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Attentional Modulation Of Infant Visual Short Term Memory

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ATTENTIONAL MODULATION OF INFANT VISUAL SHORT-TERM MEMORY

by

Shannon Ross-Sheehy

An Abstract

Of a thesis submitted in partial fulfillment
of the requirements for the Doctor of
Philosophy degree in Psychology
in the Graduate College of
The University of Iowa

December 2005

Thesis Supervisor: Professor Lisa M. Oakes

ABSTRACT

Previous work has demonstrated that infant visual short-term memory (VSTM) capacity increases dramatically between 6 and 10 months of life (Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development, 74*, 1807-1822). However, it is unclear if this increase is a function of improving memory abilities, or alternatively, if it is a function of improving attentional abilities. Moreover, it is currently unknown if infants, like adults, can use attention to form stable VSTM representations in situations where they would otherwise fail. Four experiments explored the relationship between visual attention and VSTM in 5.5- and 10-month-old infants. Results indicated that 1) 10-month-old infants are able to use attention to selectively encode items into VSTM, 2) this ability does not appear to be present in younger infants, 3) this ability does not appear to interact with the complexity of the test array, and 4) attentional facilitation requires a relatively salient cue. Taken together, these results are the first to demonstrate that infant VSTM representations can be mediated by visual attention, and that this mediation relies on relatively well-developed visual attention mechanisms.

Abstract Approved: ______________________________
Thesis Supervisor

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Title and Department

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Date

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Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

Shannon Ross-Sheehy

has been approved by the Examining Committee
for the thesis requirement for the Doctor of Philosophy
degree in Psychology at the December 2005 graduation.

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To my family and friends for their unwavering optimism, and especially to Andrew Sheehy and Jake Ross-Sheehy for their steadfast and tireless support. I absolutely could not have accomplished this without them.

ABSTRACT

Previous work has demonstrated that infant visual short-term memory (VSTM) capacity increases dramatically between 6 and 10 months of life (Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development, 74*, 1807-1822). However, it is unclear if this increase is a function of improving memory abilities, or alternatively, if it is a function of improving attentional abilities. Moreover, it is currently unknown if infants, like adults, can use attention to form stable VSTM representations in situations where they would otherwise fail. Four experiments explored the relationship between visual attention and VSTM in 5.5- and 10-month-old infants. Results indicated that 1) 10-month-old infants are able to use attention to selectively encode items into VSTM, 2) this ability does not appear to be present in younger infants, 3) this ability does not appear to interact with the complexity of the test array, and 4) attentional facilitation requires a relatively salient cue. Taken together, these results are the first to demonstrate that infant VSTM representations can be mediated by visual attention, and that this mediation relies on relatively well-developed visual attention mechanisms.

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CHAPTER 1: INTRODUCTION

Specific Aims

Although there is an extensive literature on the development of memory in infancy (see Cohen & Gelber, 1975; and Rovee-Collier & Hayne, 1987 for reviews), relatively little is known about the development of short-term memory, how it interacts with other visuo-cognitive systems, and how they jointly constrain what infants learn about their visual environment. Before the onset of language, infants must begin to construct knowledge based on their visual experiences. Importantly, an infant's ability to form object representations is critically impacted by the developmental state of his or her visual, attentional, and memorial systems. Thus, a clear understanding of the developmental underpinnings of these early visual representations is vital for a full understanding of cognitive development in the first several months of life.

Previous research exploring the development of infant visual short-term memory (VSTM) has uncovered significant developmental changes in how much visually presented information infants can remember (Ross-Sheehy, Oakes, & Luck, 2003a). At 4 and 6.5 months infants seem to be able to remember only one visually presented object, but by 10 months infants seem to be able to remember multiple visually presented objects, perhaps as many as 3 or 4. Without a doubt, this change in VSTM capacity affects how infants learn about the visual world. This thesis seeks to untangle the interactive effects of developing visual attention and VSTM on cognitive development by investigating how infant performance on a VSTM task is enhanced by the presence or absence of an attentional cue, and if developmental changes in attention can account for 5.5-month-old infants inability to remember more than one object in a VSTM task.

The experiments presented this thesis are grounded in work that has been conducted in our lab over the past several years exploring the development of infant VSTM capacity. However, this thesis represents a significant departure from our previous work, attempting to tease apart the effects of developing VSTM and visual attention, and how they jointly determine what an infant can remember about a visual scene. In addition, this thesis explores the possibility that this interaction between attention and VSTM might be determined, in part, by the developmental state of the attentional system.

Background

Adult and Infant Short-Term Memory

Determining how infants learn about the world around them is arguably the sine qua non of infant cognitive research. For centuries, philosophers and scientists have debated the impact of early learning and experience on later cognitive abilities. Thus, understanding what infants learn from their visual experiences is critical for our understanding of child development from infancy to adolescence. Consider, for example, an infant attempting to learn a novel face that is briefly presented. The infant will note each eye, the nose, the mouth, the hairline, and so on. However, younger infants may be able to remember fewer individual features than would older infants. Clearly, such developmental differences in memory capacity would have implications for what infants at different ages learned and remembered about that face. Importantly, this early learning lays the foundation for normal cognitive development throughout childhood.

