).

By contrast, tracking the identity of displays across successive presentations may highlight the discrete properties of sets, and infants may choose to represent objects in these groups discretely. In our task, infants must decide whether the group of objects they see when a screen is lifted is identical to the one that went behind it. They could do so based on the total number of objects they saw go behind the screen, or they could do so based on the total amount of stuff they saw hidden. Furthermore, they must remember which of two familiar sets they most recently saw hidden in a particular location. Actively attending to the groups' locations may increase the likelihood that infants respond based on discrete number, possibly because discrete quantity representations for such small numbers are less variable and therefore more robust when tracking objects through occlusion events, as opposed to continuous representations, which, due to infants' relatively poor ability to discriminate differences in continuous amount (Brannon et al., 2006), may be less reliable sources of information in tracking tasks. Although Brannon and her colleagues argue that infants utilize the same Weber fraction to discriminate discrete and continuous quantities, we found evidence that they could discriminate a 2:3 increase in discrete quantity, while ignoring a 3:2 decrease in continuous quantity. Our results also show strong continuity with evidence from older children's (from two and a half to five years of age) ability to detect transformations in arrays of number (Bullock and Gelman, 1977; Gelman, 1972; Gelman and Gallistel, 1978). Children were first shown two plates with a number of toys placed on them (one plate designated "the winner", the other designated "the loser"), which were then covered and shuffled around. In other words, children were asked to track two sets of objects, either 2 vs. 3 or 3 vs. 5, just as our infants were. The children were then asked to select the "winner" plate, and were allowed to look at the other plate if they chose incorrectly. Even very young children were quite effective at detecting if a change had been made to the number of items on the winner plate, while ignoring changes to other dimensions, such as length, color, identity of the objects, and density, as irrelevant.

Another possibility is that infants utilize an attentional tracking mechanism that helps them attend to discrete number without resorting to number concepts. This mechanism allows them to individuate up to three objects concurrently (Scholl and Leslie, 1999). If infants can only resort to this mechanism when asked to attend to discrete quantity (Huntley-Fenner et al., 2002), then they should rely on continuous variables when required to track more than three objects. This set size limitation has been amply demonstrated in the literature (Feigenson and Carey, 2003; Feigenson and Halberda, 2004), although as discussed in Chapter 1, appears to hold only for local sets and not for global sets. However, the results of Experiments 1 and 2 do not allow us to distinguish between these two possibilities. In both experiments infants tracked a total of three objects – below the threshold (Scholl and Leslie, 1999). In other words, just because infants in our study respond on the basis of discrete quantity does not mean that they are responding on the basis of numerosity. Experiment 4 explores whether infants' discrete number abilities can be attributed merely to attention or indexing limits by upping the number of objects which infants are required to track. Experiment 4 takes as its starting point the ability of infants to individuate single objects (Tremoulet et al., 2000), and investigates whether infants can individuate across *pairs* of objects. In addition, Experiment 4 supports and extends the findings of Feigenson and Halberda (2004) that infants can overcome the set size limitation under certain circumstances.

Chapter Three

Experiment 3: Nine-month-olds' representations of small sets

Experiment 3

Background

Experiments 1 and 2 indicated that by 12 months, infants simultaneously track the discrete properties of two sets of objects. Are nine-month-olds also able to track discrete number? While nine-month-olds have been shown to discriminate between large numbers at a ratio of 2:3, relatively little is known about their ability to track discrete quantity for the small number range, as they fall right in between the two age groups typically tested in number studies (six to seven months, and ten to twelve months). Do nine-month-old infants show the same limitations on tracking discrete number as the six- and seven-month-olds (Feigenson, Carey and Spelke, 2002), or have they already begun to show some of the capability to track discrete number displayed by the older infants (Strauss and Curtiss, 1981; Feigenson, Carey and Hauser, 2002; Feigenson and Halberda, 2004)?

We used the design of Experiment 1 to investigate this question. Evidence from working memory studies show that by about 10 months of age, infants show the same capacity for visual short-term memory as 12-month-olds (Ross-Sheehy et al. 2003), suggesting that tracking three objects should be well within the capabilities of infants at this age. In addition, the two-screen methodology has been used successfully with nine-month-olds on studies of identification based on shape (Kaldy and Leslie, 2003). In this study, infants were familiarized to a single disc and a single triangle placed on opposite sides of a stage.

During test trials, the shapes were hidden behind separate screens, and one of the screens lifted to reveal the hidden object. Infants looked longer when the object unexpectedly changed shape, but not when it unexpectedly changed color, suggesting that infants use shape, but not color, to identify objects by nine months of age. However, the nine-month-olds differed from the 12-month-olds in one particular way: because of the trial-by-trial nature of this methodology, the younger infants typically do not detect changes in displays on the first trial, requiring at least two and sometimes three trials before they notice a change.

Methods

Design

The design of the study was identical to that of Experiment 1.

Materials

Same as Experiment 1.

Procedure

Same as Experiment 1. Rescorer percentage agreement for Experiment 3 averaged 83%.

Subjects

36 infants (15 girls, 34 weeks to 44 weeks, mean age 39 weeks, s.d. 2.43 weeks) were recruited via direct mailing from the Central New Jersey area. Infants were randomly assigned to one of four conditions - 10 in the Control condition, 9 in the Area and

Perimeter Change condition, 8 in the Familiar Number Change condition, and 9 in the Unfamiliar Number Change condition. An additional 12 subjects were tested, but excluded for equipment failure (5), fussing (4), experimenter error (2), and parental interference (1).

Results

Figure 5 displays mean looking times across trials for nine-month-olds.

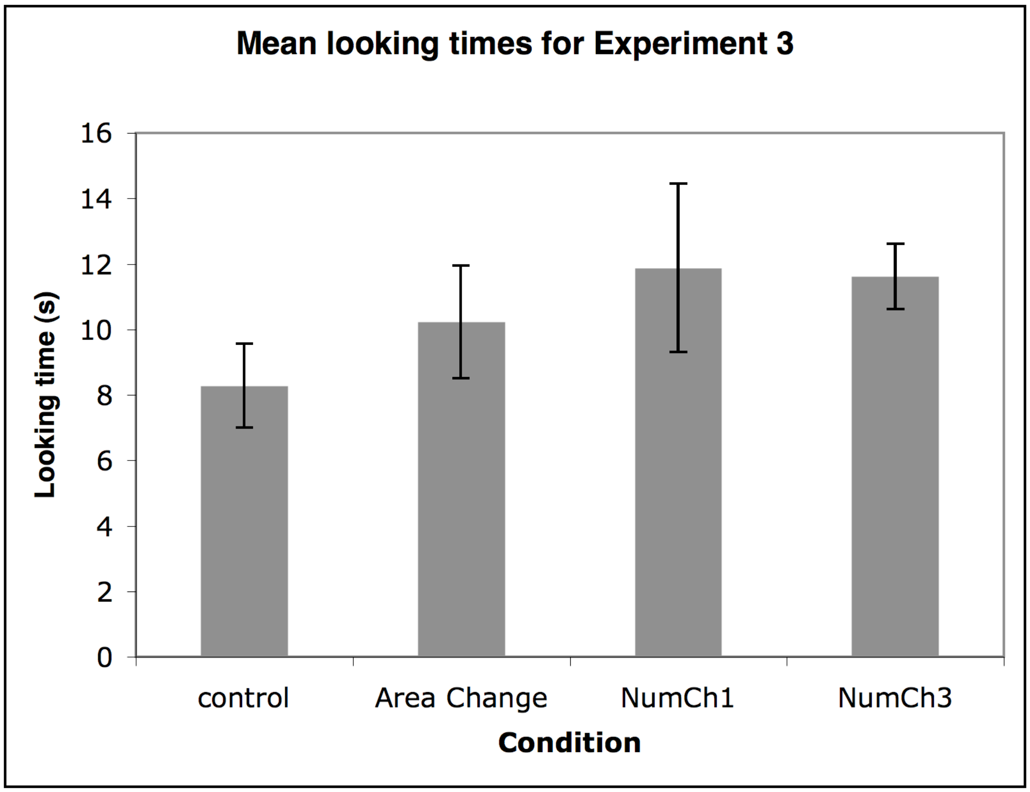

Figure 5. Mean looking times for Experiment 3.

