2003

Infant number knowledge : a test of three theories.

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INFANT NUMBER KNOWLEDGE: A TEST OF THREE THEORIES

A Thesis Presented

by

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Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

May 2003

Department of Psychology

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ACKNOWLEDGMENTS

I would like to thank my advisor, Richard S. Bogartz, for his support and guidance. From the earliest stages he was open to exploring the questions I wanted to answer, patiently allowed me to think about them, and challenged me to go beyond what was "easy." The research skills and life skills (and confidence!) I have acquired from this experience are invaluable, and I am grateful. I would also like to thank the members of my committee, Neil Berthier and Melinda Novak for their helpful comments and recommendations during this process.

I would like to thank all the parents who voluntarily came to the lab with their infants. I would especially like to thank all of the undergraduate research assistants, over the past two years, for their help in building the stage, hours of training, running subjects, and coding data. I could not have done this without them. I also thank the graduate students who voluntarily helped me run subjects during their summer break.

A special thank you to Dawn Melzer, my officemate, my colleague, my friend, for always helping me keep things in perspective during all of the highs and lows.

Thank you to my family for their encouragement and "phone support." It might have taken a while, but I did it!

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CHAPTER 1

INTRODUCTION

In the past 20 years, an abundance of evidence has suggested that infants, ranging in age from days old to 12 months old, are sensitive to numerosity (Antell & Keating, 1983; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Wynn, 1996). Infants discriminate between small sets of dots presented linearly, regardless of spatial (i.e., length and density) cues (Starkey & Cooper, 1980; Antell & Keating, 1983). Starkey and Cooper (1980) suggested that this number discrimination is limited to small sets because the infants could make a two-dots versus three-dots discrimination but not four versus six. Similar results were found when pictures of three-dimensional objects were presented in random patterns and sizes (Starkey et al., 1990; Strauss & Curtis, 1981). In these studies, infants looked longer (therefore, "discriminated") at arrays that were different in number from what he or she was initially habituated to.

Young infants also discriminate number in less discrete forms of presentation. Starkey et al. (1990) found six-month-olds discriminated number across perceptual modalities in that they preferentially attended to object presentations that corresponded with the number of drum beats heard (but see Mix, Levine, & Huttenlocher, 1997 or Moore, Benenson, Reznick, Peterson, & Kagan, 1987). Infants further discriminate even less tangible events such as actions. Wynn (1996) showed infants dishabituated from watching two jumps of a puppet when presented with a novel three jump sequence. Bijeljac-Babic, Bertoncini, & Mehler (1993) found that newborns discriminated multi-syllabic utterances, i.e., utterances of two syllables from three syllables. These infants however, also failed to discriminate four from six, similarly to Starkey & Cooper's (1980) finding. The abundance of evidence in different types of experiments suggests that young infants have some, albeit limited, number representational system present early in life.

One means of investigating the robustness of infants' proposed numerical representations has been to use tasks in which a transformation has been made on a represented set of entities (e.g., Koechlin, Dehaene, & Mehler, 1997; Simon, Hespos, & Rochat, 1995; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Wakely, Rivera, & Langer, 2000; Wynn, 1992; Wynn & Chiang, 1998). Studies involving a physical transformation differ from habituation studies in that a violation of expectation procedure is used. The infant is presented with a sequence of object-based events, during a brief occlusion some transformation is made on the number of objects, and an expectation of the resulting number is assumed to be formed. Longer looking at an outcome is assumed due to a mismatch between the expectation and what is in perception. Some of these studies using the violation of expectation paradigm have been interpreted as showing that infants possess even greater capabilities than numerical representation. The infant's ability to form an expectation that may be number-based, and then use that expectation to discriminate a perceived set of entities may involve further reasoning. Therefore, some researchers have taken the position that transformation studies exhibit infants' numerical reasoning abilities (Wynn 1992, 1995; Wynn & Chiang, 1998).

The landmark "transformation" study by Wynn (1992), and subsequent variations (e.g., Simon et al., 1995; Uller et al., 1999; Wynn & Chiang, 1998), in which infants as young as five months old seemingly performed simple addition/subtraction calculations, have supported two models of early numerical reasoning. The first model is the "accumulator," a member of a class of analog-magnitude models. In short, this model posits the workings of a neural mechanism specialized to deal with number, based on the same principles as the counting system. The second model is the "object-file" model, which rests on a mechanism of selective attention, calling upon physical knowledge only. Both models have been supported in the literature. Due to the wide variability in procedures and results, researchers thus far have been unable to provide a clear contrast between these models, nor to account for the infants' overall performance using only one model. Consequently, researchers such as Xu and Spelke (2000) and Wynn (personal communication, December 12, 2000) have suggested that perhaps both hypothesized mechanisms contribute to the development of enumerative abilities, and their relative contributions may depend on the size of the set being worked upon.

However, a third explanation has recently emerged, and quickly gained support from both habituation and transformation studies. There is evidence to suggest that a sophisticated cognitive system specialized for number may not be necessary to account for the previously accepted "sensitivity." Instead, simple perceptual factors may be adequate in accounting for infants' behaviors. Primarily, the infants may be showing familiarity/novelty preferences, preferences for "more" to look at, and sensitivity to changes in spatial dimensions. These factors are often confounded with the arithmetically possible and impossible outcomes in the transformation studies (Cohen & Marks, 2002; Simon et al., 1995; Wynn, 1992). The present research will contrast these three positions and test the assumptions upon which they are based, shedding light on the underlying nature of 10-month olds' knowledge of number. Specifically, the experimental design will allow for a determination of whether abilities exhibited in these tasks are based on the use of an accumulator counting mechanism, an object-based attentional mechanism, or simple perceptual processes.

The Theories: Background

Wynn (1992) changed the approach of studying infant number knowledge, from the previously standard habituation paradigm, to a violation of expectation paradigm. Wynn claimed that five-month-olds, over three experiments, showed evidence that they could "calculate" the results of simple arithmetical operations on a small set of objects.

In the first experiment, there were two conditions: addition and subtraction. In the addition condition, each trial began with the infant seeing one doll on the puppet stage. The experimenter's hand entered the stage to the infant's right side, and held up the doll to call attention to it. A screen rotated up to occlude the one doll, and a second doll was brought onto the stage from the right-hand side, tapped on the floor, squeaked, then placed behind the screen as the infant looked on. The screen rotated down to reveal either one or two dolls, an impossible or possible event, respectively.

In the subtraction condition, the infants initially were shown two objects on the stage. The experimenter's hand entered from the right side, wiggled and squeaked them one at a time, then exited the stage empty-handed. The screen rotated up, and the empty hand returned, took the right-most doll from behind the screen, squeaked and tapped it on the stage floor in the infant's sight, then exited the stage to the right with the doll in hand. The screen then rotated down to reveal either one (possible) or two (impossible) doll(s). Wynn predicted longer looking in both conditions to the impossible, or arithmetically incorrect, outcomes. Indeed, the 5-month-olds discriminated the possible outcomes (1 +

1 = 2 and 2 – 1 = 1) from the impossible (1 + 1 = 1 and 2 – 1 = 2). These results were replicated in a second experiment.

In a third experiment, infants correctly discriminated a 1 + 1 = 2 event from a 1 + 1 = 3 event. The five-month-olds looked longer at three dolls than at two, indicating that not only did the infants have an expectation for the outcome to be "more than one," but that the infants had an expectation to see "exactly" two dolls. In accordance with the hypotheses, the infants looked longer to impossible events in both the addition and subtraction conditions, in all three experiments. Although Wynn (2000) claims these findings to be "robust and consistent," as they have been partially replicated in other labs (Simon et al., 1995; Uller et al., 1999), there has also been some failure to replicate as well (e.g., Feigenson et al., expt 7, 2002; Poirier, 2001; Wakely et al., 2000). Moreover, a study by Koechlin, Dehaene, and Mehler, (1997) claims "infants looked reliably longer at impossible events than at possible events" (p. 98), and is often cited as such. But this finding was only significant in the subtraction condition (2 – 1 = 1 or 2), with no difference in looking time in the addition condition (1 + 1 = 1 or 2). This difference has yet to go reported in the literature.

Still, Wynn's (1992) findings led to the claim that infants "possess true numerical concepts" (p. 750) by the age of five months. The infants were able to encode numerical relationships, make internal manipulations, and represent a numerically meaningful outcome. This was demonstrated by the precision of their calculations. Wynn (1992) suggested that the arithmetical abilities demonstrated support for an innate mechanism of enumeration. She posited the "accumulator model" as the best fitting account for enumerative abilities evidenced at birth in infants and animals (Wynn, 1995, 1998).

The Accumulator Model

In 1983, Meck and Church proposed a neural model that accounts for both perceptual timing and enumerative abilities in rats. Their model provides a mechanism for making numerical discriminations. It is based on the premise that continuous quantities are stored in memory in terms of a system that is analogous to the principles of counting (Gallistel, 1990). Discrimination between two quantities occurs when a magnitude stored in memory is compared to what is in perception. When in counting mode, there is a neural pacemaker generating pulses at constant intervals. A gate opens and closes in one-to-one correspondence with each item to be counted, allowing the pulses to enter a storage area where they are incrementally accumulated. The final pulse, or gate closure, is tagged with a single analog value, representing the entire amount. Gallistel and Gelman (1992) suggested that, in humans, these analog representations are symbolic representations comparable to numerical integers, and are later mapped onto number words. Both the proposed accumulator mechanism and verbal counting are guided by and dependent upon principles of one-to-one correspondence, ordinality, and cardinality (Gallistel, 1990; Gallistel & Gelman, 1992). Therefore, it is plausible that such a mechanism, which operates on similar principles to counting, may underlie preverbal counting abilities in humans.

Evidence for an accumulator mechanism has been found in rats (Meck & Church, 1983), pigeons (Roberts & Mitchell, 1985), monkeys (Brannon & Terrace, 1998), human adults (Whalen, Gallistel, & Gelman, 1999), young children (Huntley-Fenner, 2001; Huntley-Fenner & Cannon, 2000), and infants (Wynn & Chiang, 1998; Xu & Spelke, 2000). However, the means by which the model is tested varies, depending on the assumption investigated. For example, the model allows for tests of distance effects, Weber's law, and cardinality. Of central importance here is cardinality. Because the last item is tagged with a single analog representation of the accumulated value, this has implications for memory. The mechanism stores one value in memory, as opposed to a separate representation for each item that has entered the accumulator. This implies that there is no capacity limit on the quantity that can be accumulated and held in memory. Also, there can be several accumulators working at one time. Although there are no limitations to the values working accumulators can hold, the question of how many accumulators can be working at one time has yet to be investigated.

Another operation assumed in the model is the comparison of values. The value given to the stored amount is compared to either a value in perception, or another value in memory. Because a comparison of analog magnitudes is being made, discrimination is best when differences are large (e.g., 8 versus 16 as opposed to 8 versus 12). This is considered to be the distance effect subject to Weber's Law. However, a comparison of two versus three items is not necessarily much more difficult than discriminating two from one, because the numbers are still relatively small. Likewise in tasks of numerical estimation, as the number of items to be estimated gets large, errors increase in a constant proportion to the associated comparison magnitude, i.e., the value held in memory (see Gallistel & Gelman, 1992, Whalen, Gallistel, & Gelman, 1999). Distance effects are indirectly due to this scalar variability in the stored value, and are simply a function of the ratio of the pair of numbers (Gallistel & Gelman, 2000). Unless the ratio between two quantities is also large (e.g., 1:2), a simple discrimination task will become increasingly difficult as numbers (or quantities) increase (Gallistel & Gelman, 1992).

Evidence for the accumulator, based on the Weber's Law principle alone, has been obtained in estimation tasks from adults (Whalen et al., 1999) and young children (Huntley-Fenner, 2001), as well as discrimination tasks looking at distance effects in young children (Huntley-Fenner & Cannon, 2000) and infants (Xu & Spelke, 2000). The infant studies testing specifically for the accumulator model have employed both the violation of expectation paradigm (Wynn, 1992; Wynn & Chiang, 1998) and the habituation paradigm (Xu & Spelke, 2000). According to the model, when there is discrepancy between the accumulated value held in memory and the value held in perception, this mismatch will elicit longer looking from the infants. In the study by Xu & Spelke (2000), infants who were habituated to displays of eight dots were found to dishabituate (looked longer) when presented with displays of 16 dots, but did not dishabituate to 12 dot displays. The six-month-olds discriminated or detected the numerical difference between eight and 16, but not eight and 12. This finding supported the accumulator model, in that the infants appeared to detect numerical mismatches within the constraints of the Weber's Law fraction. By six months the infant can discriminate between two numerically large sets of items presented in a 1:2 ratio, but not 2:3, where the ratio is smaller.

The infant arithmetic results found by Koechlin et al. (1997), Simon et al. (1995), & Uller et al. (1999), partial replications of Wynn (1992), can be interpreted by a different account of early enumeration. This account addresses the arithmetic studies and interprets their results in terms of the infant's knowledge and representational abilities for objects. The infant's ability to track objects through space, form a representation of an occluded object, and hold this information in memory may account for the results of the transformation studies, not number, per se. This non-numerical, representational account constitutes the basis for a very different sort of interpretation: the object-file model.

The Object-File Model

Initially proposed by Kahneman & Treisman (1984), the object-file model was suggested as a mediating representational mechanism between perception and long-term memory. The hypothesized account states that for every item in perception, a file is created and identified by the spatiotemporal information regarding that object's location. However, with online processing, features and properties may gradually be added to the file. Further, each object-file can remain intact during motion, thereby implying that objects can be individually tracked (Kahneman, Treisman, & Gibbs, 1992).