Visual short-term memory is particularly important in the process of learning about objects. VSTM is a short-term, active store for visual information that has not yet been encoded into long-term memory (Baddeley, 1986). These representations are formed very quickly, are prone to interference, and are highly capacity limited (Baddeley, 1986; Baddeley & Logie, 1999). The latter of these features is perhaps the most striking, as VSTM capacity for adults is thought to be around 3-4 object's worth of information (Luck & Vogel, 1997). The limited capacity of VSTM constrains the amount of information that one can keep active in memory, which may have important processing consequences. For example, when driving on a crowded interstate, in order to change lanes quickly, you must be able to maintain VSTM representations for cars behind you, to your left and to your right. Clearly, VSTM capacity limitations have some practical significance here. If there are fewer than 4 cars, this problem should be relatively trivial, and the driver should be able to maintain representations for each of the cars. However, if there are more than 4 cars, then our driver would likely remember only a subset of the total cars. Undoubtedly, this driver would be in a dangerous position, as they would need to constantly recheck the mirrors to update their VSTM representations. Moreover, this constant re-sampling of the visual scene likely makes it nearly impossible to focus attention on the road ahead.

This example highlights the practical significance of understanding VSTM capacity limits and how that impacts our daily lives. Fortunately, despite the extreme limits on our VSTM, adults are able to act and react in the world with little difficulty. This may be possible in part, due to our ability to limit attention to a meaningful subset of information present in a given visual scene, such as the location of a particular car, in a particularly relevant lane. Because infant VSTM capacity appears to be limited to just one object for the first 6 months (Rose, Feldman, & Jankowski, 2001; Ross-Sheehy et al., 2003a), the role of attention is perhaps even more significant. For example, even very young infants are able to recognize the face of their mother by attending to only a subset of the facial features such as the eyes or the hairline (Bartrip, Morton, & De Schonen, 2001).

Infant VSTM

Short-term memory for visual information may be necessary for infants to have a coherent experience of the visual world. At birth and for the first several months of life, infant vision undergoes a dramatic period of development (Atkinson, 1984). Because these pre-linguistic infants rely heavily on visual information to fuel their conceptual development, the ability to detect and remember objects, people, and events is essential for normal cognitive development. VSTM is critical because it allows infants to form stable representations despite the relatively fragmented visual input (e.g., eyeblinks, saccades, and occlusion) available to the infant. Indeed, relatively stable object representations are necessary for cognitive processes such as comparison, categorization, and word learning, and for motor processes such as reaching and exploring.

Object Representations and VSTM

There has been a good deal of work examining object representations and object individuation in infants (Káldy & Leslie, 2003, in press; Káldy & Sigala, 2004; Leslie & Káldy, 2001; Tremoulet, Leslie, & Hall, 2001; Wilcox & Chapa, 2002). For example, Káldy and Leslie (in press), demonstrated that infants can use shape to individuate an object (i.e., form an object representation), but that this ability does not occur until around 6.5 months, and has a highly limited capacity of just one item. Infants were shown familiarization displays that included either one or two objects (i.e., a disk and a triangle). These objects were then sequentially hidden behind two occluders. After a brief delay, the occluders were removed to reveal the objects in either the familiar, "expected" locations or in unfamiliar, "unexpected" locations. Results indicated that infants looked longer in the unexpected condition than in the expected condition, demonstrating that these infants had formed object representations that included both shape and location. Importantly, follow-up experiments revealed that infants were only able to remember the properties of a single object, precisely the last object that they saw hidden. Thus, the authors conclude that infants are able to form object representations that include object identity information (i.e., shape) and location by the time they are 6.5 months of age (Káldy & Leslie, in press).

It is tempting to conclude that the limited capacity and susceptibility to interference demonstrated by the infants in this task is indicative of VSTM representations. However, because infants are very familiar with the objects and because trials lasted for several seconds, it is impossible to rule out the possible effects of LTM on infants' performance in this task. Nonetheless, these results and others like it indicate that by 6.5 months, infants are able to form object representations, and that they can use the features of those representations to individuate those objects—likely components of stable VSTM representations.

Other work has focused less on what features (e.g., shape or location) infants use to individuate objects, and have looked more closely at the mechanism by which infants are able to maintain separate, spatially discriminable object representations. Two theories, *object files* (Kahneman, Treisman, & Gibbs, 1992) and FINST theory (Pylyshyn, 2001) describe in a complementary manner the evolution of object representations. This approach has been applied to the study of VSTM in both adults (Wheeler & Treisman, 2002; Wolfe & Bennett, 1997) and infants (Carey & Xu, 2001; Feigenson & Carey, 2003; , 2002a; Feigenson, Carey, & Spelke, 2002b). In fact, Carey and Xu (2001), state that infant object representations can be thought of as the developmental precursors of object files. In general, proponents of object files argue that as visual attention sweeps a visual scene, object-based attention serves to bind the spatiotemporial properties of an object into a preconceptual representation called an object file. These files can be simple spatiotemporal place-holders, or can be richly elaborated with feature information. The primary purpose of these object files is to allow the viewer to track multiple objects as they move through space and time.