Exploration of the data identified 3 outliers who were eliminated from analyses. One-way ANOVA on Condition (4) found $F_{3, 29} = 2.135$, $p < .12$, $\eta^2 = .18$. Observed power was low at .49 at $\alpha = .05$. Post-hoc analyses with Dunnett's *t* showed significantly longer looking than controls only for the Familiar Number Change group ($p = .042$). Planned comparison collapsing the two No Number change groups and the two Number Change groups showed significantly longer looking in Number Change groups (7.88 s vs. 10.05, $t_{31} = 1.71$, $p = .048$, one-tailed).

Discussion

Infants do not respond solely on the basis of continuous quantity at nine months, because infants in the Area and Perimeter Change condition do not look significantly longer than infants in the Controls. This failure to respond based on area could be due to the fact that our infants may simply be too young to detect the relatively small amount of continuous change presented in our displays. However, infants also do not seem to be responding solely on the basis of discrete quantity, as they look longer only at a change in number from two to three, but fail to look longer at a change from two to one. It is possible, however, that our sample size was too small for us to be confident, given the low observed power. Planned comparison suggested that while an effect of Number Change may be confirmed with a larger sample, our current results suggest that we can be confident only that infants of this age respond to a 2 vs. 3 comparison. The failure of nine-month-olds in our study to detect a surreptitious replacement of two smaller discs with one large discs is consistent with the results of Feigenson, Carey and Spelke's (2002) replication of Wynn's 1+1=2 study, in which they found that seven-month-old infants did not look longer when two small dolls were placed behind a screen and the screen lifted to show one large doll. However, Li, Baillargeon and Leslie (2007) found that infants do detect the change in number, but that the change in continuous extent has a bigger effect on looking times; our results point to a similar phenomenon.

The results of Experiment 3 suggest that if nine-month-old infants represent discrete properties of occluded sets of objects, these representations are far more fragile than those of 12-month-olds. It is possible that our infants were insufficiently familiarized to the displays by the time test trials began and that their looking expressed a preference for a globally familiar number of 3 discs. Adding trials in the familiarization and the test phases, in addition to adding subjects, might be required by this age group in a two-screen methodology applied to number. However, invoking familiarity as the reason for longer looking in this condition seems unlikely given that infants only begin to look longer at the outcome of three on the third trial (vs. controls, $t_{15} = 2.42$, $p = .029$, two-tailed). On trials 1 and 2, there are no significant differences between looking times in these conditions. If infants are reacting based on familiarity, one would expect to find longer looking on even earlier trials. Alternatively, infants at this age may not be able to track on a trial-by-trial basis the locations of a set of one and a set of two objects simultaneously. It might be that our infants did not know which screen the set of two and the set of one were behind on a given trial but did know that neither screen hid three objects. Recall that we found that, even in the case of 2 vs. 3, our infants were surprised only by the third test trial. Kaldy and Leslie (2003) found that their infants were surprised by a shape swap only by the second test trial and suggested that with the trial by trial alternation infants may take some time to become alerted to violations: they have first to become “suspicious” following the outcome of the previous trial before they pay close enough attention to the start of the next trial to note exactly what went behind which screen and thus be able to detect a violation when the screen is removed.

If tracking difficulties imposed by the two-screen methodology are to blame, switching to a single-screen with alternating-trials methodology (Kaldy & Leslie, 2005) might yield different results. In this design infants would be familiarized with a single set of objects on stage in any one trial, but the size of the set would alternate from trial to trial. Thus, on familiarization trial one, infants might see a single disc followed on trial two by two discs, trial three one disc, and so on throughout familiarization trials. On test trials the alternation is continued but now a screen is first placed on stage and after introducing the disc or discs they are moved behind the screen. When the screen is removed it can reveal either the for-that-trial expected number or the for-that-trial unexpected number. Kaldy & Leslie (2005) found that infants of 6 months found the single screen alternation task easier than its two-screen counterpart.

However, our results do contain several points of interest. While we cannot completely rule out that infants at this age will respond solely on the basis of continuous quantity (because of the relatively small change in continuous quantity), it seems possible that at nine-month-old infants begin to attend to changes in discrete quantity information. Infants look significantly longer at the Familiar Number Change condition, and slightly (though not significantly) longer in the Unfamiliar Number Change condition. By trial three, infants in the Unfamiliar Number Change condition are looking, on average, 14.68 seconds (vs. 6.95 seconds on trial 3 for the control group). This difference is not significant due to high variability in looks to the Unfamiliar Number Change display on the third trial.

Figure 6 shows looking times for all three trials split by conditions.

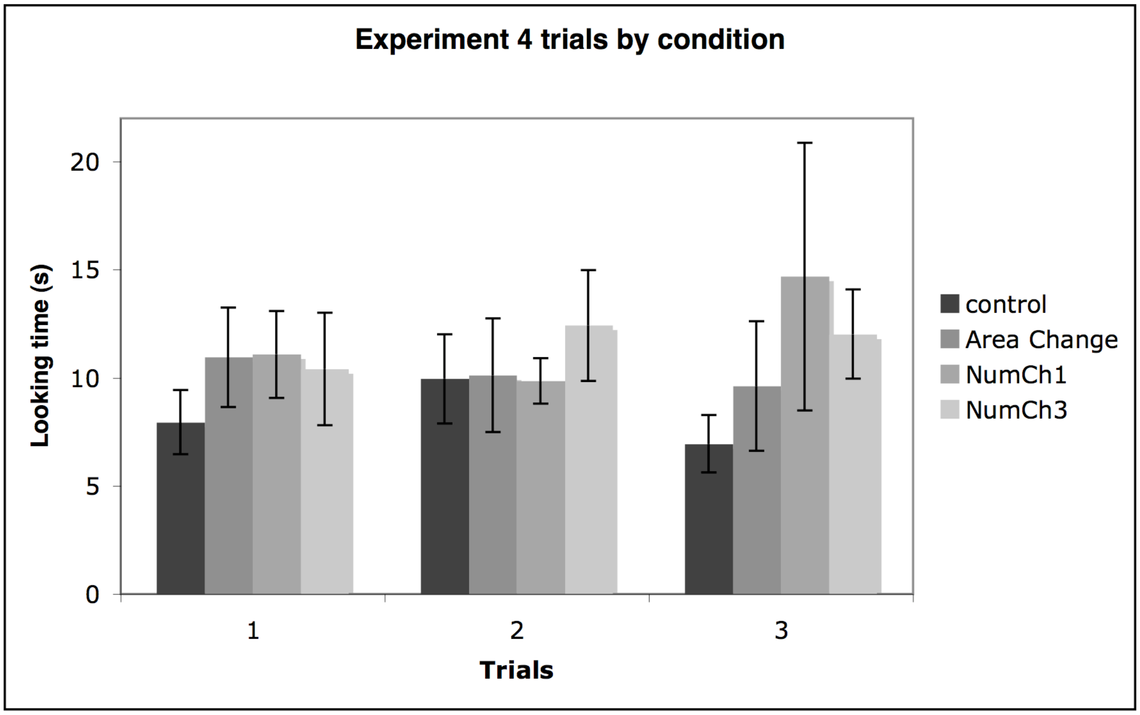

Figure 6. Nine-month-old looking times across trials by condition.

However, it is puzzling that the nine-month-olds notice a number change of two to three but not a change of two to one, just as Feigenson, Carey and Spelke's (2002) seven-month-olds failed to notice a change of two to one. As we have discussed, there are several possible explanations. The first was that nine-month-olds, unlike 12-month-olds, are susceptible to forming a preference for familiar number (Cohen and Marks, 2002), based on global set size. If infants were insufficiently familiarized to the displays, they may not exhibit the novelty preference demonstrated by the 12-month-olds. While this explanation seems unlikely, as such an interpretation does not account for why infants only begin to display a familiarity preference on the third test trial, it cannot be ruled out. Alternatively, infants may simply need more exposures to detect changes in number.

While they detected shape changes on the second trial (Kaldy and Leslie, 2003), perhaps their ability to track number lags behind. Another possibility is that infants looked longer simply because there were more objects to look at. Even the 12-month-old infants looked slightly longer at the outcome of three than at the outcome of one (although this difference was not significant).