Trick and Pylyshyn (1993, 1994) expanded on the object-file framework, as a means of describing attentional differences for subitization and counting processes. According to their model, the individuation and enumeration of an item is a preattentive parallel process. Indices are created for each item, assigned a variable name or reference token, and a pointer is assigned to that item's location. They further assumed that these indices operate on perceptual representations, (as opposed to retinally-based or higher-order representations), and therefore there is an upper limit to how many can be kept track of at one time. The model accounted for some of the results in the early infant habituation literature such as Starkey and Cooper (1980), where young infants discriminated two from three, but not four from six. They posited that this was because the limit on the number of individual representations held in memory is very small (2-3 items) in early infancy, and both four and six exceeded the capacity of items that could be tracked and held in memory.[1]

Leslie, Xu, Tremoulet, & Scholl (1998) proposed a model of a working object-file system to account for the infant arithmetic studies (e.g., Wynn, 1992, Simon et al, 1995). They proposed an object-file may take on the following properties: 1) the index is a 'mental token' serving as a pointer toward an object in some location; 2) the index itself is not a representation of the object properties and features, however, this information can be 'bound' to the index; and 3) because the mechanism involved in indexing is a process of selective attention, it is limited in capacity. Leslie et al. (1998) cited evidence to suggest this limit is no greater than four, and later tested specifically for this limit (Leslie, 1999). To this point, there is no definitive evidence of an exact limit. It may vary between individuals in the range of two to four items.

Simon et al. (1995) replicated Wynn (1992), but argued against a specific number mechanism. They indicated that in Wynn's experiment arithmetically incorrect events were also physically impossible events. The mere impossibility of an object's physical appearance or disappearance was enough to elicit longer looking on these addition and subtraction tasks. Consequently, knowledge exhibited in the task may be due to the infant's physical object knowledge.

To unconfound physical possibility from arithmetical calculations, Simon et al. (1995) tested the 1 + 1 or 2 – 1 operations with the 1 or 2 numerical outcomes, using four different outcomes for each operation. For the addition condition, the infant saw one Elmo doll, then a second Elmo doll was added. Then, one of four different outcomes was revealed: 1) two Elmo dolls (possible), 2) one Elmo doll (arithmetically impossible), 3) one Ernie and one Elmo (arithmetic possible/identity impossible), and 4) one Ernie doll (arithmetically and identity impossible). The five-month-olds consistently looked longer at the two arithmetically impossible events, as in the Wynn study, but were not bothered by changes in the identity of the objects. Simon et al. argued for a "non-numerical" explanation (Simon, 1997) of tracking objects, analogous to the object-file system. The object-file mechanism has the infants paying attention to the location of objects without encoding featural information. At five months, it is questionable as to whether the infant has mastered the concept of object permanence. Tracking objects moving behind a screen first and foremost draws the infant's attention to spatiotemporal details. When tracking the mere existence of objects, identity tends to be ignored. The infants in this study are young enough that tracking two objects places high demands on their attention and memory system, thereby only allowing for spatiotemporal information to be encoded, causing the longer looking to the arithmetically impossible events.

Objects move continuously through space and time, from one location to another. This appearance of an object showing spatiotemporal continuity is what elicits an object-file to be opened. Koechlin et al. (1997) looked at this role by replicating Wynn's study, with one variation: after the objects were placed behind the screen, the objects were rotated such that, when revealed, they were not in the exact location on each trial. They found the slight variation in placement did not affect looking time. Infants continued to look longer at the arithmetically inconsistent outcomes, but in the subtraction condition only. Yet, this finding was interpreted as overall evidence for an object tracking system which tracks objects through space, and leaves a mental token pointing to "somewhere behind the screen." Koechlin et al. (1997) favored this object-based approach over a number mechanism because the pattern of results follows the constraints of object-based knowledge and reasoning. Further, the authors distinguished between infants manipulating object representations in these transformation studies and infants performing numerical operations. The longer looking is elicited by the mismatch of mental tokens (of objects) placed in one-to-one correspondence with what is in perception.

The Perceptual Processing Model

A study by Clearfield & Mix (1999) also challenged the claims of the infant habituation work, namely that infants are responding differentially to changes in number. They suggested results could be due to changes in more salient perceptual variables such as contour length. They pointed out that in all of the habituation studies, such continuous variables were highly correlated with number, thereby making the number claim suspect. Clearfield & Mix habituated six- to eight-month-old infants to displays of two or three squares, all of equal size. At test, the infants were shown displays of either the familiar number & novel contour length, or a novel number & familiar contour length. The infants only dishabituated to changes in contour length, and not to changes in the individual number of squares. They suggested, that at the very least, when shown stimuli in which continuous variables (such as contour, brightness, area, etc.) are separated from the number variable, infants will attend to changes in the more salient continuous variable.

A series of experiments by Feigenson, Carey, & Spelke (2002) has recently supported the previous finding by pitting number against surface area in both habituation and transformation studies. First, they replicated the habituation study of Starkey & Cooper (1980), using one versus two discrimination tests with six-month-olds, with continuous extent (surface area) and number confounded, as in the original experiment.

In the following four experiments, they habituated infants to a number of objects and tested them on either familiar number/novel extent, or novel number/familiar extent. The infants consistently failed to dishabituate to changes in number.

Feigenson et al. (2002) also replicated the transformation study of Wynn (1992), with number and extent confounded. Then in the following experiment, extent was separated from number. Specifically, infants were tested on a 1 + 1 = 1 or 2 transformation. On all trials infants saw one small object placed on stage, the occluder rotated up, and a second small object was added. The screen rotated down to reveal either two large objects (twice the surface area of the two small objects, but expected number) or one large object (surface area equal to the two small objects, but unexpected number). The events involving unexpected extent resulted in significantly longer looking times than the unexpected number events. Although the authors of this study seemed to favor an object-file interpretation, they pointed out that the infants were probably drawing upon multiple mechanisms (both physical representations and number representations). Nevertheless, the simplest perceptual variables should not be over looked in favor of these higher order processes (Feigenson et al., 2002).

Cohen & Marks (2002) tested the hypotheses that results in the simple arithmetic studies could stem from three possibilities: the actual computation of the transformation, familiarity preferences, or directionality preferences (i.e., forming an expectation based on knowledge that addition yields "more" and subtraction yields "less"). Following Wynn (1992), five-month-olds were tested in either an addition condition (1 + 1) or subtraction condition (2 – 1). However, over eight trials, the infants saw four different outcomes (zero, one, two, or three objects). Each outcome was presented twice, once in each block of four trials. Results differed from those of Wynn. For the first block of trials, the infants looked longer at the familiar number of objects (one in the addition condition, and two in the subtraction condition). The responses to these events were considered to be due to familiarity preferences, because it was the original number of objects seen on the stage before any transformation had occurred. Although the interpretation is different, the finding is also consistent with Wynn (1992). However, in the second block of trials, for both conditions, the infants looked longer at two than at one or zero. They concluded that either the infants were adding or subtracting (as Wynn suggested), or alternatively, they were showing a familiarity preference and a preference to look longer at more objects.

In a second experiment, Cohen & Marks tested for this familiarity preference, by excluding any warm-up trials, and any introductory exposure to the stimuli. This time, in the first block of trials, no difference in looking time was found between the one, two, and three objects. However, in the second block of trials, the infants showed a positive linear trend in their looking behavior. In other words, they looked longer at one than at zero, at two than at one, and longer at three than two objects. They interpreted this as strong evidence that the numerical abilities claimed for infants can also be explained in terms of simpler mechanisms. In this case, a preference for familiarity plus a tendency to look longer at more objects.

Review of Previous Research Testing the Models

The three models described are all plausible explanations for the infant arithmetic literature. Yet they are different positions assuming different processes. It is difficult to separate the confounds in many of the experiments. This has resulted in ambiguous results. Consequently, many of the studies to date can be interpreted as supporting more than one model.

Baillargeon, Miller, & Constantino (1994) conducted arithmetic studies with 10-month-olds. Instead of seeing an object placed on stage before occlusion, the infants initially saw the empty stage. After a screen raised, two objects were added, one at a time. Two (correct) or three (incorrect) objects were then revealed, and the infants looked longer at the three objects, as the authors predicted, based on the impossibility of the event. In a second experiment, they tested a 2 + 1 = 2 or 3 calculation. The screen was raised, two dolls were simultaneously placed behind it, followed by one doll being placed. The infants looked longer at two objects than at three, in this case. In a third experiment, they tested a 1 + 1 + 1 = 2 or 3 calculation, the difference being that the objects were placed behind the screen one at a time. There was no difference in looking time to two or three objects. The authors suggested this was due to the requirements of the calculation. Three updates to their representation of what was behind the screen was required, rather than simply two in the previous experiments. They concluded that infants have "intuition" about addition, but abilities are still very limited.

Uller et al. (1999) intended to test an integer-symbol model (i.e., accumulator) against an object-file model. The variable of particular interest was the placement of the first object on the stage. In the first two experiments, eight-month-olds were tested in a 1 + 1 = 1 or 2 test. Half of the infants watched one object first placed on the stage, and then occluded (the "object-first" task), as in Wynn's (1992) task. The other half saw the empty stage, the screen rotated up, and the first object was placed (the "screen-first" task), as in the Baillargeon et al. (1994) task, followed by the adding of the second object.

Longer looking at one object (the impossible outcome) was only found in the object-first condition. However, in a third experiment, the 10-month-old infants did look longer at one object (the impossible outcome) in the screen-first 1 + 1 = 1 or 2 task. Note that, although the 10-month olds did "succeed" at the task when the eight-month-olds did not, the 1 + 1 + 1 = 2 or 3 in the Baillargeon et al. study still exceeded their capacity in a screen-first procedure, suggesting this ability is very primitive.

These studies provide two important pieces of evidence: 1) the placement of an object on the stage before occlusion facilitated longer looking to the incorrect outcome, and 2) a developmental progression from five to 10 months of an increasing capacity to handle the demands of the task. For both reasons, Uller et al. support an object-file model. The object on the stage sets up an initial representation of what is expected to be there. When the object is occluded, and a second object is added, the initial representation is updated to include two objects. The younger babies struggle with the screen-first condition for the following reason: When the first object is placed behind the screen, they have to build an initial representation for "something is now behind the screen," constructed from this brief initial perceptual experience. This is shortly followed by the second object added, requiring an update to the representation of what is behind that screen. The infant holds a representation with one object-file, then two object-files. This involves memory for how many items are behind the screen, attention to the addition, updating the existing representation (more than once in the screen-first condition, such that they are operating upon operations), and therefore, at least some crude form of object permanence to hold a representation of something behind the occluder. These demands on memory are not of issue to the accumulator, which simply holds the last "count" value in memory. Nor does the initial set up in the object-first condition differ from the screen-first procedure (for the accumulator). Furthermore, Uller et al. pointed out that in the object-first 1 + 1 events by Wynn (1992) and Koechlin et al. (1997), five-month-olds were tested, and results of longer looking to one object over two objects were much less robust. By the time the infants were eight months old, they succeeded outright in the object-first task, and, by ten months, in the screen-first condition. This gradual developmental progression is indicative of the expected improvements in information-processing, and these processing demands are precisely what an object-file system would rely upon.

In a final experiment, Uller et al. (1999) tested eight-month-olds in a screen-first, 1 + 1 = 1 or 2 task once again. The goal was to see if the eight-month-olds could succeed when the processing demands are reduced. If so, it would be stronger evidence of an object-file mechanism at work in these tasks. To reduce the demands placed on memory, they used a two-screen procedure, where one object was placed behind each screen. Hence, the two screens served as perceptual location markers, which would perhaps help the infants individuate the objects, and possibly facilitate the representational construction by providing greater spatiotemporal information. As predicted, the eight-month-olds did succeed, they looked longer at the impossible event (one object) than the possible. Using the two-screen procedure facilitated eight-month-olds' success at the task. Therefore, Uller et al. (1999) favored this attention-based model which calls upon physical representations and knowledge, and has the capacity to improve both in accordance with information-processing refinements that normally develop with age and with the reduction of processing demands within the task.

On the assumption that a limited capacity object-file mechanism was being used, Leslie (1999) attempted to find the limit of objects that could be tracked and represented by 10-month-olds. The infants were tested in either a 2 – 1 = 2 (unexpected) condition, or a 2 – 0 = 2 (expected) condition. The slight change in methodology from previous arithmetic studies (i.e., the constant outcome) was used to avoid baseline problems and required the infant to set up a specific expectation for two objects. The infants did look longer overall in the unexpected condition than the expected. However, when tested in a 3 – 1 = 3 or 3 – 0 = 3 procedure, there was no difference in looking times between the two groups. Therefore, it was concluded that 10-month-olds lacked a specific representation for three objects, which may be coded as "many" or "more than two." Furthermore, he tested whether there was a general global (or total) limit to the number of objects that could be tracked at one time, or if this limit was a "per set" limit, leaving the possibility of perhaps two objects of one kind (e.g., identity) and, one or two objects of a different kind tracked and stored in memory. The conclusion drawn by Leslie only touched upon the issue of a global limit.