One possible mechanism by which these object files are indexed is based on Pylyshyn's FINST theory (2001). Pylyshyn claims that the primary constraint on the number of objects a viewer can keep track of is the ability of the visual system to maintain pointers to these object files, or what Pylyshyn calls "fingers of instantiation," or FINST. Thus, these two complementary theories explain apparent capacity limitations in memory as a limitation in the neural resources needed to maintain pointers or indexes to these object files, rather than as a limit on a memory store *per se*.

Are object representations and object files synonymous with VSTM representations? Though the tasks designed to study object representations in infants have important implications for studies of VSTM, these tasks may involve the use of long-term memory systems because infants shown the test displays for many seconds—more than enough time to form a LTM representation. This, of course, does not preclude the role of VSTM in tasks such as these—it does, however, make it difficult to dissociate the effects of VSTM and LTM systems on infants' behavior. To illustrate, researchers interested in infant representation of quantities have shown that infants respond to violation of "expectancy" in a manner consistent with an object files account. Feigenson, Carey and Hauser (2002a) demonstrated that 10- and 12-month-old infants will successfully reach into the one of two containers in which a greater number of crackers were hidden. Interestingly, this ability is limited to cracker sets of three or fewer on either side, which the authors argue is consistent with an object files account for tracking small sets of objects. Importantly, infants failed to reach correctly (i.e., to the barrel containing the most crackers) when the cracker ratio was 4:3, 4:2, or even 6:3. The authors argued that this evidence suggests that infants are forming representations of quantity for the two hiding events, and that the scale of these representations is limited by constraints on object files.

However, this task requires infants to maintain these representations over periods of several seconds, and it is unclear if this tracking system is operating at the level of VSTM. Moreover, these tasks likely recruit LTM systems, as infants are familiarized with the displays for several seconds, which is more than enough time to map these short-term representations onto more meaningful long-term memories or even concepts (e.g., "more" versus "less"). Further research using tasks such as these promise to reveal much about how representations are created, maintained and manipulated, and if these abilities coincide with the development of VSTM in infants. However, as of yet, tasks that do not isolate VSTM from other memory systems can only hint at the possible involvement of VSTM, and how VSTM develops over time.

The Appearance and Durability of VSTM

As stated previously, VSTM representations are formed quickly, are highly capacity limited, and are prone to interference. The research reviewed thus far has begun to address issues of capacity and encoding, but there has also been a good deal of work addressing the development of durability in VSTM. For example, using a modified delayed-response procedure (DR), researchers have been able to document the appearance, development, and stability of VSTM representations (Diamond & Doar, 1989; Gilmore & Johnson, 1995; Hofstadter & Reznick, 1996; Reznick, Fueser, & Bosquet, 1998; Reznick, Morrow, Goldman, & Snyder, 2004). In these tasks, infants are most often seated in front of two hiding wells. The experimenter then shows the infant an attractive toy or food reward and subsequently hides the object in one of the two wells. It has been argued that this task taps working memory because 1) it is directly analogous to the DR procedure used in non-human primates (Diamond, 1990), 2) LTM representations are not beneficial for success in this task (Reznick et al., 2004), and 3) infants must form a representation for the exact location at which *a particular* event occurred, hold on to that representation across occlusion and delay, and use that representation to guide their reaching to the appropriate location (Diamond, 1990; Diamond & Doar, 1989). This task has also been adapted as a peek-a-boo game (Reznick et al., 2004; Schwartz & Reznick, 1999).

Using this type of task, researchers have determined that infants can form stable VSTM representations that persist across occlusion for up to 2 seconds at 5.5 months (Reznick et al., 2004), for around 3 seconds at 8 months (Diamond & Doar, 1989), and for 20 seconds by 9 months (Schwartz & Reznick, 1999). The jump in performance that occurs between 6 and 9 months, has been suggested to reflect the development of dorsolateral prefrontal cortex (DPC) (Diamond & Doar, 1989), based largely on non-human primate data in which lesions of the DPC lead to impairment on DR tasks (Diamond, 1990).

This research assesses infant VSTM for object location, and also provides a developmental timeline for the onset of the ability to form short-term object representations more generally. However, this research tells us little about the development of VSTM for object identity, or changes in VSTM capacity across development. Even studies that purport to assess short-term visual recognition memory (e.g., Rose et al., 2001) cannot be used to argue for the presence or absence of VSTM for object identity, because nearly all of these studies have used habituation or novelty preference procedures to assess infant memory.