We believe the most likely explanation is that infants do know that they are tracking three objects, in a group of one and a group of two. However, they are unable to track the changing locations of these groups simultaneously, and therefore do not form an expectation about the specific location of either group at any time. In other words, they make no specific prediction about which group they should see when the screen is lifted, as long as the number of objects matches the number of one of the groups to which they were familiarized. Their failure to react when shown either a group of one or a group of two (regardless of individual size of the discs) contrasts with their longer looking when they see what appears to be all three of the discs on one side, an impossible result.

Further methodological adjustments to the number of familiarization and test trials might yield clearer results. A single screen study showing infants successive presentations of a group of one and a group of two, such as the one described above, should eliminate any possibility of a familiarity preference for a group of three; infants should not form a familiarity preference for three if they never see three discs simultaneously. A swap study using the design of Experiment 2 would establish whether or not infants at this age track both groups simultaneously. A failure to do so would lend strength to our assertion that infants know they are tracking three objects, but do not form specific expectations as to their locations.

Our results suggest that infants at nine months of age have begun to detect changes in discrete quantity. However, their representations of discrete quantity remain fragile. In particular, their success at detecting changes of two to three coupled with their failure to look significantly longer when presented with a change of two to one suggests that at this age, infants' ability to discretize sets still rests at this age on attentional mechanisms, or suffers from interference from such mechanisms.

Chapter Four

Experiment 4: 12-month-olds' individuation by pairs

Experiment 4

Background

Experiments 1 and 2 showed that by 12 months, infants simultaneously keep track of a group of one and a group of two, for a total of three objects. Experiment 4 investigates whether they can keep track of two groups of two, for a total of four objects. Several studies have found that infants display a set size limitation for sets of four or more objects (Feigenson, Carey and Hauser, 2002; Feigenson and Halberda, 2004). However, Feigenson and Halberda (2004) found that "chunking" a display of four objects into two simultaneously-presented groups of two objects aided 14-month-olds in searching successfully for four objects. Can infants do the same for sequentially-presented groups of distinct objects? Can younger infants form expectations of two pairs of objects if looking-time methods are used?

We took as our starting point the shape identification studies of Tremoulet, Leslie and Hall (2000). In this study, twelve-month-old infants were tested on whether they could use shape to individuate and identify how many objects were behind a screen. Infants saw two objects (a disc and a triangle) presented sequentially from behind a screen; the two objects were never seen together. Infants were then tested on the control outcome of a disc and a triangle, or on test outcomes of two discs or two triangles. If infants used shape only to individuate the presented items, then they should be satisfied to see any outcome of two objects. If infants used shape to identify as well as individuate presented items, they should look longer at an outcome of two identical objects. Tremoulet et al. found that infants looked longer at the unexpected outcome of two identical items, suggesting that infants used shape information to both individuate and identify objects. In other words, infants individuated objects because they recognized that they saw two distinct shapes, and used that information to form an expectation that there should be at least two shapes behind the screen. They also identified the objects using shape information because not only did they expect to see two things behind the screen, they had specific expectations about which objects they should see. We wanted to see if infants could extend this ability over pairs of objects.

In a preliminary study (Leslie and Chen, 2007; experiment 1), we showed infants pairs of objects to see if they would form expectations based on how many things they should see. In the XX/YY familiarization condition, infants were familiarized to two homogeneous pairs of objects. In this condition, infants saw two of the same object (either two discs or two triangles) being brought out behind the screen one at a time, and displayed together for two seconds. The pair was then returned behind the screen, and the other pair brought out in the same way. Infants never saw both shapes displayed together. First-presented shape varied across familiarization trials and across subjects. If infants realized that they saw two distinct pairs of shapes, they should expect to see two distinct pairs when the screen was lifted, a total of four objects. In the XY/XY familiarization condition, infants were familiarized to two heterogeneous pairs, each consisting of a disc and a triangle. In this condition, infants saw first one shape being brought out behind a screen, followed by the second shape. Both shapes were displayed together for 2 seconds and then returned behind the screen. The two shapes were then brought again, one at a time, in the reverse order. Again, first-presented shape varied across familiarization trials and across subjects. Although the displays appeared to observers to be simply the same (single) pair of shapes again, infants actually saw two distinct XY pairs. However, they should only expect to see a single disc and a single triangle when the screen was lifted, and should be surprised to see two discs and two triangles. Subjects in both familiarization conditions were shown the same displays in the test trials – one of two configurations made up of two discs and two triangles together (XXYY or XYXY). Leslie and Chen (2007) found that infants in the XX/YY familiarization condition did not look longer, suggesting that they were able to individuate across pairs and correctly predict that they would see four items, or at least two pairs, when the screen was lifted. However, infants in the XY/XY familiarization did look longer, suggesting that they expected to see only two objects, and were surprised to see more shapes than they expected. The design of this preliminary study is illustrated in Figure 7.

Experiment 4 extended the results of Leslie and Chen (2007; experiment 1) by testing infants on a simplified test display. In order to confirm the results from the previous study, we familiarized infants to the same two conditions, XX/YY and XY/XY. During test trials, infants saw a display of only two items – a single disc and triangle pair. This new outcome should reverse the expectations of the previous study – infants in the XY/XY condition should now expect to see the test outcome, and should not look longer, while infants in the XX/YY condition, if expecting two distinct pairs of items, should now look longer at an unexpected display of only two objects.

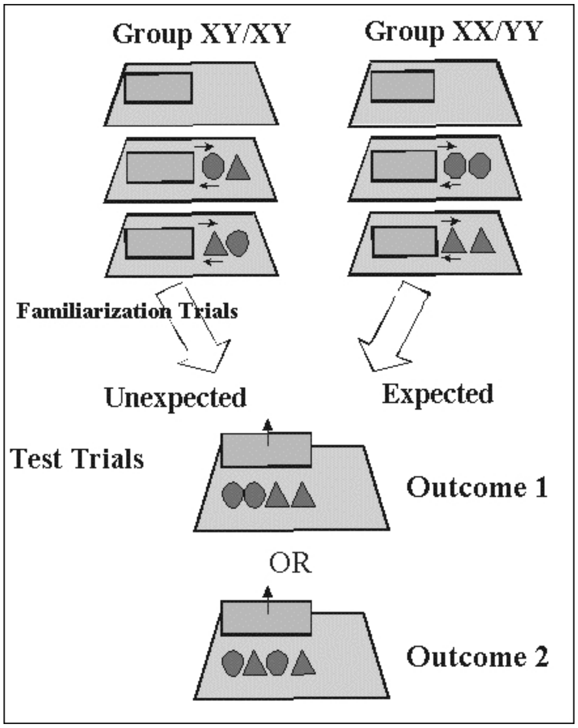

Figure 7. The design of Leslie and Chen (2007; experiment 1). The figure is drawn from the perspective of the experimenter.

Method

Design

The design of Experiment 4 is illustrated in Figure 8. This design is modeled after Leslie and Chen (2007; experiment 1) but simplifies the test outcomes to reverse looking-time expectations.

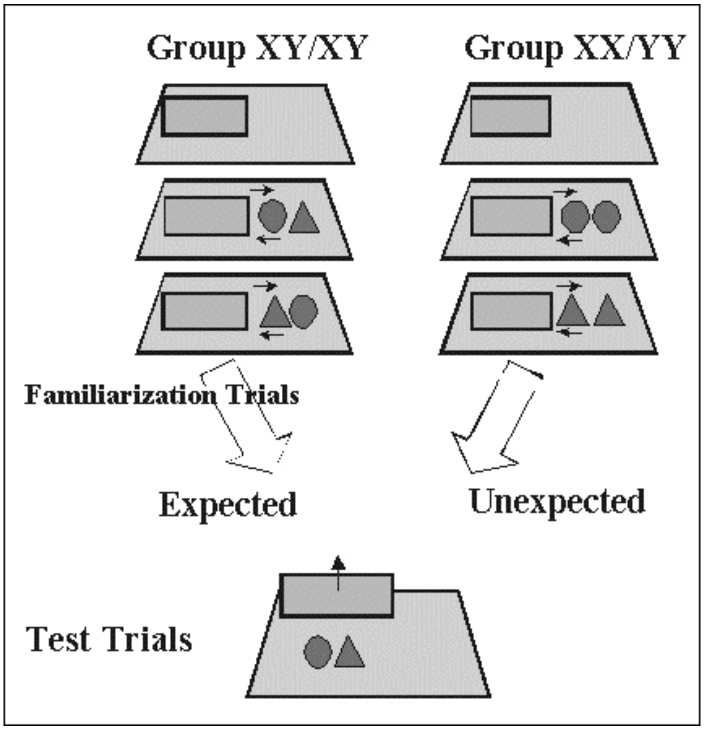

Figure 8. The design of Experiment 4.