So the question of whether this representation is a global or per set limit was still unanswered at this point. Xu & Carey (1996) had 12-month old infants tracking one duck and one truck, two distinct items needing to be represented. But was this just two "things" being tracked, or was it specifically "one truck" and "one duck?" Leslie and his colleagues did several experiments to test if identification by feature served as an important marker held in the infant's formed representation. If so, such a finding might implicate per set tracking limits. In one experiment, 12-month-olds were shown one triangle placed behind a screen, then one disk behind the screen. The screen was then removed to reveal the disk and the triangle (expected) or two disks (unexpected) or two triangles (unexpected). A similar procedure was used to test for size discriminations. The infants were shown a small disk and a large triangle. The screen was then taken away to again reveal the small disk and large triangle (expected) or the large disk and small triangle (unexpected). The infants looked longer at the inconsistent outcome. Furthermore, Leslie et al. (1998) found that although 12-month-old infants did appear to encode location, shape, and size when tracking two sets containing one object, changes in the color of the objects went undetected. They claimed this was because not all featural information had been bound to the index.

It was previously established that 12-month-olds could track two distinct objects in a simultaneous fashion, and hold quite a bit of featural information in their representation. So Leslie (1999) tested to see if this number "two" again was a global limit or per set, by increasing the number to three objects. Twelve-month-olds were familiarized to the following scene: An occluding screen was raised on the stage. Two frogs were placed behind the screen, followed by one fish placed behind it. Each object was then individually lifted and again shown to the infant for two seconds, then replaced. At test, the screen dropped to reveal either two frogs and one fish (expected event) or one frog and two fish (the unexpected event). The infants showed no difference in looking times to the events. Leslie (1999) concluded the change in numerosity of the two sets went unnoticed. He claimed that in the first year of life, the infant has a tracking limit of one object per set, and an overall global limit to track two objects.

There are a few problems with Leslie's (1999) argument. Spatiotemporal features are first to be encoded, the most salient feature to the object-file system. Leslie et al.

(1998) indicate that an individual file can have featural information bound to it, but this information is not obligatory for creating a new file. Thus, in the previous study, identity features may not be bound yet. This is a gradual process requiring more exposure, greater processing demands, or more efficient encoding strategies that develop over time. As we see, in a set of two objects, 12-month-olds seem to be able to encode and bind some, but not all features to the index. What has been encoded and bound can be retrieved from memory in conjunction with the index, and compared to what is in perception. However, if files are opened for three objects, increased processing demands may in turn cause the infant to simply encode the spatiotemporal information, without features bound to the index. Consequently, three indices or "pointers" at the screen would in fact be opened. Upon comparison of the two fish and one frog (the unexpected event), there would be no mismatch to what is held in memory. This is contradictory to Leslie's (1999) claim that the limit of the object-file must be two. If the system is most responsive to tracking objects to some location, then it would be expected that when three objects were hidden, and three revealed, there should be equal looking time. The finding that there was differential looking to <u>two</u> featurally different items means that the featural information was able to be encoded into the file, and may have facilitated retrieval. But the lack of differential looking to three objects, changed in features, may simply mean that the featural information was not available upon retrieval of the files from memory. Perhaps by 12 months of age the infants actually are able to track three items. The only indicator that three objects may be over their tracking limit is the 3 – 0 = 3 versus the 3 – 1 = 3 test, but this may be misleading because of the ambiguity of a "zero" transformation. The hand entering the stage, going behind the screen, and then exiting the stage empty, could simply be a distraction and disruptive to what is held in memory.

A second problem with this study is that the author claims that two frogs, and one fish placed behind one screen, comprise two sets of objects. Yet, the object indexing system is location sensitive. As the Uller et al. (1999) paper emphasized in the final experiment, distinct location markers (two separated screens in that case) are fundamental to the object-file mechanism. Because the three objects behind the one screen only varied in identity, it was the only cue to facilitate the retrieval of those files in memory. As previously mentioned, featural information may not have initially been bound to the file. Another possibility is that the objects, all placed in one location (behind one screen) was more indicative of one set of objects to be tracked. On the other hand, if two screens were used in the display area, the distinction of two sets would have been perceptually more salient and could have facilitated the encoding of featural information. All this study can tell us is that three general objects were tracked behind a screen. The change in identity, similar to the results of Simon et al (1995) went undetected. Because the infants saw three objects placed behind one screen in both conditions, and showed equal looking time in both the expected and unexpected conditions, which both revealed a total of three objects, it cannot be determined whether the three objects exceeded their tracking limit (as the authors claimed), or was handled by a feature-insensitive tracking system that could track three objects. Furthermore, the same outcome (equal looking times between conditions) would also be expected if an accumulator mechanism were responsible. Three objects were placed, therefore the accumulator stored a value equivalent to three in memory. The accumulator is not responsive to identity issues. It is specific to number.

Or, by the Cohen & Marks perceptual account, the infants in both conditions may have had no expectation at all of what was to be revealed behind the screen. Instead, they may look for a longer time at three objects than anything less than that number, simply because three is more to look at. Because both groups contained three objects, they each had the same amount of "stuff" to look at and therefore the groups would not differ in their looking times according to this perceptual model.

The question of whether tracking limits are of global number or per set remains unclear to this point. Furthermore, most studies favoring an object tracking system, cannot rule out the possibility of a number mechanism or perceptual mechanisms as contributors to the obtained results. The current study makes unique predictions for each model. Additionally, the design allows for the determination of tracking limits, given that an object-file system is utilized in the task.

The Present Study

The violation of expectation paradigm was used in this study to test 10-month-olds in a two-screen, addition task. Infants' looking times were measured as they were presented with a total of five objects, which exceeds any representational capacity limits previously proposed.

One object was placed on the left-hand side of the stage, behind an unraised screen. Then the left side screen was raised, occluding the one previously placed object. One object was added behind the left, raised screen. Then one object was placed on the right hand side of the stage, behind an unraised screen. The right side screen was then raised, occluding the one object, and two objects were simultaneously added behind that screen. Therefore, only two updates had to be made, one per screen location. The sequence of events were counterbalanced, such that half of the infants saw one object added behind the left screen, and two added behind the right screen, and half the infants saw two objects added behind the left screen and one added behind the right.

There were eight test trials in which the infants always watched this same sequence of events. On four of the trials, the right screen was lowered to reveal the objects, and on the other four trials, the left screen was lowered. There were three conditions tested between subjects: 1) two objects revealed on each trial; 2) three objects revealed on each trial, and 3) two or three objects revealed. Therefore, in the first two conditions, all infants were presented with eight trials of the same sequence presentation, and all infants in the same condition saw the same number of objects in each outcome. Both the physical and arithmetical possibility and impossibility of the event depended on which screen was lowered and what had been placed behind the screen. In the third condition, four trials revealed two objects and four trials revealed three objects. Each infant saw two trials of two objects, which were arithmetically possible, two trials of two objects that were impossible, two trials of three objects possible, and two trials of three objects impossible.

To demonstrate, if the infant was in the "two objects revealed" condition, and watched one object added behind the left screen (for a total of two), and two objects added behind the right screen (for a total of three), then the left screen was lowered, to reveal two objects. This would be a physically possible event. However, if the right screen was lowered, and revealed two objects, this would be a physically and arithmetically impossible event. Therefore, the accumulator model would predict longer looking at the arithmetically impossible event (right screen down) than the possible event (left screen down).

Predictions of the object-file model in this example would vary, depending on the number of objects the infant could keep track of in memory. It is generally accepted that the infant cannot track more than four objects. Therefore, the presence of five objects exceeds the infant's representational storage limits. The questions of interest are as follows: What is the actual limit of items that can be tracked? When presented with an overload, which indexes get dropped from memory; the first ones established, or the most recent? Or, by overloading the attentional tracking system with more than it can handle, will this be disruptive and cause the infant to resort to relying on either an "analog-magnitude" mechanism, or simple perceptual processes to reduce the work of the attentional system?

The issue raised in the latter question is a plausible one that has never been fully addressed. In some of the previous transformation studies, it appears that the increase in processing demands (due to the number of objects, the number of updates, and the number of event sequences and event outcomes the infant is exposed to), may lead the infant to resort to some other mechanism, either perceptual or number, which may or may not elicit longer looking to an incorrect outcome. As demonstrated in the Uller et al. (1999) experiments, reducing processing demands of the task may increase the likelihood of an object-file mechanism being used successfully. Therefore, the demands placed on the object-file mechanism were reduced as much as possible by: 1) using two distinct and separate screens which serve as perceptually available location markers, 2) placing one object on the stage before the screen occludes it, as in Uller et al.'s (1999) object-first conditions, and 3) reducing the number of updates to two, (one per location) by adding two objects in at one time, as in Baillargeon et al. (1994).

Also, it may be the case that the infants fall back on perceptual mechanisms when presented with a greater variety of sequence events or outcomes, as in Poirier (2001), which presented four different sequence events within eight trials, and Cohen & Marks (2002) in which four different outcomes were revealed over eight trials. The majority of studies arguing for object-file or accumulator mechanisms have used a standard 'one presentation sequence – two different outcomes' design (e.g., Uller et al., 1999; Wynn, 1992), or a 'two different sequence – one outcome' design (e.g., Leslie, 1999; Wynn & Chiang, 1998). The addition of the third condition addressed this issue. If there is one mechanism that deals with object knowledge and number, and it is robust, then looking times should be consistent with one of the models' predictions in all three conditions. If infants rely solely on perceptual variables, such as looking at more objects, then this should be exhibited by longer looking at the three object trials than the two object trials in the "reveal two or three" condition. Additionally, they would exhibit overall longer looking in the "reveal three" condition than in the "reveal two" condition, with no other differences within each of these conditions[2]. However, if the presentation of four different outcomes is responsible for the "perceptual account," then the infants would exhibit the longer looking at three items than two items in the "reveal two or three" condition only, and could actually fit the predictions of a different model for the "reveal two" and "reveal three" conditions.

To address the former questions, regarding tracking limits, predictions can be exemplified using the procedural example of two objects placed left, three objects placed right. In this case, assume the ten-month-old infant has a tracking capacity of two objects, and can only hold on to the first two in memory, but loses the final three (primacy hypothesis). If the left screen rotates down and reveals the two objects, this is consistent with what is in memory; the number of files initially opened for that location matches the number of objects in perception. Therefore, there should not be long looking time for that trial. However, when the right screen rotates down to reveal two objects, the infant would have no files opened in memory for this location. This type of mismatch may yield longer looking[3].

On the other hand, what if the infant has a capacity to hold two object-files, but only retains the final two (recency hypothesis)? Then, if the left screen is lowered to reveal two objects (a possible event), the infant should look relatively long due to the fact that no files were open for the objects at that location. If the right screen is lowered to reveal two objects (an impossible event), and the infant has kept only two files open in that location, then looking time would be relatively short, as there would be a match between the files in memory and in perception. This is an instance where a distinction is made between the accumulator and the object-file. The object-file system, with a limit of the last two objects (objects 4 and 5 placed on the stage) provides the basis for viewing two objects revealed on the right as "consistent," whereas the accumulator would register this as "inconsistent" with the value for three objects previously placed behind the screen. In contrast, if the infant is simply relying on perceptual processes, there should be no preference for either event of seeing two objects. Rather, for the perceptual processing model, looking times should be fairly invariable from trial to trial, yet, on average, should yield shorter looking times than the average of the "reveal three" condition.

A list of all predictions made by the theories is presented in Tables 1-3. Table 1 displays the predicted looking times for the "reveal two objects" condition and "reveal three objects" condition for Event Sequence A, and Table 2 displays predictions for these conditions, for Event Sequence B. Note that for each model, the predictions (presented in the corresponding row) across the two conditions are unique. It is assumed that if one model is robust, the pattern of looking will fit the predictions for both conditions. These two conditions can make unique predictions for tracking up to three items only.

The "reveal two or three" condition makes unique predictions which include the infant tracking up to four objects, as presented in Table 3, with both Event Sequences included in this table. For Table 3, each models' predictions are represented by row. Note that for this table, each object placed is assigned a number, meaning the order of placement. So, for Event Sequence A, two objects are placed behind the left screen, (objects "1" and "2") and then three objects are placed behind the right screen (objects "3," "4," and "5," respectively). For Event Sequence B, objects "1" "2" and "3" would be placed behind the left screen, and objects "4" and "5" would be placed behind the right screen. Each column displays a prediction for trials of Event Sequence (A or B), number of objects revealed in the trial (2 or 3), and the screen lowered (right or left), as well as whether the outcome was considered possible or impossible.

CHAPTER 2

METHOD

Participants

Forty-eight full-term 10-month-old infants participated in this study (M = 10 months; four days, range = 9;20 – 10;15). The 28 males and 20 females were randomly assigned to one of three conditions (16 infants tested per condition). Participants were identified and recruited through state birth records for the Amherst, Massachusetts vicinity. Parents were contacted via letter and a follow up phone call. Written parental consent was obtained for each infant. Participation was voluntary, and a certificate was given in appreciation.

Apparatus

Objects were presented on a puppet stage with an opening 48 cm high, 85 cm wide and 37.5 cm deep, and raised 102 cm from the floor. The stage floor was made of black foam board. The side walls were covered in black fabric, with a hole on each side for the experimenter's hand to enter. The back wall was made of yellow foam board, which had a black grid pattern (58 cm^2) to camouflage the lines from the hidden trap doors. The two trap doors were cut out exactly on the black gridlines, each 7.62 cm from center stage. Each door measured 15.24 high cm x 15.24 cm wide. A black curtain was attached at the front of the stage. The experimenter pulled on a string to raise the curtain so the stage display could not be seen between trials. At the beginning of each trial, the curtain dropped down to reveal the stage. The room lighting was dimmed during the entire experiment, with the exception of the stage lighting: two 40 Watt tubular light bulbs toward the front of the stage, and one 15 Watt fluorescent placed directly above the center of the stage, out of the infant's direct line of sight. This lighting minimized the amount of shadows cast by the screens and objects. Classical music was played in the background at a low volume, which helped mask any sound made by the opening and closing of the trap doors.