For example, in these procedures infants are familiarized to a particular stimulus or set of stimuli during a familiarization or habituation phase. Memory for the stimulus is inferred if infants increase their looking, or *dishabituate*, to a novel test stimulus, or show a visual preference for a novel stimulus when paired with a familiar stimulus. Results from these studies have shown that even infants a few hours old can encode and remember a visually presented stimulus (Slater, Earle, Morison, & Rose, 1985; Slater & Morison, 1991), and that infants remember the information encoded in these procedures for hours or even days (Fagan, 1970, 1973; Rose, 1981). Taken together, studies in infant memory represent an important framework for interpreting behavior in visual memory tasks. However, because it is possible to form LTM representations in a matter of seconds (Richards, 1997; Rose, 1981; Rose & Feldman, 1987), any study based on a familiarization procedure cannot be used to study VSTM.

The Capacity of VSTM

VSTM, Object Complexity and Capacity

Intuitively, it seems reasonable that the complexity of an object might weigh heavily on an infant's ability to remember it. Why is this? Most likely, an infant's ability to encode an item into VSTM is influenced by the amount of information present on the toy, or the *visual load*. It remains to be seen whether two complex multi-faceted objects take up the same number of "slots" in infant VSTM as two simple objects. Indeed, this question has only recently been addressed in adults (Alvarez & Cavanagh, 2004). Although Vogel and Luck found that adults were just as good at remembering single featured objects (colored squares) as multi-featured objects (concentric squares) (Vogel, Woodman, & Luck, 2001), other research has demonstrated that the complexity of the object and the subsequent load imposed on the visual system may play a role in the number of objects that can be encoded into VSTM (Alvarez & Cavanagh, 2004). Specifically, Alvarez and Cavanagh (2004) found evidence of a capacity/complexity trade-off, with the visual load of each object determining, in part, the total number of objects that could be remembered. One reason for the apparent discrepancy was Alavarez and Cavanagh's use of complex, multi-part stimuli such as Chinese characters and shaded cubes.

Unfortunately, object complexity is a difficult dimension to operationally define in infant research—partly because infants cannot be explicitly informed as to what constitutes an object in a particular set of stimuli, and partly because sensitivity to Gestalt perceptual cues is still developing. In fact, recent work in our lab indicates that symmetry, a powerful perceptual cue for determining which areas of a visual scene are objects for adults, is not an effective cue for infants before six months (Ross-Sheehy, Oakes, & Vecera, 2003b, 2003c). Nonetheless, studies demonstrating an effect of complexity in VSTM capacity compel us to consider this dimension when designing visual tasks. The ability to detect novelty is clearly a function of the complexity of the object, and the total number of objects, and requires some specific memory for the properties of the toys.

Research on Infant VSTM Capacity

As mentioned previously, VSTM representations are formed very quickly, capacity limited, and subject to the effects of interference. These characteristics make VSTM very difficult to isolate in infancy because typical visual techniques—such as habituation and visual paired comparison—require relatively long periods of familiarization (e.g., tens of seconds). Recently, however, Ross-Sheehy, Oakes, and Luck (2003a) developed a paradigm that effectively isolates VSTM in infants. Infants were seated on a parent's lap in front of two computer monitors, and shown two concurrent displays of colored, blinking squares. On one display, the color of a single, randomly selected square varied at each onset, while on the other display, the colors of the squares remained constant across each onset (see Figure 1). Thus, for each trial, infants saw both a change and a no change stream. To illustrate, consider a set size three trial. On one monitor, the infant would see a changing stream (e.g., red, green, blue, followed by red, yellow, blue, followed by orange, yellow and blue, etc.). On the other monitor, the infant would see a no-change stream (e.g., blue, purple, black, followed by blue, purple, black, etc). This on-off cycle continued at a rate of 1.25 Hz for the duration of the 20 s trial. We assumed that infants would look longer to the changing stream than to the non-changing stream, but only if the number of squares did not exceed the capacity of VSTM. This task taps VSTM because to detect a change in color infants must remember the colors of the squares from one onset through the brief delay to the next onset. If infants are unable to maintain the colors of the squares in VSTM long enough to detect a change, then they should look equally long to both displays. Thus, infants' preference for change should be stronger for smaller set sizes that are well within the capacity of VSTM, but should decrease systematically as set size increased and capacity was exceeded. We observed that 4- and 6-month old infants significantly preferred the changing stream only when each display contained one object, whereas 10- and 13-month-old infants significantly preferred the changing streams for arrays of one, two, three and four objects, but not for six objects (see Figure 2). Thus, infant VSTM develops considerably over the first year of life (Ross-Sheehy et al., 2003a). A control experiment confirmed that when adults were tested with stimuli that were nearly identical in size, color and luminance to those used in our infant study, VSTM capacity was estimated to be 4.3 objects (Ross-Sheehy et al., 2003a) very similar to indirect capacity estimates for our 10- and 13-month-old infants.