In a between-subjects design, we familiarized infants to one of two conditions. In the XX/YY condition, infants saw a pair of identical shapes (either discs or triangles) brought out from behind a screen and displayed for two seconds. The pair was then returned behind the screen and a different pair of identical objects (whichever pair was not brought out the first time) was then brought out, displayed for two seconds and returned behind the screen. The sequence was repeated to complete one familiarization trial. In the XY/XY condition, infants saw a mixed pair of shapes – one disc and one triangle – brought out from behind a screen and displayed for two seconds. The pair was then returned behind the screen, and a different pair of a disc and a triangle was brought out in the reverse order of the first mixed pair (in other words, if the first pair was displayed in the order disc-triangle, the second pair was displayed in the order triangle-disc), displayed for two seconds, and then returned behind the screen.

Infants in both conditions saw a total of four familiarization trials; first-presented shape in both conditions varied across trials and subjects. All infants, regardless of familiarization condition, saw the same test condition – a pair made up of a single disc and a single triangle. The infants who were familiarized to the XX/YY condition were therefore the Unexpected Pairs condition – they should look longer at an outcome of only two discs if they detected two distinct pairs in the familiarization condition. The infants were familiarized to the XY/XY condition were the Expected Pairs condition, and should not look longer, as the test display of one disc and one triangle should be consistent with their representation of the objects behind the screen.

Materials

The materials consisted of two wooden discs, 10.5 cm in diameter, and two wooden triangles, 11.5 cm high and 10.5 cm at the base. All were painted red. Items were presented from behind a screen 21 cm high x 48 cm wide on a stage 55 cm high, 90 cm wide, and 45 cm deep. The stage was illuminated by two 40-watt bulbs; both the stage and screen were constructed from white posterboard. The screen was covered in a blue paper rectangle. The back of the stage was constructed so that the experimenter could reach through it to manipulate objects on the stage through a slit concealed by white elastic cloth. The slit ran the entire width of the stage. The experimenter wore white elbow-length gloves when presenting objects.

Procedure

Familiarization trials began when the experimenter lowered a curtain covering the stage and signaled to the observer to turn on the lights illuminating the stage. In the initial display, infants saw just the posterboard screen sitting in the center of the stage. The experimenter then began to remove objects from behind the screen, always to the infants' left. Each object was moved one at a time, tapped twice on the stage, and then displayed for two seconds. Infants saw objects presented together for two seconds, before being replaced behind the screen in order of appearance. A second pair of objects was then brought out and presented in the same way. These presentations were repeated to complete the familiarization trial; infants saw each pair presented twice in a familiarization. In the XX/YY condition, infants first saw a XX/YY familiarization trial, followed by a YY/XX familiarization trial. These two trials were repeated for a total of four trials. In the XY/XY condition, infants first saw a XY/YX familiarization trial, followed by a YX/XY familiarization trial. These two trials were also repeated for a total of four trials. Thus the first-presented object was counterbalanced across familiarizations. In addition, the first-presented object was counterbalanced across subjects in each condition. In both conditions, infants actually saw two distinct pairs, although in the XY/XY condition it appeared that they only saw one identical pair presented in different orders. However, two pairs of objects were used to ensure that the mechanics of presentation were identical across conditions.

During test trials, infants saw the objects presented as in their familiarization trial – a XX display followed by a YY display for the XX/YY condition infants, a XY display followed by a YX display for the XY/XY condition infants. In both conditions, the experimenter surreptitiously placed one disc and one triangle on the ledge of the screen, and then shook her left wrist, wearing a string of bells, in front of the screen to attract the infants' attention to the display. She then raised the screen, showing infants a single disc and a triangle. A hidden observer, blind to condition, began timing the infants' looking at the display once the screen was lifted. A trial continued until the infant looked away for more than two seconds. Infants had to look at the display for at least two seconds in order for the trial to be recorded. When the infant looked away for more than two seconds, the stage lights went dark, and the experimenter drew up the curtain to conceal the stage. Two more test trials were given for a total of three trials. The arrangement of the disc and triangle varied across presentations, and were based on which item was presented first. If the first-presented object was a disc, then the disc was presented to the infants' left and the triangle to the infants' right, and vice-versa if the first-presented object was the triangle. After the experiment was completed, all test trials were blindly rescored by at least one other observer. The percentage agreement averaged 79%. In cases of large discrepancy, differences were resolved by a third scorer.

Subjects

24 infants (43-57 weeks, mean age 50 weeks, s.d. 4.3 weeks, 10 females) were randomly assigned to one of two conditions, with 12 in each condition. An additional five subjects

were tested, but not included in the data analysis due to fussing (3), equipment failure (1), and being distracted (1).

Results

First, in order to determine that infants displayed no baseline looking preference between the different familiarization conditions, we recorded the average total looking times during familiarization trials for all subjects from the taped sessions. One subject's videotape was not included due to equipment malfunction. We found no significant difference in baseline looking times during familiarization between conditions (XX/YY = 37.2 s, SD = 3.4, XY/XY = 35.0 s, SD = 2.8, $t_{21} = 1.65$, $p = .113$, two-tailed), indicating that infants did not find either the XX/YY or XY/XY displays intrinsically more interesting. These baseline looking times were consistent with those from the preliminary study.

Test trial looking times were converted to log form for analysis to correct for rightward skew. Repeated measures ANOVA with factors Trials (3) x Pairs (2) (XX/YY or XY/XY) and Sex (2) found no significant main effect of Trials or Sex. There were no significant interactions. There was a significant main effect of Pairs ($F_{1,23} = 8.3$, $p = .009$, $\eta^2 = .29$). Planned comparisons on first trial looking times showed that infants in the XX/YY condition looked longer (13.4, SE*M* = 1.8) than infants in the XY/XY condition (7.4 s, SE*M* = 0.9). This difference was significant ($t_{22} = 2.61$, $p = .008$, one-tailed). Mean looking times for Experiment 4 are shown in Figure 9.

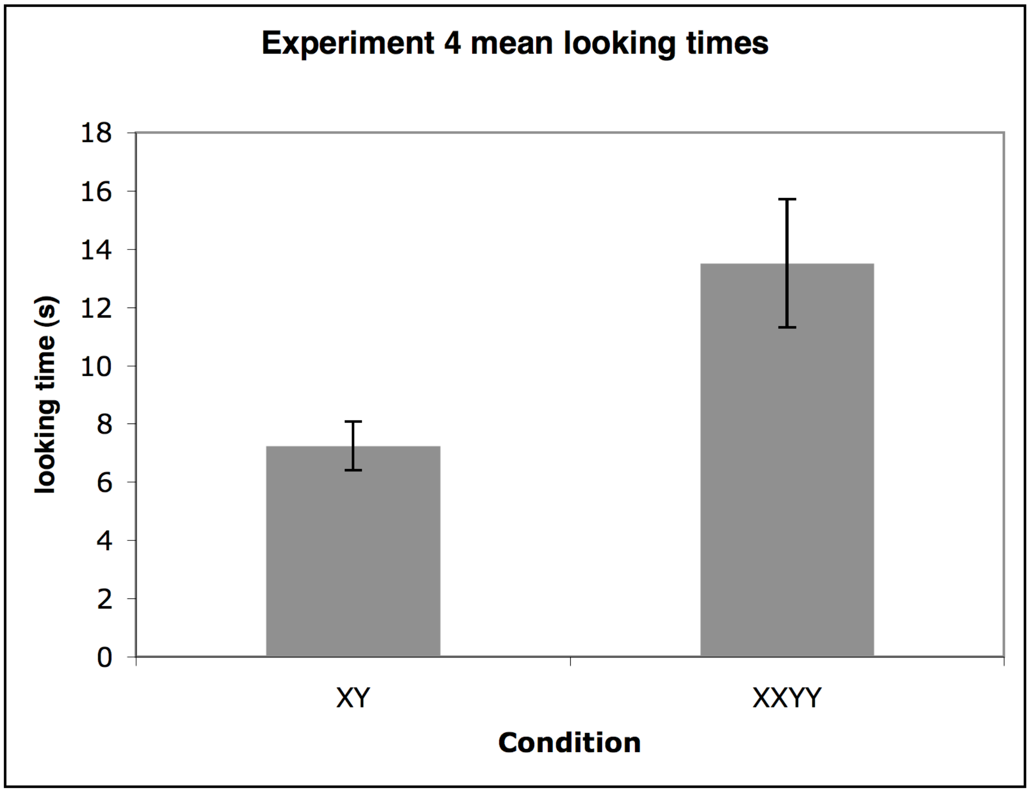

Figure 9. Mean looking times by condition for Experiment 4.