In the center of the stage were two foam board screens (22.9 cm high x 21.6 cm wide) each placed 3.81 cm from center (7.62 cm apart). The left hand screen was attached to a plastic black pipe 1.6 cm in diameter, while the right hand screen was attached to a wooden dowel, placed through the pipe, measuring .95 cm in diameter. The entire extension of the dowel from stage left to its end point, just past the right hand screen, was 70.13 cm. The dowel extended just slightly past the right screen (2.22 cm) where it was fastened to the floor but could still be rotated freely. The pipe, which held the dowel, extended 46.31 cm from stage left to right, ending at the point just past center where the second screen, connected to the dowel, began. These rods were controlled by a second experimenter, who sat on the left side rear of the stage, out of the infant's sight. This experimenter used the dowel and pipe to rotate the screens up and down (from flat against the stage floor up to a 90 degree vertical angle and back down) to occlude and reveal portions of the stage. When the screens were rotated up, they were white in color, distinctly different from the black floor, sides, and yellow background. When the screens rotated down, they were black and blended with the floor color. The objects used in this study were rectangular red foam blocks with plastic googly eyes and a yarn smile (15 cm high x 7.5 cm wide) and would squeak when squeezed. The experimenter wore long black gloves to blend in with the surrounds, so as to focus the infant's attention on the object.

Equipment

A video camera, discretely placed at the front of the stage, atop the stage ceiling, recorded each infant straight on. A second camera, placed behind the infant recorded the events as they occurred on the stage. A video mixer, in a separate room, allowed the two camera inputs to be recorded onto one tape. The primary large image was the view of the infant, while the smaller insert at the bottom of the screen revealed the event that occurred on the stage. A monitor was placed in a separate room so an experimenter could code the infants' looking times online. The online coding information fed into a computer. The program accumulated the looking time, and signaled (via an audible beep) the end of each trial, so that each trial was infant-controlled.

Procedure

Infants sat in an infant seat, placed 30 cm from the front of the stage. They were placed at a height where their eyes were approximately at the midpoint of the rotating screens (12 cm above the stage floor). The parent sat behind the child, and was asked not to interact with the child during the test trials. Three experimenters were needed for the experiment. The first was positioned behind the stage, out of the infant's view, and presented the objects. The second experimenter sat at the side of the stage, also out of the infant's view, and controlled the rotation of the screens. A third experimenter was at the computer in a separate room, viewing the infant and coding looking time.

Infants were assigned at random to one of three conditions: *reveal two objects*; *reveal three* objects; or *reveal two or three*. The conditions will hereafter be referred to as Condition 2, Condition 3, and Condition 2/3, respectively. All infants went through the same introduction procedure.

Introduction Phase

Following the method used in other studies, using a double-screen procedure (e.g., Wynn & Chiang, 1998; Uller et al., 1999, expt 4) the infants were exposed to the experimenter's gloved hands, and also given one of the objects, and encouraged to manipulate and explore it for 60 s. The infant was then introduced to the stage. The curtain was lowered and raised twice. Then the infant viewed the two screens rotate up to vertical separately, the left screen raised to vertical and lowered, followed by the right. Next, the left screen rose to the vertical, then the right. While both screens were raised, the gloved hand entered from one side, moved in front of the screen, stopped at center between the screens and tapped the floor. The hand retracted, tapped the floor at the other side of the screen, then moved behind the screen to center and tapped the floor, then the back wall, to emphasize the solidity. Then the hand retracted, and both screens lowered. Then the right screen rose, followed by the left. The experimenter repeated the sequence entering from the other side, so that the infant had seen the hand enter from both sides of the stage, and the hand move behind and between both screens. This has been suggested to not only help the infant understand the boundaries of the solid floor and back wall, but also the boundaries of the screens. The partially hidden trajectory of the gloved hand serves as an additional cue of two solid screens separated in space at two distinct locations (Uller et al., 1999).

Condition 2

Eight infants in this condition were shown an event sequence A, and the other eight were shown event sequence B. In Event Sequence A, the infant watched two objects placed behind the left screen, then three objects placed behind the right screen.

This event sequence occurred in the same order on all familiarization and test trials. In Event Sequence B, the infant watched three objects placed behind the left screen, and two behind the right, always in that order on all trials.

Familiarization trials

The familiarization trial procedure was modeled after similar studies that have used a violation of expectation paradigm, in which the infant viewed the entire sequence of events (i.e., objects presented on the stage, screens raised, objects placed behind the right screen, then objects placed behind the left screen) with the exception that the screens never rotated down to reveal an outcome. There were two trials of this type. Each trial began when the curtain was raised, and ended 4 s after the sequence of events.

All trials began with the infant seeing an empty stage. A gloved hand entered from the left side of the stage holding one object, as the experimenter said, "Look baby! Look at this!" The experimenter then squeaked it once and placed it on the left-hand side of the stage. The left screen then rotated up, occluding the one object placed there, as the experimenter said, "Up goes the screen!" Next, one object was brought in from the left, squeaked, and placed behind the left screen, while the experimenter said "Look baby! Look at this! Where's he going? Where's he going baby?" This script, and that below, is taken from the Wynn (1992) study, not reported in the paper, but obtained from Wynn (personal communication, December 12, 2000).

A hand then entered from the right side of the stage with another object, repeated "Look baby..." squeaked it, and placed it on the right side of the stage. The right screen then rotated up, occluding the object on the right side, as the experimenter said, "Up goes the screen!" The hand reentered from the right, this time holding two objects, squeaked them, and placed them behind the right screen, while repeating "Look baby! Where are they going? Where are they going Baby?" The curtain then closed, and the event was repeated for one more trial. Infants in the Event Sequence B saw two objects added behind the left screen, and one object added behind the right, in that order.

Test trials

There were eight test trials. On four of the test trials, the left screen rotated down to reveal an outcome of two objects. On the other four test trials, the right screen rotated down to reveal an outcome of two objects. Therefore, in Event Sequence A, the left side revealed resulted in an arithmetically possible event, whereas the right side revealed resulted in an impossible event, and vice versa for Event Sequence B.

The eight test trials contained two blocks of four possible/impossible outcome pairings, (four blocks of P/I and I/P combinations) such that a possible event always directly preceded or followed an impossible event. There were a total of 16 unique trial type orders, as shown in Table 4. All trial type orders were used in each condition, half with Event Sequence A, and half with Event Sequence B. Table 5 displays the balancing of Trial Type and Event Sequence across conditions 2, 3, and 2/3.

Test trials began when the curtain lowered, revealing the empty stage. The infants saw the same procedure as in the familiarization trials, except that at the end, one of the screens lowered to the stage floor to reveal an outcome of two objects. If the infant watched two objects placed behind the screen that was to be lowered, and two objects were revealed, this was considered a "possible" trial type. If the infant watched three objects placed behind the screen that was to be lowered, and two objects were revealed, this was considered an "impossible" trial type. For this to occur, the experimenter surreptitiously removed one object through a trap door in the back wall while the screen was still rotated up to vertical. On trials where the number revealed was consistent with the number placed, a trap door was also opened and closed, to keep any sound made by its opening consistent throughout all trials. Looking times were measured from the moment the screen lowered until the infant had either looked away for 2 seconds, or when 30 s had elapsed. The computer collecting the data beeped to signal the end of the trial. The curtain was then raised to occlude the stage. Ten seconds elapsed before the start of the next trial.

Condition 3

Familiarization trials

Familiarization trials were exactly the same as in condition 2. Half of the infants in this condition saw Event Sequence A and half saw Event sequence B.

Test trials

Test trials were also exactly the same as Condition 2, except that three objects were revealed when one of the screens was lowered. Therefore, on trials considered to be "impossible" (meaning, two objects were placed behind a screen, but three were revealed), the experimenter surreptitiously added one object through the trap door behind the screen. Again, infants were randomly assigned to a Sequence and Trial Type order, which were the same impossible/possible sequences as in condition 2. However, the screens revealed (left side or right side) for possible and impossible trials are opposite that of condition 2. For example, in Condition 3, Event Sequence B ("3B"), after three objects are placed behind the left screen and two behind the right, revealing three objects behind the left screen would be a "possible" trial type, and revealing three objects behind the right screen would be an "impossible" trial type. In contrast, an infant in Condition 2B, if given the same order of P/I trials (as shown in Table 5), the "possible" trial type would be the right screen revealing the two objects, and the "impossible" trial type would be the left screen revealing two objects. For this reason, each P/I trial order alternated by Event Sequence A or B. This method balances trial type with side revealed.

Condition 2/3

Familiarization trials

Infants watched the same familiarization trials as in the previous two conditions. Half were presented with Event Sequence A and half with Event Sequence B.

Test trials

Infants in this condition were tested on trials similar to the previous conditions, with one exception: they were exposed to four different outcomes, as opposed to two. In the previous two conditions the infants watched the same event sequence, always followed by the same outcome number. Trials varied only by which screen was lowered. In condition 2/3, the infants watched the same event sequence (A or B) with the following outcomes revealed: 1) left screen lowered to reveal two objects, 2) left screen lowered to reveal three objects, 3) right screen lowered to reveal two objects, and 4) right screen lowered to reveal three objects. Whether or not a trial was a possible or impossible trial type depended on which event sequence was presented and what was revealed. Each infant saw two trials of two objects revealed/impossible event, two trials of two objects/possible event, two trials of three objects/impossible event, and two trials of three objects/possible. The eight trials were blocked into two blocks of each of the four outcome events. Two object trials were paired with three object trials, and possible trials were paired with impossible trials, and randomized within each block. Sixteen sequences of P/I events resulted, as shown in Tables 4 and 5. In addition to the Possible/Impossible combinations paired, trials alternated by number of objects revealed. Therefore, the first 4 trials had one trial of each kind (possible/two objects, impossible/three objects, impossible/two objects, and possible/three objects).

Measures

The dependent measure of interest in the study was looking time (in seconds) from the lowering of the revealing screen until the infant had looked away from the display for 0.5 seconds or longer. Because the experiment is testing a potentially fragile memory, it is assumed here that any sort of look-away from the objects will decrease attention to and memory for them. This is a slightly different measure than those typically used in looking time studies. Most studies using looking time measures use "total looking time" measured by the length of time looking at the display until 30 s had elapsed, or the infant had looked away for two seconds. However, upon review of the previous looking time studies with infants, one can see that the majority of infants are in the 4.5-8 month range in age. Ten- to twelve- month old infants are often more difficult to study in a looking time paradigm, because they are much more active at this age, and do not want to be sitting still for very long. The infants who were included in this study were able to sit still during at least four trials, but they did have some look-aways of up to 1.9 seconds long before ever having a two second look-away. It only takes half a second for an infant to completely turn his face away from the display and back again. These brief look-aways could interfere with the memory of events that just took place on the stage. For this reason, 0.5 second look-aways were used as the cut-off for looking time to each trial. In the present context, this is a more sensitive measure of attention than time until a two second look-away. However, analyses were conducted on 'total looking time" also, because the trial lengths did use the criterion of a 2 s look-away for the trial to end. These results, as well as detailed analyses of the number of "shorter than 2 s look-aways" can be found in the appendix.

Design and analyses

The study was a factorial design with Condition and Event Sequence as between-subjects variables, and Trial Type and Number as within-subjects. The first variable of interest was condition, tested between-subjects. Condition 2 infants always saw an outcome of two objects, Condition 3 infants always saw an outcome of three objects, and Condition 2/3 infants saw outcomes of both two and three objects. Therefore, the variable number of objects (two or three) was tested between-subjects for Condition 2 and 3, and within-subjects for Condition 2/3. Trial type designates the within-subjects variable for impossible versus possible events. Other variables looked at were tests for differences in event sequence A and B (between-subjects) and side revealed (right or left screen, within-subjects) were also conducted. No effects were predicted for these variables.

An accumulator mechanism should produce a significant main effect of trial type in the omnibus ANOVA across all three conditions, and in all other analyses. If the mechanism is robust, infants should consistently look significantly longer to arithmetically impossible trials than possible ones, regardless of the condition or the event sequence they were tested in. If the perceptual processing position is correct, there should be a main effect of number, such that the infants look longer at outcomes of three objects than at outcomes of two objects. However, an omnibus ANOVA cannot test the variable number of objects. If the perceptual processing is correct, there could potentially be a slight effect of condition due to the nature of outcomes in conditions 2 and 3. This position can therefore only be analyzed by testing Condition 2 versus Condition 3 separately (a test of the variable condition = a test of the variable number), and testing for number within Condition 2/3 separately. Contrasts were conducted for the Object-file predictions made in Tables 1-3. If the Object-file mechanism is dominating the response, average looking times should fit one of the patterns (presented in the Table rows), and should be significant for all three conditions if this mechanism is robust.

CHAPTER 3

RESULTS

Interobserver Reliability.

A primary observer (ENC) scored looking time on each trial for all 48 infants, and a secondary observer (KO) scored looking time on each trial for 18 of the 48 infants. A mask was placed over a portion of the monitor to prevent the observers from seeing which events occurred. A Pearson's r of .91 indicated interobserver agreement was high. The primary observer's judgments were used for analysis.