It is possible that our set size effect was driven not by limits in VSTM capacity, but rather by the increasing processing demands imposed by the larger arrays. To rule out this alternative hypothesis, we showed an additional group of 6.5-month-old infants the exact same streams of one, two and three colored squares, only this time we eliminated the VSTM load by removing the delay interval between subsequent array presentations. Thus, the squares remained on the screen without interruption, the entire duration of the trial. As in our previous experiments, half of the streams incorporated a color-change, such that every 500 ms the color of a single, randomly chosen square changed. If infants in our previous experiments failed to detect the change at larger set sizes due to perceptual or processing limitations, then performance on this task should mirror performance on our previous task, as the perceptual demands for both tasks are nearly identical. Conversely, if the failure of 6.5-month-old infants to detect the change at larger set sizes was due to limits in VSTM systems, then infants should do very well on this task as all memory requirements have been removed. Our results support the latter of these two accounts. Infants in this task looked significantly longer to the changing streams than to the non-changing streams for set sizes one, two and three. Taken together, the results of these two control experiments further bolster our claim that our task isolates the same VSTM system in infants that the Luck and Vogel (1997) task isolated in adults.

Location and Binding in VSTM

Using the same paradigm described above, we have found evidence of a similar developmental timeline for VSTM for object location (Ross-Sheehy, Oakes, & Luck, 2004). In these experiments, 6- and 12-month-old infants were shown two streams of colored, blinking circles. As in Ross-Sheehy et al., (2003a) infants were shown two types of streams, one changing stream and one no-change stream. However, in these experiments, the location of a single, randomly chosen circle changed from blink to blink. Our results indicated that like memory for object color, 6.5-month-old infants were able to hold the location of only a single object in VSTM, whereas 12-month-old infants were able to remember the locations of three objects. Importantly, these results map nicely onto our results for object identity, supporting the idea that memory for both object identity and location develop at a similar time, possibly indicating the development of a more domain-general multiple object representation system. In addition, these results are potentially important to researchers who employ DR type procedures (Diamond & Doar, 1989; Hofstadter & Reznick, 1996; Reznick et al., 2004), as they demonstrate that infant memory for location might be underestimated using procedures which require long delay periods, or visual or manual responses.

In addition to spatial memory, we have used our task to explore binding in VSTM (Oakes, Ross-Sheehy, & Luck, in press-a). Visual binding is the process by which the visual system associates or *binds* object features such as color and location, into a single object representation. This process is necessary, because different types of visual information are processed in different regions of the brain. Even in adults, this process is prone to error as illustrated by the tendency of adult subjects to report illusory conjunctions when test sets included multiple 2-featured objects (Treisman & Schmidt, 1982). That is, under certain conditions, adults who are shown a red triangle and blue circle might report that they saw a red circle and blue triangle. Recall that researchers interested in object individuation found evidence for the binding of *shape* and location at 6.5 months (Káldy & Leslie, in press). However, even 9-month-old infants have failed to bind color and location (Káldy & Leslie, 2003). One possible reason for this failure is that the methods employed in these tasks are not ideally suited for tapping binding at the level of VSTM.

To test this, we showed infants a no-change stream paired with a binding-change stream. For the binding-change streams, the colors of the squares remained the same from cycle to cycle (e.g., always blue, red and green), however, the color-location bindings changed at each onset (e.g., blue, red, green, followed by red, green, blue, followed by green, blue, red, etc.). If infants were encoding both the color and location information of the squares, then they should look longer to the binding-change streams than to the no-change streams. That is precisely what we found. When shown these displays, 7.5- and 12.5-month-old infants, but not 6.5-month-old infants, looked significantly longer to the binding-change streams than to the no-change streams, indicating a dramatic shift in the ability to bind color and location between 6.5 and 7.5 months (Oakes et al., in press-a).

Taken together, these studies give us a clear picture of the development of VSTM in infancy, and enable us to make some inferences regarding the development of underlying neural mechanisms known to support VSTM in adults. First, we know that by 4 months, neural systems are sufficiently well developed to enable the representation of the identity of at least one object in VSTM. Second, we know that the capacity of VSTM jumps dramatically somewhere between 6.5 and 10 months postnatally, indicating a relatively rapid change in the underlying neural mechanisms necessary for representing multiple objects including the parietal lobes and dorsolateral PFC. Third, we know that the capacity of VSTM for spatial location is about the same as the capacity for object identity, and that the developmental timeline is also quite similar. Finally, we now know that by 7.5 months, infants are able to bind color and location in VSTM.