Discussion

The results of Experiment 4 support the idea that 12-month-old infants are able to use shape information to individuate across sequential presentations of pairs of objects. Infants who are shown two distinct pairs use that information to form an expectation that they will see a total of four objects behind the screen; when this expectation is not fulfilled, they are surprised and look longer. However infants who see two mixed pairs do not individuate across the displays; they expect to see only two items behind the screen and look longer only when this expectation is violated. Our results converge with and extend those of Feigenson and Halberda (2004), who used a reaching paradigm to show that 14-month-old infants succeeded at searching for four objects only when those objects were broken up into two simultaneously-presented spatiotemporally distinct “chunks” of two objects. We found that even younger infants can perform much the same task but with sequential presentations, using a looking-time task.

How did infants succeed in this task? Infants could not have indexed each individual object, because they have only three indexes available in total (Scholl and Leslie, 1999). Nor could infants have succeeded simply by assigning an index to each set without also forming a specific representation of what was indexed. Because the index is agnostic, infants could only make comparisons on the basis of the information contained in the object representation. Infants might have used continuous quantity information to succeed, but this explanation seems unlikely given that they made their judgments based on specific shape information. In addition, a simple explanation on the basis of continuous quantity fails to explain why Feigenson and Halberda's (2004) 14-month-olds apparently could not use the total continuous amount of hidden toy to guide successful search. Ruling out continuous quantity leaves the alternative that infants had to make the comparison based on discrete quantity, exactly the kind of explanation object indexing has been proposed to avert.

Infants, then, could only have succeeded on our task in one of two ways. One possibility is that infants simply counted the number of objects that they saw across trials and summed up a total number across presentations. In other words, the XX/YY infants detected that they saw two objects in one presentation and another two objects in the next presentation. Unable to form simultaneous indexes for all of the presented objects, on subsequent presentations they counted the total number of objects in the display, summed across them, and expected to see 2+2 objects when the screen lifted. Infants may not necessarily have formed a specific expectation for “4”; rather, they may simply have realized that 2+2 should equal something more than 2, and looked longer on that basis.

Alternatively, infants may have formed some kind of set representation for the pair that provided the basis for comparisons across presentations – rather than expecting 2+2=4, perhaps they expected that a pair + another pair should add up to more than one pair. What might such a set representation look like? Feigenson and Halberda (2004) suggest that by “chunking” the groups presented to their infants, they lowered the cost of representing more objects than could be concurrently represented by object indexes. By binding these representations into two sets, infants can exceed the “hard and fast” set size limitation. However, Feigenson and Halberda refused to commit to a description of how sets are represented.

LeCorre and Carey (in press) propose that infants form sets consisting of a non-numerical summary representation of the individuals in the set; while these sets are not numerical, infants can compare the items within the set to each other or to objects in the real world using one-to-one correspondence. LeCorre and Carey’s model offers a good explanation for success on tasks such as the graham cracker task, in which infants must choose between two sets on the basis of size, but is not explicitly formulated to deal with tasks such as ours, which require infants to compare multiple sets in memory not to *each other*, but rather to a displayed set. Similarly, Feigenson and Halberda’s task requires infants to compare items extracted from the box with items stored in their memory. In principle, LeCorre and Carey's model can be flexible enough to account for how infants can simultaneously hold two distinct sets in their long-term memory and compare the items in both sets to items in the real world. However, their model does not provide predictions for what infants should do in this case.

Although our results do not necessarily conflict with their model, one must question how many sets this system can represent in parallel, and what kinds of comparisons that can be made between them. What are the limits on the power of their model? How many different sets infants can hold in memory, and what limits this number? In addition, long-term memory should not be subject to capacity limits, and yet LeCorre and Carey explicitly limit the number of individuals per set to three. As discussed in Chapter 1, this threshold is an arbitrary one from the point of view of number and is presumably imposed by working memory or attentional limitations. Studies of adult visual short-term memory find a trade-off between the complexity of the objects being represented in memory and the capacity of short-term memory (Xu and Chun, 2006). One might expect that such a bottleneck at the level of short-term memory might affect representations in long-term memory, especially for infants. However, the theory is inappropriately vague about the representations of individuals at the set level. What information gets sacrificed in order to store information in memory? LeCorre and Carey's model can be extended to provide an explanation for any data, yet is vague enough that it is hard to derive clear predictions regarding the abilities of 12-month-olds.

Another possible explanation for how infants succeed comes from the third core endowment offered by LeCorre and Carey – the "set-based quantification" ability that allows infants to form representations of the kinds of sets described by single, plural, "dual" and "trial" markers. However, these abilities supposedly manifest themselves only in 22-month-olds who have acquired the linguistic terms that capture these descriptions (Kouider et al., 2006), so it is extremely unlikely that our infants, who are 10 months younger and largely still pre-verbal, have access to this system. It is more likely that infants possess a concept such as PAIR, which would allow them to represent two individuals with a single index. This representation could be further specified as DISC PAIR, TRIANGLE PAIR, or DISC, TRIANGLE, and would allow infants to track a total of four objects while still representing the total numerosity of the set.

This latter proposal could be strengthened by further studies investigating whether infants also identify objects across pairs. In addition, such a study could also help clarify the representations that infants form for objects in sets, about which LeCorre and Carey remain agnostic. To test these questions, infants would be familiarized to the XX/YY condition, but tested on outcomes of four discs or four triangles. If infants look longer at such outcomes, this result would provide strong evidence that infants identify objects as well as individuate them across pairs, and indicates that they represent individuals in sets more specifically than "$individual_1$, $individual_2$". A further study could also rule out the possibility that infants in Experiment 4's XX/YY condition were simply reacting to seeing a heterogeneous pair, having only been familiarized to homogeneous pairs. In this study, infants would again be familiarized to the XX/YY condition, but instead tested on outcomes of just two discs or just two triangles. If infants look longer at such outcomes, this result would confirm that their longer looking in Experiment 4 was due to an unexpected numerical outcome, rather than to any effect of homogeneity or heterogeneity.

By 12 months, infants are able to track sets of objects greater than the posited threshold imposed by object tracking. While it is possible that this ability is subserved by working memory capacity rather than numerical understanding, our results indicate that the ability to detect discrete quantity does not disappear as set sizes increase.

Chapter Five – Discussion

When we began the studies described here, our intention was, first and foremost, to prove that infants could track and reason about discrete as well as continuous quantity. Since that time research on infants' number concepts has flourished, and it is now clear that infants do not attend to objects in the world simply on the basis of continuous quantity. Rather, infants track continuous and large discrete quantities with equal ability (Brannon et al., 2006). However, infants' ability to represent the small number range has not been well established, and appears to have some surprising failures. In addition, it is still not clear whether young infants' ability to track discrete quantity reflects early numerical competence or whether this phenomenon can be attributed to some other non-numerical core endowment. What contributions can our results make to this discussion?

The results of Experiments 1-4 add to the overall picture of infants' ability to track discrete quantity for small sets. Under certain circumstances, infants track quantities of up to four by the end of the first year of life; Experiment 3 indicates that this ability has only begun to develop by nine months of age. At nine months, infants do not respond solely to changes in continuous quantity, but their ability to track discrete quantity has not yet been firmly established and has not been widely studied. While infants at this age may have begun to attend to discrete number, these representations differ from those of older infants in their stability, as infants detect certain changes (a change from two to three) but not others (a change from two to one). This failure to detect a change of 2:1 while total area remains constant is consistent with results from seven-month-olds

(Feigenson, Carey and Spelke, 2002), but success in detecting the 2:3 change indicates that nine-month-olds might have begun to represent the total number of objects in the set. While this pattern of looking could be dismissed as insufficient familiarization resulting in a familiarity preference rather than a novelty preference, this explanation seems unlikely as infants do not display a familiarity preference throughout trials, looking significantly longer only on the third trial. As discussed, the failure of our nine-month-olds may be due to methodological issues, as their looking-time patterns are consistent with representing the total number of objects present, but not their specific locations. We believe that nine-month-olds have already begun to attend to discrete quantity, but that their competence may not be demonstrated in Experiment 3 due to task demands imposed by the two-screen methodology. Wynn and Chiang (1988) report essentially the opposite result in eight-month-olds, who are surprised by a "magical disappearance" but not a "magical appearance" with a two-screen display. In their study each screen either hides a single object or one of the screen hides nothing. Infants are surprised by unexpected 1 vs. 0 outcomes, but not by unexpected 0 vs. 1 outcomes. Clearly this age group deserves further study.