Omnibus Analysis:

Test for the Accumulator and Perceptual Processing Models.

Analyses were conducted using the length of each infant's looking time to an event prior to the first look away. A 3 x 2 x 2 x 2 ANOVA was performed for Condition (2, 3, or 2/3) x Trial Type (Possible or Impossible) x Block (Block 1 = trials 1-4 or Block 2 = trials 5-8) x Event Sequence (A or B), with condition and sequence as between-subject variables, and block and trial type as within-subject variables. There was a significant effect of block, $F(1, 42) = 14.69$, $p < .01$, where length of first look was greater in block 1 ($M = 5.68$, $SD = 2.05$) than in block 2 ($M = 4.36$, $SD = 1.35$). There was also a significant effect for trial type, $F(1, 42) = 5.39$, $p < .05$. Over all three conditions, the length of the infants' first looks was longer for arithmetically impossible trials ($M = 5.41$, $SD = 2.08$) than for arithmetically possible trials ($M = 4.62$, $SD = 1.39$). There were no significant interactions.

Because attention is best at the beginning of the experiment, the following analyses are only for those trials in Block 1. Using the first four test trials only for analysis should yield the most reliable data for the following reasons: 1) Criterion for the data being included in the analysis was that the infant had to complete four test trials. Therefore, all of these data points are included in the analysis. Although the average number of trials completed by infants in this study was 7.06 (SD = 1.22,), the number completed ranged from four trials (3 infants) to eight trials (26 infants). Therefore the means in Block 2 are not reliable. Experimenters also agreed that by trial 5, infants showed an increasing amount of disinterest and fussiness, therefore some trials were excluded from the analysis, or the experiment ended early if the child became too fussy to sit in the seat, thereby completing fewer trials. 2) Analyses within all Conditions showed a significant effect of Block, with looking times in the four trials consistently longer than in the last four trials. A detailed analysis within each block of each condition, using dependent measures first look, total looking time, and number of look-aways can be found in the appendix.

When the above ANOVA was repeated for trials within block 1 only, there were no significant effects or interactions found across all three conditions. The previous effect of trial type is misleading, as it was largely influenced by the last four trials. If the accumulator is the underlying mechanism influencing behavior in this task, it should be present across all trials. The accumulator mechanism is not a learning-based mechanism that improves with experience. Therefore, the omnibus analysis including blocks 1 and 2 should not be taken as support for the accumulator.

The data for length of first look was recoded to test for effects of Side the objects were revealed (right or left), and tested in an ANOVA for Condition, Sequence, and Side within the first four trials. The variable side could not be included in the previous analysis because it is confounded with trial type. For example, in Condition 2, given event sequence A, the impossible trials were always revealed on the right side, and the possible trials were always on the left side. In Condition 2, given event sequence B, impossible trials were always revealed on the left side, and possible trials were always revealed on the right side. An overall preference for one side might play an influential role in these results, and should be considered when interpreting this data.

In the ANOVA there was an effect of side, $F(1, 42) = 3.95$, $p = .05$, such that infants looked slightly longer to the objects revealed behind the right screen ($M = 6.17$, $SD = 3.28$), than to the objects revealed behind the left screen ($M = 5.19$, $SD = 2.03$). This slight preference for the objects revealed from behind the right screen may be due to: 1) an inherent preference to look toward the right side, 2) the side of presentation always went from objects placed behind the left-side screen and then behind the right-side screen (a recency effect), or 3) some factor due to the experimental variables being manipulated (e.g., condition or sequence). For this reason, the side variable was included in all subsequent analyses. There was a side x sequence interaction, $F(1, 42) = 4.09$, $p = .05$, as shown in Figure 1. Although there was no difference in the length of the first look to either side when presented with sequence A, the infants preferred to look at the objects revealed from behind the right side when presented with sequence B. This difference between left and right side revealed in sequence B is significant, $t(23) = -2.76$, $p = .01$.

Conditions 2 and 3:

Tests for the Accumulator, Perceptual Processing, and Object-File Models.

Analyses for Condition 2 and 3 were conducted to test the predictions for all three theories. An ANOVA was conducted for variables sequence, condition, and trial type.

There were no significant effects within the first four trials of these conditions. The Accumulator model predicted longer looking for the impossible trials. However, this model was not supported, as impossible trials (M = 5.69, SD = 2.92), yielded looking times across both conditions similar to the possible trials (M = 5.41, SD = 2.64). The Perceptual Processing Model predicted no difference in possible versus impossible test trials within Conditions 2 and 3, so this part of the prediction was supported. However, the crucial second part of the Perceptual Processing prediction, namely the longer average looking time to events in Condition 3, for which more objects were revealed on each trial, was not supported. In fact, the infants actually looked longer, on average, in Condition 2, where two objects were revealed (M = 5.91, SD = 2.04), than in Condition 3, where three objects were revealed (M = 5.19, SD = 2.11). However, this difference was also not significant. When the data were recoded for the variable side, there were no significant effects or interactions.

In testing for the Object-file predictions on the dependent measure first look, contrasts were performed based on the predictions made in Tables 1 and 2. There was a significant effect for the prediction that the infants remember the last two objects placed behind the right-hand screen, $F(1, 28) = 5.49$, $p < .05$. None of the other Object-file predictions approached significance.

Condition 2/3:

Tests for the Accumulator, Perceptual Processing, and Object-file Models.

An ANOVA was conducted within block 1 for between-subject variable sequence, and within-subject variables number and trial type. There was a significant effect of trial type, $F(1, 14) = 6.30$, $p < .05$, with longer first looks to the impossible trials

($M = 6.74$, $SD = 2.94$) than to the possible ($M = 5.14$, $SD = 1.68$). The type x number interaction was significant within this these first four trials, $F(1, 14) = 9.56$, $p < .01$. As shown in Figure 2, two object trials did not differ in looking times to different trial types ($M_{TWO/POSSIBLE} = 5.98$, $SD = 2.76$; $M_{TWO/IMPOSSIBLE} = 5.24$, $SD = 2.60$). But, looking times differed considerably for three object trials ($M_{THREE/POSSIBLE} = 4.30$, $SD = 1.34$; $M_{THREE/IMPOSSIBLE} = 8.24$, $SD = 4.50$). T-tests revealed these means were significantly different for the following comparisons: a) two objects/possible versus three objects/possible, $t(15) = 2.43$, $p < .05$; b) two objects/possible versus three objects/impossible, $t(15) = -2.30$, $p < .05$; c) two objects/impossible versus three objects/impossible, $t(15) = -2.71$, $p < .05$; d) three objects/possible versus three objects/ impossible, $t(15) = -3.35$, $p < .01$. There was also an interaction of sequence x number, $F(1, 14) = 4.43$, $p = .05$, as displayed in Figure 3. There was longer looking time to three objects when infants were tested in sequence B, than in sequence A, and very little difference looking at two objects, regardless of whether the infant was initially presented with sequence A or B. A t-test revealed the difference between two objects and three objects revealed in sequence B was significantly different, $t(7) = -2.43$, $p < .05$.

When recoded for side, there were no significant main effects. There was the side x sequence interaction, $F(1, 14) = 9.56$, $p < .01$, as displayed in Figure 4. Whereas sequence A showed a decrease in looking time from left side to right side, sequence B showed an increase. Even more informative was a sequence x side x number interaction, as shown in Figure 5. Although there was little difference between presentation sequence and side when two objects were revealed, there was much more variability when three objects were revealed. Moreover, Figure 5a reveals that there was no effect of trial type when two objects were revealed. When two objects were revealed on the left, infants looked longer if given sequence A, which was a "possible" trial, than sequence B, which was an "impossible" trial. When two objects were revealed on the right, there was no difference in looking time. In Figure 5b, this sequence x side interaction for three objects revealed appears to be the source of the trial type effect in Condition 2/3. When three objects were revealed on the left side, infants looked longer if given sequence A, which was an "impossible" trial, than infants in sequence B, which was a "possible" trial. When three objects were revealed on the right side, infants looked longer when in sequence B, which was an "impossible" trial, than those in sequence A, which was a "possible" trial.

Although the significant effect of trial type found in Condition 2/3 fits the prediction of the Accumulator model, these interactions do not. Therefore, there is limited support for this model, because the Accumulator cannot account for the influences of side revealed and presentation sequence on looking time behavior. Thus, a different sort of explanation may be required in interpreting this data.

The Perceptual Processing model predicted longer looking in this condition to the three object trials than two. This model was not supported by the data, as looking to three objects ($\underline{M}$ = 6.27, $\underline{SD}$ = 2.35) was not significantly different than to two objects ($\underline{M}$ = 5.61, $\underline{SD}$ = 2.28). However, as can be seen in the type x number interaction in Figure 2, longer looking occurred when three objects were revealed if it was also an impossible trial. Furthermore, mean looking time was even greater, as shown by Figure 5b, when three objects were revealed, it was an impossible trial, and it occurred on the right side. This result may, in part, be due to some contributing influence of perceptual processing.

To test for the possibility of the Object-file mechanism being used in this condition, contrasts were performed on trials within Block 1, based on the predictions made in Table 3. There was a significant effect of the infants remembering the last four objects presented, $F(1, 14) = 5.99$, $p < .05$. This effect appears to be a product of confounding factors, inflating the rightmost column mean in Table 3; that being for sequence B, three objects, right side, impossible; rather than real support for the Object-file predictions, and will be addressed in the discussion to follow.

CHAPTER 4

DISCUSSION

If there were only one numerical processing mechanism responsible for number and object knowledge, the candidates being the Accumulator, the Object-file, and Perceptual Processing mechanisms, and it was robust, then the looking times displayed by 10-month-olds would be consistent with its predictions across all three conditions. The present study does not consistently support one of the three mechanisms. No single mechanism accounted for the infants' responses in this number-based task. Rather, the results show a complex pattern, requiring a complex explanation. Specifically, the results can be interpreted in terms of all three mechanisms contributing to the pattern of looking behaviors.

The strongest evidence overall favors the Object-file model. The results best fit the predictions made for Conditions 2 and 3. This is because of the significant contrast indicating that infants remembered the last two objects placed behind a screen. This interpretation is further supported by the lack of any interactions in these conditions, as none were predicted by the model. In contrast, Condition 2/3 appears to fit the prediction of the Accumulator model, namely longer looking at the impossible trials. However, the Accumulator model also does not predict the presence of any interactions. Therefore, the interactions found in Condition 2/3 weaken the argument for an accumulator account for looking behavior in this task.

The Accumulator

If the infants used an accumulator mechanism to discriminate quantity then, in all conditions, they would look longer to the arithmetically impossible test trials than to the possible trials. At first glance, this appeared to be the case, because the Omnibus analysis of all eight trials showed this pattern of looking. Yet, when the omnibus analysis was repeated for the first four trials only, when attention was at its best, the effect disappeared. Moreover, the means displayed in Figures 6 and 7, which separate two object trials from three object trials, reveals the "Trial Type" effect seems to be coming only from the three object trials in Condition 2/3.

Condition 2/3 taken by itself, appears to provide some support for the Accumulator model. Infants in that condition looked longer to arithmetically impossible trials than possible trials. This finding supports the findings of Wynn (1992) and others. An analog-magnitude mechanism could explain the data found in Condition 2/3, to a degree. The pattern of longer looking to the impossible events only appears in trials with three objects revealed, but not two objects. This finding is similar to that found in Koechlin et al. (1997). In their study, in the 2 – 1 subtraction condition longer looking times to two object (impossible) trials was solely responsible for the "possibility effect." Looking to the impossible addition trials (1 + 1 = 1) was not different from the possible addition trials (1 + 1 = 2). In this sense, the possible/impossible trial type effect occurred on the trials with the greatest number revealed and with arithmetical impossibility. The results in Condition 2/3 fit the same pattern. These results no more support the interpretation that all infants looked longer to impossible trials than to possible, than did the results of Koechlin et al., despite their making such claims, and thereby contradicting their own results. Looking longer to impossible trials was only found in Condition 2/3, and occurred only when three objects were revealed. The question now becomes, if the Accumulator mechanism was used to make numerical calculations in Condition 2/3, the attentionally more demanding condition, why was it not responsible for performing the simpler, more repetitive calculations needed in Conditions 2 and 3?

Perceptual Processing

The results do not support the Perceptual Processing Model as the sole mechanism in guiding looking behavior. There were no significant effects of number in any of the conditions tested. Of course, the Perceptual Processing Model cannot be completely discounted because the Cohen & Marks (2002) model, which these predictions were based on, takes the position that it is the effects of familiarity and a tendency to look longer to larger numbers of objects ("more") that elicit the longer looking. By only testing one piece of the assumptions made by the model ("more" versus "less"), the present results may not be an entirely accurate reflection of the model because there was never a "familiar number" outcome.

Although the number variable was not significant, it did interact with other variables in Condition 2/3, in such a way that reflects a preference to look at "more," given the right circumstances. In Condition 2/3 the infants looked longer to the impossible trials, as previously discussed. Interestingly, the longest looking times were found when three objects were revealed AND the trial type was impossible, as reflected by the Type x Number interaction in Figure 2. This could be because of some perceptual processing. Within Condition 2 and within Condition 3, the same number of objects were always revealed. In contrast, in Condition 2/3 different numbers of objects were revealed on different trials. The varied number outcomes presented may have contributed to the differential looking pattern across trials because some trials had "more" to look at, and some had "less," whereas in Conditions 2 and 3, the "amount" to look at was always the same across trials.