Vision and Attention

For decades, researchers have been interested in determining what infants can see (e.g., Atkinson, 1984; Fagan, 1976; Fantz, 1963; Teller & Bornstein, 1987; Teller, Morse, Borton, & Regal, 1974). But seeing is not simply a matter of what an infant is able to visually resolve. The immature optics of the eye can account for some measure of visual deficit in newborn infants such as poor acuity (Atkinson, 1984) and poor color vision (Banks & Shannon, 1993). However, a large portion of infant visual deficit is caused by the relative immaturity of visual cortical areas, particularly those areas related to visual attention (Atkinson, 1984; Hood & Atkinson, 1993; Johnson, 1990).

Before our visual system can execute an eye movement or saccade, it must first select a target or location in visual space. This selection is accomplished via attention, which constrains the set of all possible eye movements to only the most immediately relevant potential targets. Adult observers then generally move their eyes directly to the target with a single large saccade, followed by one or two smaller localization saccades (Henderson & Hollingworth, 1999). At birth, this system is remarkably underdeveloped. Simple acts such as switching attention from one object to another (Atkinson, Hood, Wattam-Bell, & Braddick, 1992; Hood, 1995; Johnson, 1994) or simply disengaging attention from a current stimulus (Frick, Colombo, & Saxon, 1999; Hood & Atkinson, 1993; Richards & Casey, 1992) can be remarkably difficult for the young infant. Eye movements themselves are also somewhat different in infants. Though like adults infants do make accurate saccades to a target, they tend to make two to three smaller saccades rather than a single large saccade before localizing the target (Atkinson, 1984). Indeed, these behavioral shortcomings are often taken as evidence of immaturity in structures known to support attentional switching and eye movements, namely the frontal eye fields, and parietal cortex (Johnson, 1997). Because there is strong correlational evidence linking the development of these neural structures to changes in infant looking behavior, most theories of attentional development have been maturational, citing the maturation of the brain or an interaction between experience and maturation as the primary mechanism driving visual development (Atkinson et al., 1992; Frick et al., 1999; Hood & Atkinson, 1993; Johnson, 1990; Johnson, 1998; Posner & Petersen, 1990).

Adult Attention

Attention is not modular. Though there may be specific brain areas which support different components of attention such as switching attention or maintaining attention (Frick et al., 1999; Posner & Petersen, 1990), attention itself is most likely a distributed property of the entire brain (Desimone & Duncan, 1995). Attention putatively works by increasing the signal to noise ratio for particular neural representations. This can be accomplished by increasing the signal strength, by decreasing the noise level, or some combination of both. (Colby, Duhamel, & Goldberg, 1995; Desimone & Duncan, 1995; Moran & Desimone, 1985).

In adult visual attentional studies, subjects must generally maintain fixation to a central stimulus, while monitoring a peripheral location for the appearance of some predefined target stimulus. Several studies have demonstrated that processing of a target is enhanced (i.e., faster and more accurate) when attention is directed or *cued* to the subsequent location of the target (Collie, Maruff, Yucel, Danckert, & Currie, 2000; Eriksen & St. James, 1986; Posner, 1995; Posner & Cohen, 1984; Posner & Petersen, 1990; Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998). In addition, these attention cues are effective whether they appear before (Eriksen & St. James, 1986), or even after the target (Sperling, 1960), and attention is effectively deployed to the cued location whether the cue is endogenous (stimulus driven), or exogenous (goal driven) (Egeth & Yantis, 1997; Posner & Petersen, 1990; Theeuwes, 1991).

Moran and Desimone (1985) used single unit recordings to demonstrate how attention aids processing in nonhuman primate extrastriate cortex. Monkeys were trained to fixate a central location, and two stimuli (one preferred and one non-preferred) were presented in two different locations within the cell's receptive field. Results indicated that the responses from neurons were greater when monkeys attended to the preferred stimulus than when they attended to the non-preferred stimulus, even though both stimuli were present in the same receptive field at all times (Moran & Desimone, 1985). These and other findings raise important issues for infant attention researchers. If attention serves to boost the signal for the attended items while inhibiting signals from the unattended items, then perhaps infants' attentional failings are due to their inability to block irrelevant information rather than their inability to focus on relevant information (e.g., Atkinson et al., 1992). This may be a subtle distinction, but the lack of inhibitory control is often cited as a hallmark of an immature brain (Johnson, 1997), raising important questions about the quality of information processing and subsequent cognitions early in infancy. Thus, knowing what drives visual attention in infancy, as well as how it changes over development, is a vital prerequisite to understanding what infants can perceive, remember, and learn about the world around them.

Attention and Visual Load

Historically, a spotlight metaphor has been invoked to describe visual attention. Much like a spotlight, attention sweeps the visual field, enhancing processing in the attended region, and inhibiting processing in the unattended regions (Posner & Cohen, 1984). For better or for worse, this metaphor, with all its implications, has persisted—perhaps due to its intuitive appeal, perhaps to the surprising number of testable hypotheses it has generated. One of the most interesting questions, is at what point in visual processing attention exerts its effects. Early selection models (Treisman & Gelade, 1980; Yantis & Johnston, 1990) claim that attention gates visual information prior to object perception, whereas late selection models claim that attention gates visual information after object perception but perhaps before VSTM representations are formed (Treisman, 1964). However, other work indicates that when in processing attention operates is likely determined by the visual load, or the amount of perceptual information present at any one moment (Lavie & Tsal, 1994). This finding has important implications for attentional research with infants, because what constitutes a high perceptual load may be markedly different for a 6-month-old than for 10-month-old.