Our studies indicate that by 12 months, infants can track a total number of objects exceeding the threshold imposed by object indexing, up to four individuals. They attend to the contents of simultaneously presented sets of one and two and sequentially presented sets of two and two, and detect the following transformations: change in number of a subset group (Experiment 1), change in number of the overall set (Experiment 4) and a swap in location of two sets (Experiment 2). However, infants do not attend to changes in continuous properties, even though the transformation presented should be large enough for them to detect (Libertus et al., in prep). Our looking time results support and extend results from reaching tasks (Feigenson, Carey and Hauser, 2002; Feigenson and Halberda, 2004; Feigenson and Carey, 2005). Further, we suggest that infants may also be able to track changes in discrete quantity even over sets of two and three. The 2 vs. 3 comparison is of particular interest because of the success of 10- and 12-month-olds in choosing 3 over 2 in Feigenson, Carey and Hauser's (2002) graham cracker task. A simple explanation for this success is that infants chose simply on the basis of continuous quantity. However, they reliably failed to choose 4 crackers over 1, a surprising result for several reasons. Both the 2 vs. 3 and 1 vs. 4 comparisons involve the same total number of crackers, suggesting that global amount is not the limiting factor. If infants were attending simply to continuous quantity, they should always choose 4 over 1 (and do when the crackers are presented on plates, not occluded in pots), so they cannot be responding based on total amount. Finally, 1 vs. 4 is a much more favorable ratio than 2 vs. 3, according to Weber's Law, making this failure even more puzzling. What is the source of infants' errors in this comparison?

Feigenson and her colleagues argued that infants succeeded in the 2 vs. 3 comparison and failed in the 1 vs. 4 comparison because they used object-tracking. Infants failed to represent the set of four into memory because the number of objects in the set was more than they could concurrently individuate. In other words, the threshold on how many objects can be concurrently tracked applies only to individual sets, not to the overall number of items tracked. This set size limitation is consistent with the failures of 14-

month-olds in Feigenson and Halberda's (2004) study to search longer for four objects hidden one at a time in a box. The results of our Experiment 4 and Feigenson and Halberda's (2004) chunking condition suggest that this limit can be overcome under certain circumstances, namely, when the objects are chunked into smaller sets, and these successes give some clues as to how infants might succeed in the 2 vs. 3 comparison. However, how infants compare the representation of the set of two and the set of three crackers remains an open question. A rigorously specified version of object indexing cannot account for how infants track above the number of objects that can be concurrently individuated. Even if representations of these objects get entered into memory, freeing up indexes to individuate other items, these representations must be encoded in an accessible way. Object files cannot provide this service; neither can unspecified SET concepts (Leslie and Kaldy, in press). Infants must have access to another means of solving this problem. The results of Experiment 4 suggested several possibilities. First, continuous quantity representations, though unlikely, have not been completely ruled out for displays containing sets of fewer than four objects. Second, infants may form some kind of summary representation, perhaps LeCorre and Carey's parallel individuation of individuals, or an overarching conceptual representation such as PAIR, which specifies the contents of a set. Third, infants may actually count the total number of items in a set, and compare on the basis of a numerical representation.

We have already begun to investigate how infants might track sets of two and three simultaneously. For our pilot experiment, we returned to Kaldy and Leslie's (2003) two-screen methodology. This experiment tries to replicate the results of Feigenson, Carey and Hauser's (2002) graham cracker study using a looking-time paradigm rather than a reaching paradigm. There are several benefits to changing methodology. Experiment 4 found competence in tracking two sets of two a full two and a half months earlier than Feigenson and Halberda's reaching task. In addition, reaching experiments such as the graham cracker task only allow for a single trial, because of the likelihood of perseverative behaviors on the part of the infants. Looking-time studies offer infants multiple trials to track the necessary changes. In addition, the looking-time methodology offers the benefit of making fewer task-specific demands than the reaching methodology.

Lastly, this experiment utilizes stimuli that simultaneously account for changes in number, area, and perimeter. To our knowledge, such displays are unprecedented in the literature. While it is not possible to equate both total area and perimeter simultaneously for sets of one and two discs, for sets of two and larger, groups of different numbers can be constructed whose total area and perimeter are exactly equal. There are only two caveats, one principled, the other practical. No two pairs of discs with distinct diameters can in principle ever have equal areas and perimeters simultaneously. The practical limitation is that we need to make physical discs and their measurements are subject to the accuracy limits of our workshop. We estimate accuracy to be better than 1%.

One consequence of such sets is that stimuli within sets are no longer of homogeneous sizes; however, one common criticism of Experiment 1, 2 and 3 involved the possibility of whether infants detected changes in the overall contour of the displays. These stimuli therefore allow us to investigate this possibility. In addition, some of the displays presented show infants changes such as an identical pair of discs to a pair of discs that differ in size. A pilot study looked at whether infants detected changes from homogeneity to heterogeneity and vice versa, and found no evidence that they did so.

The design of the pilot experiment was based on that of Experiment 1, but instead of showing infants three discs in a group of one and a group of two, we presented infants with five discs in a group of two and a group of three. The discs were presented individually in the same way as in Experiment 1, and the group of two was always presented first. Infants saw a total of four familiarizations. Test trials were identical to the familiarization trials except that two screens were first lowered onto the stage as in Experiment 1. Discs were then presented as in the familiarization trials and moved behind the screens. The screen hiding the group of three (the last-hidden screen) was then removed. Infants saw one of three outcomes in a between subjects design. In the Control condition, infants saw the expected set of three discs. In the Number Swap (Unexpected) condition, infants saw the group of two discs, which had previously been hidden behind the other screen. In the Configuration Change (Unexpected) condition, infants saw a group of three created by taking the two discs from the group of two and adding the smallest disc from the group of three. The total area change in this condition was +2.6% and the perimeter change was +12.5%. The reason we chose this condition requires some explanation. Equating a set of two with a set of three discs on area and perimeter simultaneously results in sets with characteristic configurations which result from the geometry of the circle. The set of three is constrained to have one large disc and two very small discs. The set of two can have two medium discs of equal size or one large disc and one medium. We chose the latter type for the pair to be more similar to the triple (see Figure 10). It occurred to us that infants might encode the triple as having a configurational feature comprising the two tiny nearly equal sized discs and then miss that feature when the pair of discs was revealed. Looking times might be driven by this feature rather than by a change in number as such. Our choice of stimulus for this condition was dictated by the attempt to assess this possibility. Figure 10 shows the displays used in the pilot experiment.