But, to take the perspective that the differences in "amount" are eliciting these differential looking patterns, one could argue the looking behaviors are exclusively perceptually-based. There is evidence that infants do respond to simple changes of amount in tasks meant to be number-based. For example, Starkey & Cooper (1980) showed that four month-olds dishabituated to arrays that changed in number (two or three dots). This was not only a change in number, but also a change in amount. However, in a similar habituation procedure, Clearfield and Mix (1999) found that infants did not dishabituate to changes in number, but only to changes in contour length of the stimuli. One of greater relevance to the present study is Feigenson, Carey, & Spelke's (2002) results. In a transformation study they pitted number against "continuous extent" (i.e., surface area). They found that infants looked longer to changes in extent than to changes in number. Moreover, Feigenson, Carey, & Hauser (2002) found that when given the choice, 10- to 12-month old infants will discriminate based on extent rather than number. These studies show that infants may be more sensitive to perceptual changes along a continuous dimension rather than discrete number per se.

Is it possible then to interpret the present results as due to the detection of changes in amount only? This is a difficult claim to make in the present study, because a change in number was confounded with a change in amount. In the task, if the infant watched two objects placed behind a screen, and then two objects were revealed, it was a same number/same amount trial. If the infant watched two objects placed behind a screen, then three objects were revealed, this is a different number/different amount trial. The predictions made by the accumulator model would be the same as a model that predicted longer looking to changes in amount. Therefore, if the results were consistent in finding longer looking to impossible trials than to possible trials, then determining whether the mechanism used to make this discrimination was number-based or perceptually-based could not be teased apart.

This perceptually-based account of looking behavior faces the same problems as the number-based accumulator position. The data for Conditions 2 and 3 fail to support that infants were responding based on perceptual changes in amount (which were the arithmetically impossible trials). The only significant change in amount detected was for three objects in Condition 2/3. Likewise, this position fails to account for the finding of Starkey & Cooper (1980), where infants failed to detect the perceptual change in amount of four dots from six dots presented. While this was used as evidence for an accumulator, number-based mechanism, taken together these data argue against the position that infants only are responding to perceptual changes in amount. Such an argument could be made that this is because some other mechanism was involved in the task, which has implications for memory and set-size being represented.

Perhaps in the present study, as earlier suggested, it is the occurrence of different number outcomes facilitating differential looking to "more" (three objects) than "less" (two objects) when these outcomes sometimes involved a perceptual change in amount (possible or impossible). In a recent study by Feigenson, Carey, & Hauser (2002) 10- and 12- month-olds watched two crackers, of equal size, placed in a container. Then they watched three crackers, all same size as the previous two, placed into a second container. The infants were then given the chance to crawl to one of the containers. The infants reliably chose the container holding three crackers, indicating they understood, and preferred the container that had "more."

In the present looking time study, there does seem to be something special about revealing "more" objects than "less" objects. Not only did three objects elicit longer looking in Condition 2/3 when the trial was impossible, but a three-object trial also elicited longer looking when it was revealed on the right side. An examination of several studies by Wynn reveals that for all experiments in which a claim for the accumulator mechanism was made, all important actions and manipulations occurred on the infant's right side. For example, in the Wynn & Chiang (1998) study, a double-screen procedure was also used. It differed from the present study, in that both screens were lowered at the same time on all test trials. However, all object transformations (i.e., the addition or subtraction of an object) were always made on the right side. Therefore, any arithmetical differences that needed to be detected were always on the right. So, either there is some inherent preference for the right side, or the Accumulator and Object-file mechanisms work most efficiently when objects revealed are those to the right. But this side preference is not a property of the Accumulator model. On the other hand, the idea of a preference for looking at "more" objects in conjunction with being revealed on the right side (the most recently transformed objects) is a plausible one. The preference strongly appears to implicate the demands placed on memory. Because memory demands should not be a problem for the Accumulator nor Perceptual Processing in this task, but they are problematic for Object-file mechanism, the latter model may best explain this result.

Object-Files

One initial question of this research asked if there is an object-file system present and functioning in the infant, then what is the actual limit of items that can be tracked? The results in this study support Leslie's (1999) claim that 10-month-old infants can keep track of and represent at least two objects. The results further support Leslie's suggestion that the two-object limit is global, because the infants in the present study did not show evidence for remembering two objects on each side (a per set limit), which would have been supported by a significant contrast for remembering the first two objects placed also. However, the "first two" contrast was not significant.

Given that the tracking limit is a global one, the second question prompting this study asked which indexes get dropped from memory; the first ones established, or the most recent? The contrasts conducted between Conditions 2 and 3 indicated that the infants remember the two most recent indexes established. The most recent objects, always presented and then hidden behind the right screen, are more salient in memory, whereas the indexes presented earliest (behind the left screen) are most likely to get dropped from memory. This alone could explain the preferential looking to the right side.

The issue of what might happen to these "dropped" indexes was considered when making predictions based on the object-file mechanism. One possibility was that indexes "dropped" from memory would elicit longer looking time than events revealing an "expected," or "possible" outcome. However, the data did not support this conjecture. Looking times to events on the left side were not longer relative to the "possible" outcomes revealed on the right side. This finding is similar to that of Wynn & Chiang

(1998). There, the infants watched an object hidden behind each of two screens. When the object was taken away from the right-hand screen, the infants did not look longer to the "magical appearance" of the object on the right than they did to an "expected appearance" (when one object was added to the right-hand screen that previously had nothing behind it). The argument made was that an accumulator does not hold an expectation for zero, so there was no expectation, therefore no mismatch. It may be the case that an object-file does not hold the value zero either; that the dropped indexes for objects behind the left screen may simply decay or vanish and new files may be assigned when objects are revealed on the left. This does not require extra looking time to do, and there is no mismatch in perception, because no explicit expectation was formed due to these files being gone.

While this accounts for some of the data in the present study (in Conditions 2 and 3), it does not account for the impossible/three object trials in Condition 2/3. These trials elicited longer looking when objects were revealed on both the left and right sides. However, if infants in Condition 2/3 relied on the Accumulator mechanism for these trials, the issue of "no expectation" behind the left screen does not apply. It is assumed by the model that there can be more than one accumulator. For this study, only two accumulated values need to be held in memory, one value for the left screen, and one value for the right screen. There has been no previous evidence indicating accumulated values are dropped from memory, unless the value is zero, which is not the case here. The accumulator can account for part of the results in Condition 2/3, because the three-object trials elicited longer looking to impossible trials, regardless of whether revealed on the left or the right side. As shown in Figure 7, the pattern of looking was similar to both sides. No other condition elicited a consistent possible/impossible pattern of looking between sides revealed. In fact, of the means displayed in Figure 6 and 7, the Condition 2/3 – three-object trials were the only trials in which the differences were significant at the .05 level. But in Conditions 2 and 3, where the looking times to the left were relatively short, the best fitting explanation seems to be the right side preference due to dropped indexes, implicating the probable use of an Object-file mechanism.

Another question posed in this study was, would increasing the number of outcome types over trials to four be disruptive and cause the infant to resort to relying on either an "analog-magnitude" mechanism, or simple perceptual processes to reduce the work of the attentional system? This question was answered by the inclusion of Condition 2/3. It was speculated that the presentation of four different outcomes could result in the infants looking longer at three items than two items in the Condition 2/3 only, and could actually fit the predictions of a different model for the "reveal two" and "reveal three" conditions (Conditions 2 and 3, respectively). This turned out to be confirmed, although the results most favor the accumulator mechanism, or a number-based explanation, rather than Perceptual Processing. The reason the findings best support a number-based mechanism, rather than the detection of a perceptual change in amount is because of the failure to detect changes in amount when two objects were revealed. If infants were using total surface area as the primary cue, then they should have detected the change from three objects to only two. The finding that they did detect the difference when three objects were revealed, suggests that some other mechanism was being used, which may have had something to do with the greater number. Because the accumulator is implicated as best dealing with larger numbers, outside of the representational capacity, at this point it seems the most plausible mechanism. In Condition 2 and in Condition 3, where the trial outcomes were identical in number within conditions (they only varied by side revealed), the possible decrease in overall attentional processing demands demonstrated an efficient use of an attentional tracking mechanism for two objects. Neither the accumulator nor perceptual processing can explain or account for this pattern of looking in these conditions.

In Condition 2/3, there was a significant contrast for infants tracking the last four objects hidden, which appears to be arbitrary at first glance. However, the effect is inflated due to the mean for Sequence B/Three objects revealed/Right screen/Impossible trials. If the object-file contrasts for remembering the last two objects and the last three objects hidden were also significant, then this contrast for the last four objects would be convincing. Because these other contrasts did not approach significance, it seems most likely due to a combination of factors such as: three objects ("more"), Event Sequence B (having last seen only two objects hidden behind a screen), arithmetical impossibility, and a right side preference. Because all of these factors seem to contribute to greater looking time, the implications of the result are not decisive.

Leslie (1999) argued that the number of object-files a 10-month-old can hold in memory is two. This was based on equal looking times found in a 3 – 1 = 3 and 3 – 0 = 3 procedure. Leslie concluded that 10-month-olds lacked a specific representation for three objects, which may be coded as "many" or "more than two." Earlier in this paper it was suggested that the presence of the hand moving in and out in the 3 – 0 = 3 trials might have been disruptive to a fragile memory trying to retain three files, and they were not successful due to this disruption. The addition of a third file to memory is fragile at this age, and cannot carry identity information in the file, as suggested by Leslie et al. (1998). But the system may be efficient enough to hold a primitive third index, encoding spatial location information only. The significant contrast for Conditions 2 and 3 does support Leslie's (1999) claim of a two-object limit. But the present study does not rule out the possibility of a fragile representation developing for a third object held in memory. The pattern of looking times to events on the right side is very different than to the left side. This may further implicate the memory and processing of objects most recently seen.

To demonstrate, assume the 10-month-old infant can represent the two objects most recently hidden behind the right screen. Furthermore, assume this infant is developing an ability to keep track of three objects in memory, but this ability is not consistently successful. There are four scenarios that could have taken place in this study: First, if two objects are placed behind the right screen, and two are revealed, a short looking time to the event would be expected, because the infant can easily match the number of open files in memory to the objects in perception. This is a "possible" outcome, and occurred when infants were shown Event Sequence B, with two objects revealed on the right. Second, if two objects are placed behind the right screen, and three objects are revealed, this is a clear mismatch of the files in memory to what is in perception, and longer looking to this event would be expected. This is an "impossible" outcome, and is what occurred when infants were shown Event Sequence B, with three objects revealed on the right. Third, if three objects are placed behind the right screen, then two objects are revealed on the right, the infant views this as consistent, or "possible," because ability to open and remember two object files is easiest, and readily accessible. It is more difficult to remember the third, more primitive file opened. This third file is a graded representation of sort (Munakata, 2001). In this case, there is not longer looking to the event, which occurred when infants were shown Event Sequence A, with two objects revealed on the right side. But, in the fourth scenario, the ability to hold three open indexes in memory occurs when three objects are placed on the right, and three objects revealed, as occurred when infants were shown Sequence A, three objects revealed on the right side. The ability to open this third file and hold it in memory is fragile, but the memory is facilitated by the revealing of three objects immediately after they are hidden, with no other disruption. The third, graded representation is strengthened by the presence of the third object in perception. There is little chance of a 10-month old infant remembering three objects on the left. Too many other disruptions have taken place, such as objects placed on the right, the raising of the right screen, and the passing of more time. It is possible to remember three on the right, if the three objects are hidden, three files opened in memory, and then three objects are revealed and matched up shortly thereafter.

This notion that infants can remember at least the last two objects, and possibly more, can explain the facilitating effect of sequence B in this study. Assuming that anything placed behind the left screen has little or no chance of being remembered, sequence B gives the infant an advantage of only needing to remember those last two objects placed on the right. This results in longer looking in sequence B to three objects, than to any other type of event, because this is most likely to be detected as incorrect. The interaction of sequence with number, as found in Condition 2/3 is important, particularly because of the ease with which one might have made a blanket statement that the accumulator mechanism accounts for the results of Condition 2/3. But the accumulator mechanism should not be influenced at all by the presentation sequence or the number of objects revealed. The finding of no difference between two objects/possible and two objects/impossible in Condition 2/3 was also a problem for the accumulator explanation. The interactions of sequence with side revealed (Figure 1 across all conditions, and Figure 4, for Condition 2/3), and sequence with number (Figures 3 and 5 in Condition 2/3) requires a more complex explanation than what is offered by only one of these models.

Therefore, it is possible that this task created a conflict between a developing representational system (i.e., Object-files) and a primordial analog-magnitude system. If infants keep track of the two most recently seen objects (on the right) and they are trying to remember a fragile representation for a third object (but only when presented on the right, as in sequence A) they might not always be successful in their discriminations. This could be because the number of objects approaches the boundary of the representational capacity in memory (two or three objects). The accumulator, which is implicated in number discrimination tasks that exceed the infant's representational ability (e.g., Xu & Spelke, 2000), may take over at this point. Such a mechanism can be used, as shown in previous studies of adult estimation (e.g., Whalen et al, 1999), and young children's estimations (e.g., Huntley-Fenner, 2001), when quantities are too great, or presented too rapidly, to count with accuracy. Furthermore, it supports the argument that an accumulator mechanism may be responsible for 5-month-olds' looking behaviors in addition and subtraction tasks (Wynn, 1992, 1995, 1997). Endowing the five-month-old infant with the ability to add and subtract, or rather, make calculations and form expectations about the hidden objects, is an extravagant claim to make, when it is not conclusive as to whether infants can even represent and reason about hidden objects at all at this age (Bogartz, Shinskey, & Schilling, 2000). But, the accumulator does not necessarily rely on object representation, it is only a neural mechanism generating pulses of energy that are stored and tagged with an analog. The Object-file mechanism would not be functional at five months of age, because infants must have the ability to represent the hidden objects. By 10 months, there is no dispute that infants are able to represent and remember hidden objects. Therefore, in this task, either mechanism could have been called upon, whereas with much younger infants, an accumulator could be the only number-based mechanism available.