Because high visual load has been shown to invoke early or perceptually-based attention (Lavie & Tsal, 1994), and because attention has been shown to mediate which items are selected for encoding into VSTM (Downing, 2000; Schmidt, Vogel, & Luck, 2002), it logically follows that in displays which contain a high visual load with respect to VSTM capacity, attention would necessarily be deployed at an early, or perceptual level of processing. Thus, it is possible that an attentional cue offered to infants would be maximally beneficial in displays that contain an array of elements exceeding VSTM capacity, but non-beneficial in displays that contained an array of elements which were within VSTM capacity. Thus, VSTM capacity, visual attention, and visual load may cooperatively determine what infants can remember about complex objects.

The Development of Visual Attention

At birth, infants will attend to highly salient features of objects such as motion and areas of high contrast (Atkinson, 1984; Atkinson, Braddick, & Moar, 1977; Banks & Shannon, 1993). As infants develop, they begin to respond to other properties, such as color and form (Atkinson, 1984; Dannemiller, 1998). Attempting to understand how this system develops over the first several months of life has generated great deal of research. (e.g., Atkinson & Hood, 1997; Colombo, Mitchell, & Horowitz, 1988; Dannemiller, 1998; Fagan, 1977; Hood, 1993; Johnson, 1990; Posner & Petersen, 1990; Posner & Rothbart, 1998; Richards, 1985).

One of the most widely accepted theories of attentional development is based on the finding that infants demonstrate different orienting behavior at different ages. For example, using a spatial cuing paradigm, Johnson, Posner and Rothbart (1991) find that like adults, infant response times are faster and accuracy rates higher when a potential target is spatially cued (valid trials) than when the spatial cue appears contralateral to the target (invalid trials). Interestingly, the appearance of this facilitation coincides with an increase in parietal lobe development, which occurs from around three to six months postnatally (Johnson et al., 1991; Posner, Rothbart, & Thomas-Thrapp, 1997). Johnson et al. posit that separate mechanisms control different aspects of visual attention, and that these mechanisms each have a distinct developmental time course.

There are several behavioral phenomena in infants that are consistent with this theory. For example, "obligatory attention" (Johnson, 1997) or "sticky fixation" (Hood, 1995) refers to the tendency of one-month-old infants to perseveratively stare at a particularly salient object. This behavior has been taken as evidence for a separate attentional disengaging mechanism, and may be caused by the maturation of inhibitory connections to the superior colliculus, preventing automatic saccades to peripheral stimuli, and the relative immaturity of the parietal lobes (Hood, 1995; Johnson, 1997). Inhibition of return (IOR) or the inhibition of orienting to a previously attended spatial location has been observed both in infants and adults, and is believed to be supported by the maturation of the superior colliculus along with other structures (Hood, 1993; Hood & Atkinson, 1993; Posner & Petersen, 1990). The ability to make anticipatory saccades does not appear until around 3 months (Haith, Hazan, & Goodman, 1988), an ability which likely requires relatively mature frontal eye fields (Johnson, 1997). Though these anticipatory saccades are the first indication of endogenous or internally driven attentional control, it is likely that infants much younger than three months are able to make intentional saccades. However, because infants cannot be instructed to make eye movements, researchers are often constrained to use paradigms either that exclusively tap exogenous or stimulus driven attention or that rely on learning or conditioning processes that may be slower to develop.

Atkinson and Hood (e.g., Hood & Atkinson, 1993; Atkinson, 1984; Hood, 1995) also have argued for the importance of maturation and experience to the development of visual perception and attention. Specifically, Atkinson (1992) proposed two main phases of post-natal visual development: 1) the development of neurons that are selectively tuned to different attributes of spatial vision, and 2) the development of controlled eye movements and visual attention. Thus, Atkinson's model of visual attention development posits maturational factors (e.g., myelination of the visual pathways and the maturation of photoreceptors) as being the primary contributors to visual fixation behavior and attention. Johnson (1992; Morton & Johnson, 1991) poses a similar theory with a minor twist: Although the appearance of behavioral phenomena such as sticky fixation and inhibition of return are good markers of maturational changes in the visual system, Johnson asserts that it is the *interaction* of maturation and experience that fuels visual development. Specifically, Johnson claims that infants are born with a relatively high functioning sub-cortical attention system, that serves to bias the infant to attend to conspecifics of features, such as the spatial arrangement of a face. Johnson reasons that this biased input leads to predictable visual preferences later in infancy when cortical influences are more prevalent, a timeline that is also consistent with Posner's model (Johnson, 1992; Morton & Johnson, 1991; Posner et al., 1997).