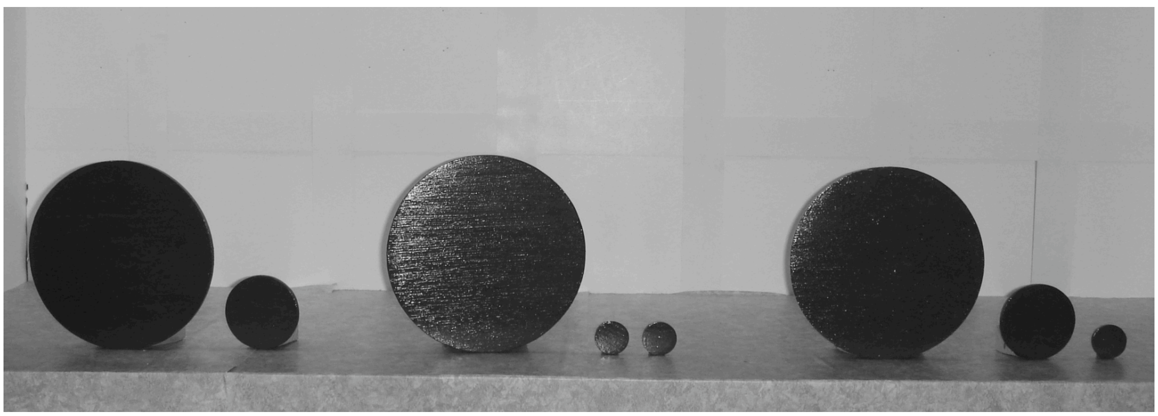

Figure 10. Stimuli from our pilot study – from left to right; group of two (Number Swap), group of three (Control), group of three (Configuration Change)

Initially, we had considered a condition with an Area Change group consisting of three discs with a 33% decrease in total area to match the total change in discrete number shown in the Swap condition. We chose instead to use the Configuration Change display because it offers an even more stringent test of number. The Configuration Change display is identical to the Swap display, except with the addition of a very small disc, making the two non-control conditions visually very similar. If infants are reacting only to overall contour of the display, then we should see that reflected in differences in looking times to these conditions. The display is made up of three heterogeneous stimuli, unlike the Control group of three, which is composed of one large disc and two identical small discs. If infants only track a subset of the discs, perhaps the homogeneous group of two R0.47" discs, they should look longer if those discs change identity. In addition, the Configuration Change display is the only completely novel test display, which means that infants should be biased towards looking longer. If infants fail to look significantly longer at this display than Controls, while the Number Swap infants look longer, then it is likely that they do attend to the number of objects being tracked.

The stimuli consisted of five wooden discs. The group of two consisted of one R2.72" and one R1.06" disc. The group of three consisted of one R2.84" and two R0.47" discs. The groups were designed so that, despite changes in number, the total area and perimeter of each set were closely equivalent to each other; indeed, the only limiting factor was accuracy of our machine shop in making the discs. The total area of the group of two was 67.9 in^2 and the total perimeter 23.75 in. The total area of the group of three was 67.68 in^2 (99.7% of the area of the group of two); the total perimeter was also 23.75 in. The front of each disc was painted red, and concealed a small weighted wooden base, which allowed each disc to be presented upright and apparently balancing on its edge. The test stimuli were identical to the familiarization stimuli. The control display consisted of the group of three discs; the swap display consisted of the group of two discs. The configuration change group was made up of the group of two discs plus one of the R0.47" discs; the total area and perimeter of this group were 69.68 in^2 and 26.72 in (102.6% and 112.5% of the expected area and perimeter, respectively).

Subjects were randomly assigned to one of three test conditions in a between-subjects design. At the beginning of all test trials, two screens were simultaneously lowered onto the stage in a position to conceal the discs when moved to their final resting places. The discs were then presented in the same way as during the familiarization trials. As the discs were moved to the sides of the stage, they were placed behind the screen. In trials of the non-control conditions, the experimenter surreptitiously replaced the group of three discs with novel stimuli. In the Swap condition, the group of three discs was replaced with a set of one R2.72" and one R1.06" disc; these discs make up the group of two discs, hidden behind the other screen. As it would appear to an adult observer that the two groups magically changed sides, we called this condition a "swap". In the Configuration Change condition, the experimenter substituted a set of one R2.72", one R1.06", and one R0.47" disc. This group is equivalent to the group of two plus the smallest disc from the group of three. The experimenter then shook her wrist before the screen to attract infants' attention to it, lifted the screen, and said, "Now" to cue a hidden observer to begin timing looking times to the display. The observer was always blind to the test condition. A trial was not considered valid unless the infant looked continuously at the display for at least two seconds. Trials ended when the infant looked away for two seconds. This presentation was repeated for a total of three test trials.

So far we have tested 14 infants (6 girls, 46 weeks to 58 weeks, mean age 52 weeks, s.d. 3.9 weeks), who were recruited via direct mailing from the Central New Jersey area. Infants were randomly assigned to one of three conditions - 3 in the Control condition, 5 in the swap condition, and 6 in the Configuration Change condition. An additional 3 subjects were tested, but excluded for fussing. Because of the very small number of subjects who participated in this study, an overall analysis was not possible. Looking times were right-skewed and converted to log form for analysis.

Comparison of overall looking to the Control and Swap conditions found a nearly significant difference ($t_6 = -2.26$, $p = .065$, two-tailed). By contrast, infants did not look significantly longer in the Configuration Change condition than to the Control display ($t_7 = -1.36$, $p = .217$). Infants also did not look significantly longer in the Swap condition than in the Configuration Change condition ($t_9 = .94$, $p = .374$).

Due to the very small N, only very tentative conclusions can be drawn from our results. However, our preliminary results indicate that infants might track both sets simultaneously on the basis of numerical identity, looking nearly significantly longer at a change in number when no change in area or perimeter occurs. By contrast, even the presentation of a completely novel set does not result in significantly longer looking when no number change occurs. The fact that infants do not look significantly longer at the Configuration Change condition than the Swap indicates that while the difference is not significant indicates one of two possibilities. One, infants do react to overall contour of the display, and their looking times may reflect that. The second possibility is that infants do realize that they are looking at a completely novel display and look longer accordingly, meaning that infants may represent some specific information about the individuals being tracked. Examining individual looking times reveals that four out of six subjects looked relatively little at the Configuration Change display (an average of 7.5

seconds, compared to an average of 4.9 seconds in the Control condition), while the other two subjects looked an average of 20.98 seconds (compared to an average of 17.7 seconds in the Swap condition). We cannot therefore predict how adding subjects would affect our overall results. However, the individual performance of our subjects indicates that while some infants apparently do notice the novel display, not all do.

Our results support those of Feigenson, Carey and Hauser (2002), and give some insight into how infants performed in their task. Based on these pilot indications, it seems unlikely that infants succeed on the 2 vs. 3 cracker comparison by using continuous quantity. Our infants appeared to detect a surreptitious switching of groups even though continuous extent for both area and perimeter was nearly perfectly controlled. Our results are consistent with set-based representations. Infants may have succeeded in tracking two groups of two in Experiment 4 because they have a concept of PAIR. If so, our results indicate that infants *may* have the concept of TRIPLE. If infants represent sets according to LeCorre and Carey's parallel individuation, our results suggest that this representation may not retain specific information beyond the list summary of individuals: that is, $individual_1$, $individual_2$, $individual_3$, since infants did not look significantly longer when a different group of three was shown. In other words, when comparing sets to each other using one-to-one correspondence, the representation of the control group of three was not different enough from the displayed Configuration Change group of three for infants to discriminate the sets from each other.

The results from Experiments 1-4 and our pilot experiment encourage us to pursue the idea that infants enumerate items within a set and compare these items on the basis of numerosity. 12-month-old infants appear to be able to exceed the object indexing threshold when the total number of objects is broken down into smaller sets. Therefore, object indexing alone cannot account for how infants track small sets of objects, although it may aid infants in attending to discrete quantity over continuous amount. Infants may individuate separate sets using object indexing and then place representations of those sets into working or long-term memory to free up indexes to individuate other objects. However, even this stipulation does not explain how comparisons can be made between those sets. There are three possibilities for how these comparisons can be made. First, infants may simply make one-to-one comparisons between individuals (LeCorre and Carey, in press). These comparisons are non-numerical in nature and do not require the infants to represent individuals at any level of specificity beyond $individual_1$, $individual_2$, $individual_3$. Second, infants may represent sets using a summary representation such as SINGLE, PAIR, TRIPLE, but not QUADRUPLE (Leslie and Chen, 2007; Leslie and Kaldy, in press). Infants cannot simply represent a non-specific SET, because such a representation does not provide a basis for comparing sets on number. Third, infants may represent sets using integer representations for ONE, TWO and THREE (but not FOUR) (Leslie et al., in press). We assume here that infants cannot represent individual sets of four or more. In all of our experiments, infants were never tested using individual sets exceeding three items, so we do not know how infants would perform on comparisons involving these sets. Infants in Feigenson's reaching tasks failed to choose quantities of four reliably over quantities of one, suggesting that the set size limitation is a robust phenomenon. Whether infants in a looking-time task would behave as though they cannot represent a group of four is an open question. A previous study run in our lab indicates that infants can understand and reason about displays of four objects (Leslie and Chen, 2007). Therefore, it is possible that infants might succeed in a looking-time version of the one vs. four comparison, perhaps because the task demands of looking time tasks are far lower than those of reaching tasks. Even if they do not, however, it is not clear that the sole reason for their failure is the capacity limitation of working memory. Infants may simply lack a way to represent displays of more than three objects unless they are broken down into smaller sets, for which they do have concepts.