Then, given these two mechanisms (Object-file and the Accumulator) are both available, what factors decide their fates? Perhaps it is perceptual factors, namely, the number of objects revealed. As suggested by the Cohen & Marks (2002) model, as well as by others (e.g., Koechlin et al., 1997), looking at "more" may take longer than looking at "less," the simplest reason being that there is more "stuff" to look at when there is more. If, 1) it takes longer to look at "more," and 2) an impossible event typically elicits the longer looking than possible events, then, by this reasoning, one could argue the longest looking time should occur on trials with "more" (three objects) that are also impossible, and the shortest looking time should occur on trials involving "less" (two objects) that are possible. On the other hand, perceiving fewer objects ("less") could facilitate processing of the information that the amount is equivalent to the files being held in memory. The perception of "more" could take longer because there is more to look at, and the amount may or may not be too large to be represented in memory, at which point the accumulator may take over.

The 10-month-old is trying to represent objects and quantities in the real world. The early perceptual processes and analog-magnitude mechanisms are contributing to this rapidly developing ability to represent and remember. The findings reported here support the Xu & Spelke (2000) suggestion that the use of an analog-magnitude mechanism or the use of an Object-file mechanism may depend on the size of the set being worked upon. Future work to test the claims made herein would be helpful, such as reducing the numbers to one and two objects hidden and revealed, and testing if the predictions hold up for the object-file model. The issue of a right-side preference and a recency effect should be tested by presenting the objects on the right side, then the left side. Also, testing 12-month-olds could answer the question of the fragile representation of "three objects" in memory. By this age, the representation may not be so fragile.

To summarize:

1) There is some supporting evidence for the Object-file model. Namely, 10-month-old infants can successfully track and store at least two objects in their memory. In Conditions 2 & 3, the infants showed looking behavior in accordance with the prediction made between the two conditions for representing and remembering the last two objects hidden behind a screen.

2) Analyses across all three conditions indicated that infants' initial looks to an event were longer for arithmetically impossible events. However, the effect only occurred in trials revealing three objects in Condition 2/3. There was no difference in looking time to possible and impossible events when two objects were revealed. Therefore, there is minimal support for the Accumulator Model,

which seems to be used in circumstances of high attentional demand and the number of objects revealed exceeds representational memory capacity.

3) The perceptual processing model cannot be completely discounted in this experiment. Although the infants did not always look longer to events revealing three objects than events revealing two objects overall, there was something unique about the trials that revealed "more" objects (three), than "less" (two). The trials that were arithmetically "impossible," elicited longer looking times only if three objects were revealed, but not when two objects were revealed.

4) Testing for number-based representational abilities, or any higher-level cognitive abilities, in a procedure where the each infant is presented with the same events and the same number of objects revealed has an important advantage. The chance of obtaining results due to simple perceptual processes as familiarity preferences or size preferences are eliminated. In the present study, Condition 2 and Condition 3 provide a sort of baseline for Condition 2/3. The complex results of Condition 2/3 illustrate the delicacy of the processing that occurs in the 10-month old, and how easily a seemingly simple change in procedure can elicit a change in the interpretation of results.

Based on these results, it is suggested that 10-month-olds are in a transitional period of representational development, where two mechanisms, an analog-magnitude mechanism (accumulator) and an attention-based object-file system are in "competition" when faced with a task involving a number of objects just slightly over what the limit the object-file can track and represent. Whereas the object-file attention-based mechanism may be readily functional for representing small numbers of objects at this age, the accumulator could be best equipped to deal with processing larger numbers of objects than can be represented and held in memory. Simple perceptual mechanisms, such as detection of "more" and "less" may be used as a bootstrapping mechanism dictating which representational mechanism will dominate the infant's response.

Table 1: Looking Time Predictions for Each Theory in Conditions 2 and 3, for Event Sequence A

	Condition 2: Reveal 2		Condition 3: Reveal 3	
	Left screen lowered *(Possible)*	Right screen lowered *(Impossible)*	Left screen lowered *(Impossible)*	Right screen lowered *(Possible)*
Accumulator	SHORT	LONG	LONG	SHORT
Perceptual/Number	SHORT	SHORT	LONG	LONG
Object-file				
Limit first 2	SHORT	LONG	LONG	LONG
Limit last 2	LONG	SHORT	LONG	LONG
Limit first 3	SHORT	LONG	LONG	LONG
Limit last 3	LONG	LONG	LONG	SHORT

Note. Event Sequence A = 2 objects behind left screen, 3 objects behind right screen.

Table 2: Looking Time Predictions for Each Theory in Conditions 2 and 3, for Event Sequence B

	Condition 2: Reveal 2		Condition 3: Reveal 3	
	Left screen lowered *(Impossible)*	Right screen lowered *(Possible)*	Left screen lowered *(Possible)*	Right screen lowered *(Impossible)*
Accumulator	LONG	SHORT	SHORT	LONG
Perceptual/Number	SHORT	SHORT	LONG	LONG
Object-file				
Limit first 2	SHORT	LONG	LONG	LONG
Limit last 2	LONG	SHORT	LONG	LONG
Limit first 3	LONG	LONG	SHORT	LONG
Limit last 3	LONG	SHORT	LONG	LONG

Note. Event Sequence B = 3 objects behind left screen, 2 objects behind right screen

Table 3: Looking Time Predictions for All Theories in Condition 2/3, for Both Event Sequences

	Sequence A				Sequence B			
	Two Objects Revealed		Three Objects Revealed		Two Objects Revealed		Three Objects Revealed	
Outcome	Left *possible*	Right *impossible*	Left *impossible*	Right *possible*	Left *Impossible*	Right *possible*	Left *Possible*	Right *impossible*
Accumulator	SHORT	LONG	LONG	SHORT	LONG	SHORT	SHORT	LONG
Perceptual/Number	SHORT	SHORT	LONG	LONG	SHORT	SHORT	LONG	LONG
Object-file: 12	SHORT	LONG	LONG	LONG	LONG	LONG	LONG	LONG
Object-file: 45	LONG	LONG	LONG	LONG	LONG	SHORT	LONG	LONG
Object-file: 123	SHORT	LONG	LONG	LONG	LONG	LONG	SHORT	LONG
Object-file: 345	LONG	LONG	LONG	SHORT	LONG	SHORT	LONG	LONG
Object-file: 1234	SHORT	SHORT	LONG	LONG	LONG	LONG	SHORT	LONG
Object-file: 2345	LONG	LONG	LONG	SHORT	SHORT	SHORT	LONG	LONG

Note. Event Sequence A = Two Left, Three Right. The object-file predictions are in the left column are named in terms of the number order which the objects were placed. For Sequence A, objects number 1 and 2 are behind the left screen, and objects 3-5 are behind the right screen. Event Sequence B = Three Left, Two Right. Objects number 1-3 are behind the left screen, and objects 4 and 5 are behind the right screen.

Table 4: Sixteen Trial Type Orders for Possible/Impossible Pairings

	Trials 1-4			
	PIPI	PIIP	IPPI	IPIP
Trials 5-8				
PIPI	PIPIPIPI	PIPIPIIP	PIPIIPPI	PIPIIPIP
PIIP	PIIPPIPI	PIIPPIIP	PIIPIPPI	PIIPIPIP
IPPI	IPPIPIPI	IPPIPIIP	IPPIIPPI	IPPIIPIP
IPIP	IPIPPIPI	IPIPPIIP	IPIPIPPI	IPIPIPIP

Note. P = Possible, I = Impossible.

Table 5: Event Sequences (A or B) tested in 16 Trial Type Orders for Conditions 2, 3, and 2/3

	Trials 1-4			
Trials 5-8	PIPI	PIIP	IPPI	IPIP
PIPI				
Condition				
2	A	B	A	B
3	B	A	B	A
2/3	A	B	A	B
PIIP				
Condition				
2	B	A	B	A
3	A	B	A	B
2/3	B	A	B	A
IPPI				
Condition				
2	A	B	A	B
3	B	A	B	A
2/3	A	B	A	B
IPIP				
Condition				
2	B	A	B	A
3	A	B	A	B
2/3	B	A	B	A

Figure 1: Sequence x Side interaction for First Look across all three conditions

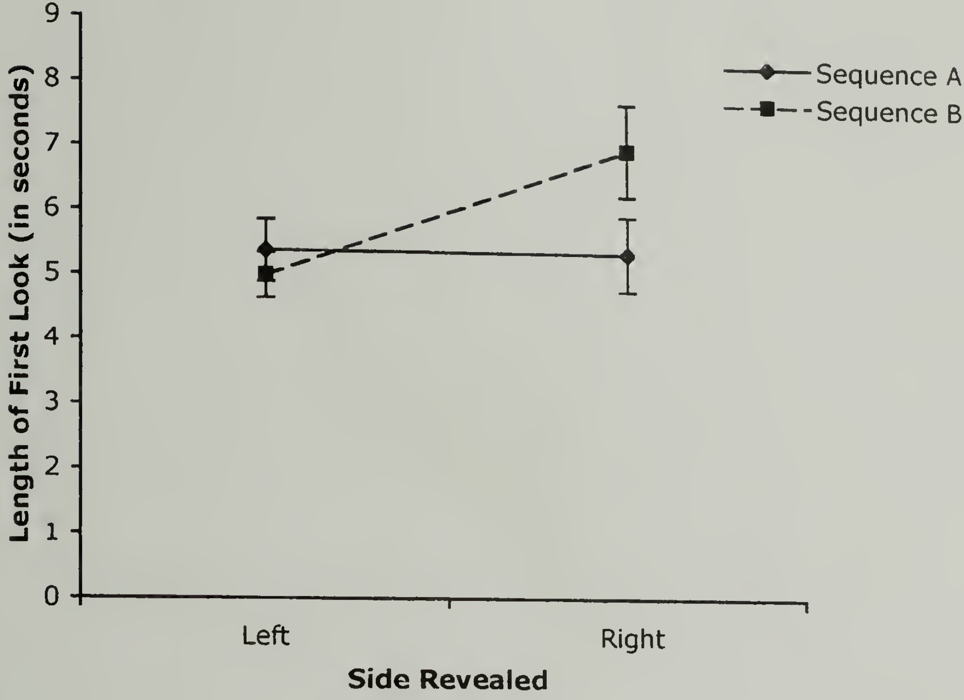


Figure 2: Type x Number interaction for Length of First Look within Block 1 of Condition 2/3

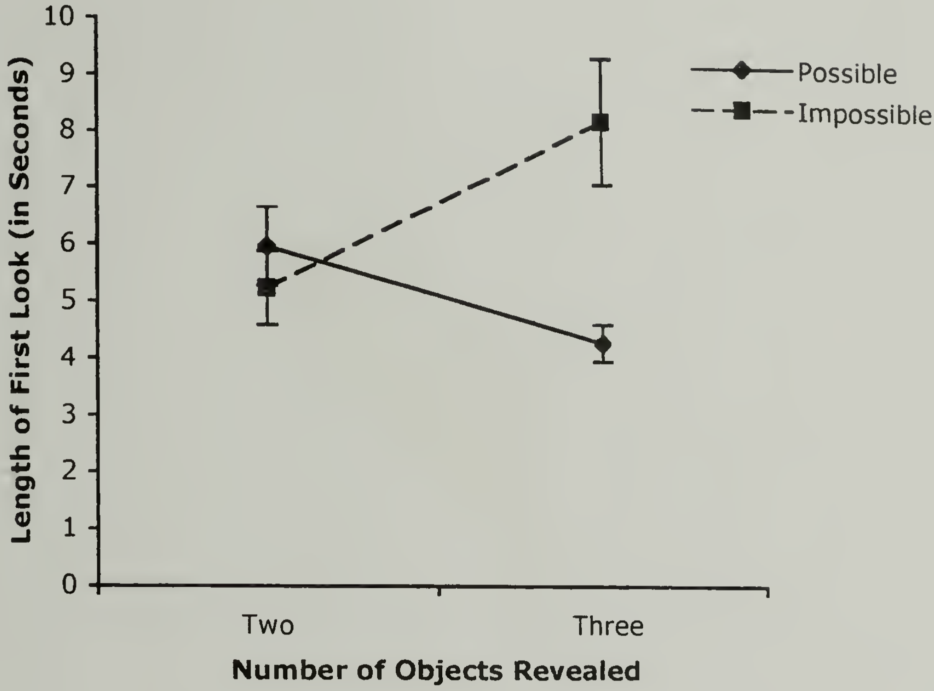


Figure 3: Number x Sequence interaction for Length of First Look within Block 1 of Condition 2/3

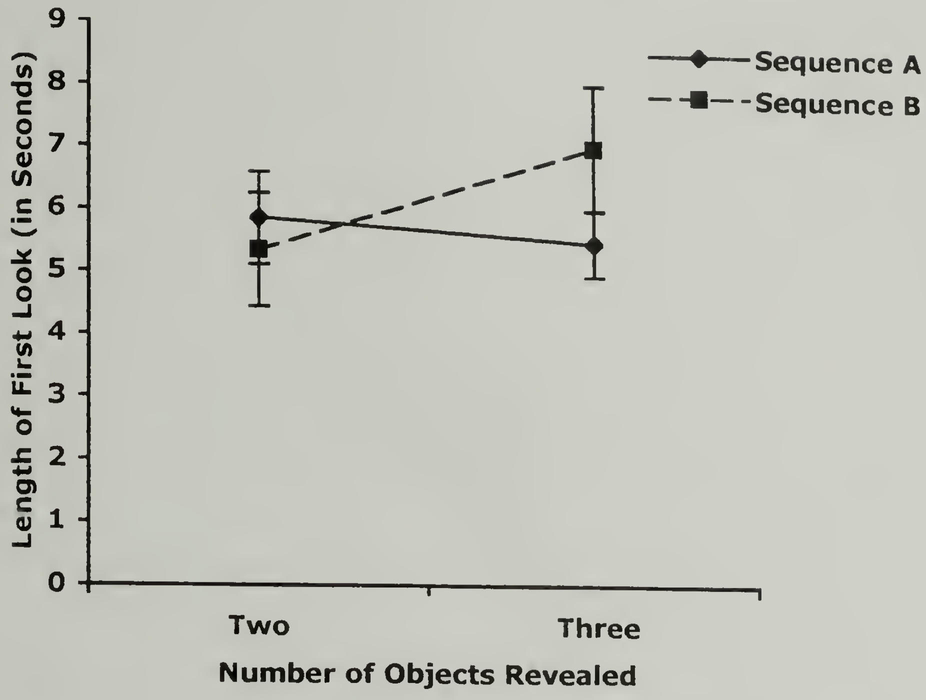


Figure 4: Side x Sequence Interaction for Length of First Look within Block 1 of Condition 2/3.

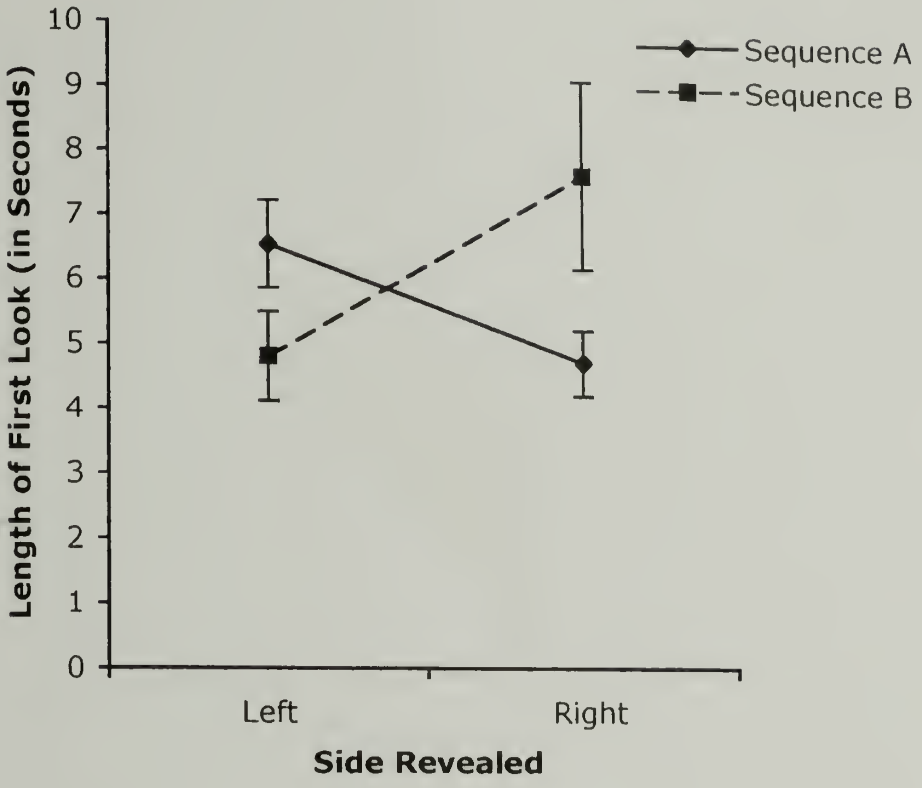
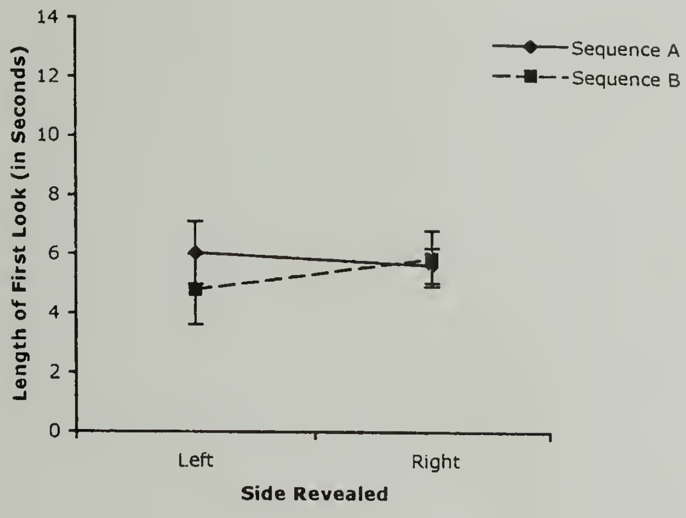


Figure 5: Sequence x Side x Number interaction for Length of First Look within Block 1 of Condition 2/3.

A) Two objects revealed



B) Three objects revealed

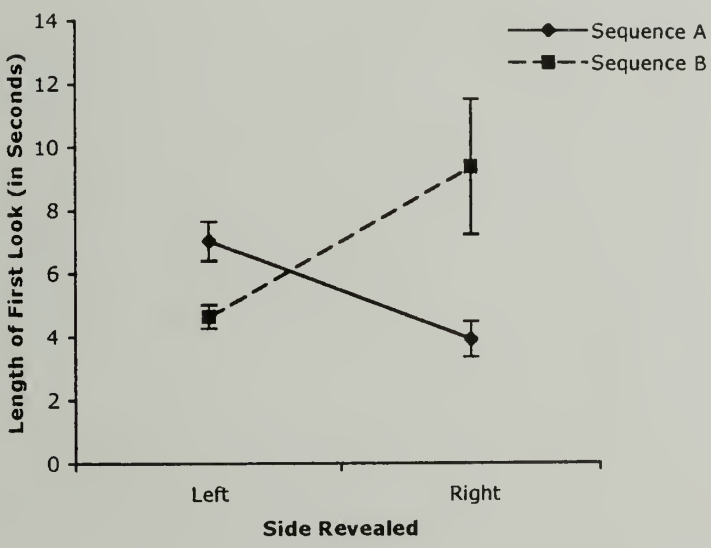


Figure 6: Length of First Look (in Seconds) to Possible and Impossible Events of Two Objects Revealed on the Left and Right Sides

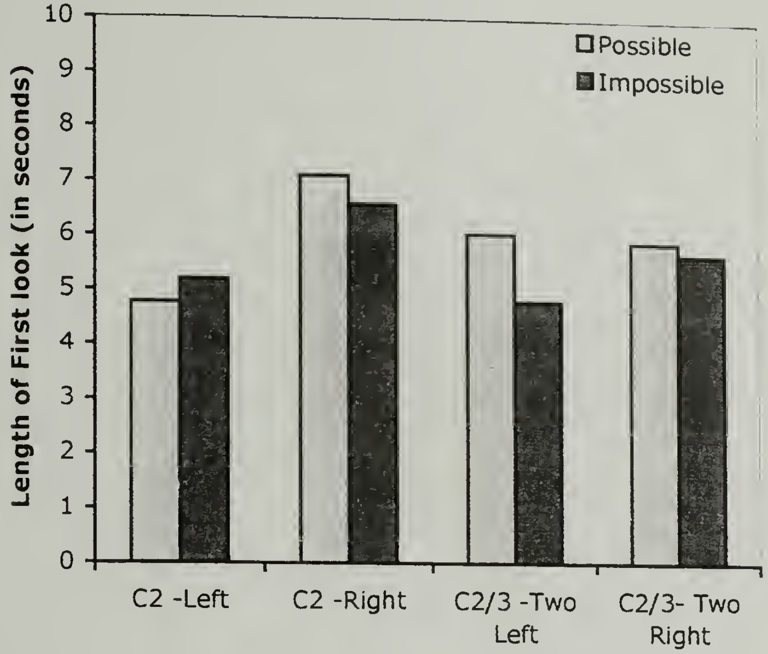
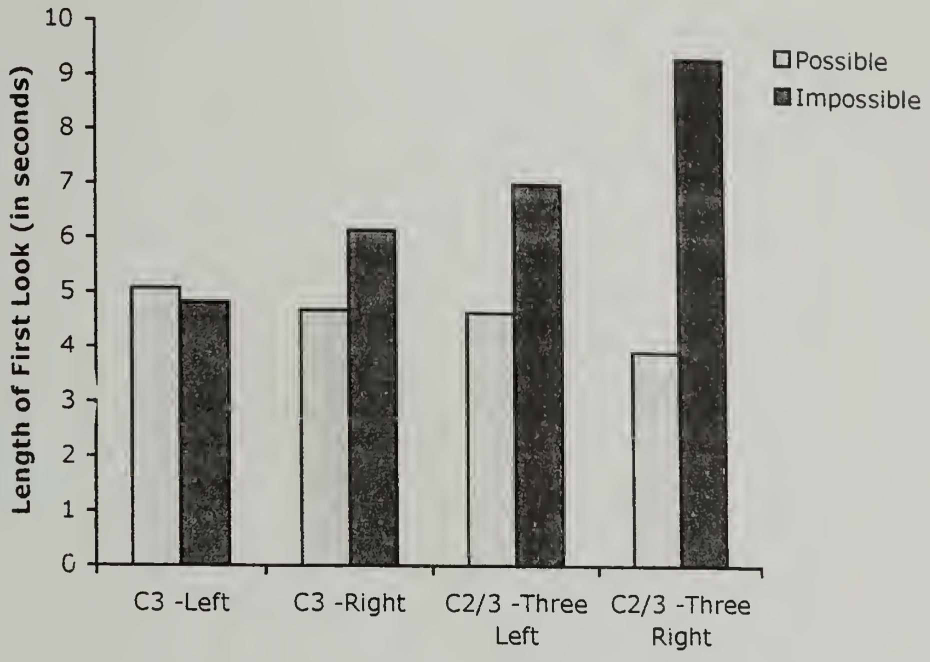


Figure 7: Length of First Look (in seconds) to Possible and Impossible Events of Three Objects Revealed on the Left and Right Sides



ENDNOTES

[1] Trick and Pylyshyn (1994) used this object-file type of model to account for adult subitization, a rapid nonverbal enumeration ability, which has been proposed to utilize the same process or mechanism as infant preverbal enumeration. Adults can typically subitize up to four or five items. Notice that the explanation of failure in the Starkey & Cooper (1980) four to six comparison is due to the number of items being too large for infants to track and hold in memory. It seems a plausible argument can be made that this is evidence for a limited-capacity tracking mechanism which is limited to two or three items in infancy, but with development, increases to four or five. However, the accumulator model, which has also been suggested to underlie adult subitization, as well as the infant preverbal number studies discussed herein, can also account for the failure of the four-versus-six discrimination. The numbers are large, but this model would posit that it was the 2:3 ratio which is important, in addition to the distance effect (there is only a difference of two), and therefore discrimination is more difficult than even a two-versus-four discrimination (where the difference is also two, but the ratio of items is 1:2). Thus, both models can account for the results of the Starkey & Cooper (1980) study.

[2] In the study by Cohen & Marks (2002), they claimed that the role of perceptual processes is exhibited through a looking preference for the familiar, plus a tendency to look at more objects. Because there is no "familiar" outcome in this study, predictions are made by this model solely on the assumption of longer looking to more objects.

[3] It remains unspecified in the object-file literature how the infant will respond to the lack of open files in memory when the right screen reveals three objects. No open files might constitute a definite expectation for nothing (zero objects) behind the

occluder. In this case, the "magical appearance" (Wynn & Chiang, 1998) of an object could elicit longer looking due to the mismatch between the perception of three objects and the expectation of zero objects. Alternatively, the lack of open files pointing to that particular location might mean that no expectation exists whatsoever. This could result in several possibilities, not all mutually exclusive: 1) looking time is not as long to this "appearance" (regardless of the number of objects) than to an outcome that clearly mismatched (e.g., two files had been opened and compared to three objects in perception) because there was not necessarily a mismatch in this case, simply assignment of new files to the objects, 2) the assigning of new files to the objects may or may not result in long looking times, because nothing is known about the time involved in "de-assigning" files from one location and "re-assigning" them to a new location, as described by Leslie et al. (1998), and 3) longer looking may occur to three objects than two, due to no expectation and therefore falling back on a simpler perceptual mechanism of looking longer at more objects. Conversely, there may be equal looking time to two and three objects revealed in a location with no files in memory, because no outcome was expected, and therefore both are equally unexpected. Because it is unclear how infants will react in such a case if they are using an object-file mechanism, some of the predictions involving the tracking limits of two or three objects, where instances of no open files for a particular location may occur, are made with caution. Patterns of looking are considered when data was analyzed, to address these concerns. For purposes of this thesis, the author assumed in the predictions that the assigning of new object files to a new location involves longer looking time than if opened files were simply matched with those in perception.

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