What is the mechanism by which infants compare small sets of objects? As discussed in Chapter 1, the answer to this question will help researchers understand something about the nature of human numerical representation. When infants successfully discriminate small sets on the basis of discrete number, does this success reflect true knowledge of number? Or should their success simply be attributed to some kind of mechanism that allows infants to solve these problems without number? The first possibility, using one-to-one correspondence as the basis of comparison, is explicitly non-numerical and is consistent with theories of number learning based on exposure to culturally-determined terms for quantifiers and numbers. The second is non-numerical because the SINGLE, PAIR, TRIPLE are not ordered by magnitude. One may as well write PAIR, SINGLE, TRIPLE, etc. Yet they allow infants to represent sets of different magnitudes. If infants represent sets as PAIR and TRIPLE, exactly how these representations eventually match up with integer has yet to be determined. Only the third assumes that the child possesses numerical representation and supports ordering.

How can we decide amongst these hypotheses? LeCorre and Carey (in press) cite two different kinds of data which could help distinguish the possibilities. The first concerns the mapping of numerals to cardinal values. If children do not have access to analog magnitude representations or precise integer representations of number, then they should be limited to assigning cardinal meanings to the amounts that can be represented by the capacity-limited enriched parallel individuation system (that is, three or four and below). The second type of data concerns whether representations of small numbers exhibits scalar variability consistent with the Weber fraction that governs representations of the large number range.

Unfortunately, results from infant looking-time tasks cannot provide this kind of disambiguating data. All three explanations are consistent with the data from 12-month-olds. However, while we cannot rule out that infants enter a representation of a set of two individuals and a set of three individuals into long-term memory during our pilot experiment, it is implausible that they would also enter into long-term memory the transient locations of these sets. Yet they have to track the transient locations of the sets in order to succeed in Experiments 1, 2, and the pilot study described here. Repeatedly overwriting the locations of the sets should produce severe proactive interference in long-term memory, yet we see no evidence for such interference. LeCorre and Carey's model provides no way of accounting for how infants track the locations of sets in addition to their identities.

If we assume the more optimistic view of our nine month data, that they are tracking the total number of displayed objects but not their locations, Carey and her colleagues' theory of parallel individuation does not handily explain why infants would display working memory limitations when comparing sets of one and two but not sets of two and three. It is also unlikely that infants represent sets such as SINGLE, PAIR, as such representations would lead to success in discriminating 2 and 1. Representing the total number of tracked objects, but not the specific location of sets, would best explain why nine-month-olds behave as they do. If, on the other hand, we assume that our nine-month-old infants simply fail to attend to discrete quantity altogether and instead fall back on familiarity and/or representations of continuous quantity, then it is unlikely that they represent the sets as integers or sets. Further studies must clarify the precise nature of nine-month-olds' ability to track discrete quantity.

However, parallel individuation also fails to provide a satisfactory explanation for why infants might utilize continuous amount representations in one case and familiarity in another. In other words, while parallel individuation accounts for the behavior of the 12-month-olds, it does not appear to offer a good explanation for our nine-month data. Indeed, it is questionable whether parallel individuation can even account for Feigenson, Carey and Spelke's (2002) failure to replicate Wynn. They argued that infants did not represent two individuals behind the screen as discrete entities; rather, infants sum across the total continuous amount of the objects and do not look longer when they see a numerically unexpected display with expected area. Infants are required to track only two objects at the most, well within the number of objects that can be tracked. Why does the parallel individuation system fail in this case? LeCorre and Carey (in press) do not offer reasons why this system might sometimes yield to continuous representations. In other words, there is no indication that if infants use parallel individuation, that they may tailor their representations to whichever is most appropriate to the task at hand. One possible explanation that utilizes the parallel individuation system is that seven-month-old infants' working memory limitations may keep them from entering more than one object into their working memory (Ross-Sheehy et al., 2003); when the time comes for them to make a one-to-one comparison, only one object has made it into long-term memory, and its representation is insufficiently distinguished from the displayed object for the infants to detect a mismatch. However, to reiterate a point raised in Chapter 1, if long-term memory storage capacity is determined by the limits of working memory capacity, why does the threshold of the number of objects that can be indexed not increase along with it? It is unclear why long-term memory should have the same limits as working memory. Why are infants unable to concatenate smaller sets in long-term memory to represent larger sets of 4, 5, 6, etc.? Why should parallel individuation mechanisms be required to establish one-to-one correspondence between long-term memory set representations and perceptual sets: why could this not be done serially? Basic questions like these need to be addressed before the account can be assessed. Moving sets from working to long-term memory grants the system a little flexibility in terms of the number of sets that can be simultaneously represented, but gains no other benefits of long-term memory.

The theory of parallel individuation seems to fall short of offering a convincing explanation for how infants compare sets. Several innate endowments must be invoked to explain how infants can succeed at tasks involving number without representing number, each of which is limited to related but distinct functions for no apparent reason except to conform to existing data. In addition, the description of how older children eventually learn concepts of number through bootstrapping lacks explanatory power, and is inconsistent with research indicating that even very young children command an explicit understanding of number (Gelman and Gallistel, 1987; Gallistel and Gelman, 1992; Cordes and Gelman, 2005).

An undue amount of energy is expended on explaining away infants' and young children's competence, far more than explaining the nature of that competence. A simpler explanation may be that if infants appear to behave as if they understand something about number, perhaps they do. Perhaps infants' success on small and large number comparisons can be attributed to an innate numerical endowment. Like adult humans and animal species, they may have access to innate mechanisms for number, which govern nonverbal counting (Meck & Church, 1983; Gallistel and Gelman, 1992; Cordes, Gallistel, Gelman, & Whalen, 2001), which are not subject to cultural influence (Gelman and Gallistel, 2004). They may also represent the range of small numbers under four using integer concepts (Leslie et al., in press). The process of learning numbers may not be a laborious endeavor dependent on whether one's linguistic inventory permits the mapping process between two mechanisms for representing sets; rather, early understanding of number forms the basis for later numerical and mathematical competence in life. We are aware that, conservatively speaking, the strongest claim that can be made based on the results of the studies presented here is that 12-month-old infants are far better at tracking and reasoning about small numbers than previously believed. However, we believe that further studies should continue to investigate the idea that infants are numerical creatures. Specifically, three studies should be conducted to pursue the ideas outlined here. First, the pilot experiment described in this chapter should be expanded with more subjects. Can infants really simultaneously represent sets of two and three? If so, then a second experiment should investigate whether infants can simultaneously represent another global set of five, broken up into sets of one and four. If infants succeed on a one vs. four comparison using a looking-time paradigm, this finding would weaken the claim that the numbers smaller and larger than four are represented by different number systems. Finally, the results of our nine-month-olds from Experiment 3 require explication. Do infants fail to detect a change of two to one simply because they have not yet made the transition from a familiarity preference to a novelty preference? Or is their failure due to their inability to track two sets by number? If it can be shown that infants track the total number of objects, but not by location, this result would lend strong support to the idea that infants represent integers even at a very young age.

Acknowledgment of Previous Publications

The studies presented in Chapter 2 have appeared in the following:

Chen, M.L., & Leslie, A.M. (2007). Continuous versus discrete quantity in infant multiple object tracking. In *Proceedings of the 6th IEEE International Conference on Development And Learning*, Imperial College, London, UK.

Chen, M.L., & Leslie, A.M. (2007). Continuous versus discrete quantity in infant multiple object tracking. In D. S. McNamara & J. G. Trafton (Eds.), *Proceedings of the 29th Annual Cognitive Science Society* (pp. 64-70). Austin, TX: Cognitive Science Society.

The study presented in Chapter Four has appeared in the following:

Leslie, A.M., & Chen, M.L. (2007). Individuation of pairs of objects in infancy. *Developmental Science*, 10:4, 423-430.

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Barner, D., Thalwitz, D., Wood, J.N., & Carey, S. (in press). Children's ability to distinguish "one" from "more than one" and the acquisition of singular-plural morpho-syntax. *Developmental Science*.

Barner, D., Wood, J., Hauser, M. & Carey, S. (under review). Evidence for a non-linguistic distinction between singular and plural sets in wild rhesus monkeys.

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