Though adults, and to a lesser extent infants, demonstrate facilitation when attention is applied to a cognitive task, it is important to note that there are two distinct attentional orienting systems. Covert attention is the effortful, goal-directed attention system often studied in adult attention studies. Conversely, overt attention, is an automatic, stimulus driven attention orienting system. Both of these systems have been argued to reside in functionally and developmentally distinct areas of the brain (Johnson, 1992; Morton & Johnson, 1991; Posner et al., 1997). Although developmental research on both of these attentional systems is ideal, the practical logistics of testing infants nearly precludes the study of covert attention systems. That is, because researchers cannot instruct the infant to attend in a particular way, they must rely on exogenous attention cues such as motion, sudden onset or flicker. Thus, infant studies of attention, in contrast to adult studies of attention, are almost exclusively devoted to characterizing the development of covert attention systems.

Toward an Interactive Account

Attention and VSTM

Despite the significance of VSTM for infants' processing of visual information, very little research has been aimed at documenting how infant VSTM capacity develops, and how that development impacts information processing. Perhaps even more significant is the lack of research aimed at understanding how changing limits in VSTM capacity interact with other developing visual systems such as visual attention. Because attention serves to select which items are processed, it is likely that attention has an important effect on which items get in to VSTM and are subsequently processed. Indeed, researchers have only recently begun to address this question in adults (Downing, 2000; Schmidt et al., 2002).

For example, Schmidt et al. (2002) showed adult subjects memory arrays containing several colored squares. Prior to the onset of the memory array, the location to be occupied by a single square was cued, presumably drawing attention to that location. After a brief delay interval, subjects were given a test probe that appeared in one of the previously occupied locations; either in the same location of the cue (valid), or in one of the other locations (invalid). Subjects were required to indicate whether the probe matched the color of the memory-array item in the probed location. On half of the trials, the probe matched, and on half the trials it had changed to a different color. Results indicated that subjects were much more accurate at detecting changes for the valid trials than for the invalid trials (Schmidt et al., 2002). Thus by selectively determining which items will be encoded into VSTM, attention offers an important solution when VSTM capacity is exceeded. This finding has important implications for infants, both because the stimulus properties which automatically capture infant attention, as well as the capacity of VSTM, change so dramatically over the first 10 months of life (Atkinson, 1984; Rose et al., 2001; Ross-Sheehy et al., 2003a).

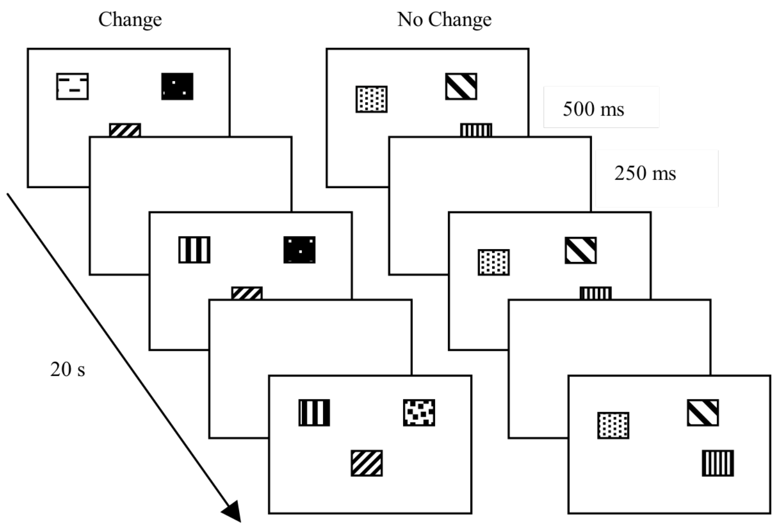
Clearly, the differing developmental trajectories of attention and visual short-term memory serve to constrain object representations over the first year of life in complex and dynamic ways. For example, some researchers have argued that infants first attend to global then local aspects of visual stimuli (Colombo, Freeseman, Coldren, & Frick, 1995), while others have demonstrated the opposite (Cohen & Cashon, 2001; Cohen & Younger, 1984). Most likely, infant attention is flexibly determined based on the infant's visual development, properties of the stimulus, and task demands (Oakes & Madole, 2000). To illustrate, when faced with a complex visual stimulus, such as a face, that contains more information than an infant can process, there are several possibilities for how he or she might attempt to learn about and remember the stimulus. One strategy might be that the infant simply encodes the maximum number of features into VSTM that he or she can. In this case, younger infants would encode very few features and older infants would encode more features. Our previous research suggests that infants take this strategy when presented with random arrays of simple shapes (Ross-Sheehy et al, 2003). However, despite the finding that 6.5-monthold infants have a VSTM capacity of a single item (Ross-Sheehy et al., 2003a), we have demonstrated that VSTM for object identity is effectively reduced to zero when the test item is embedded in an array of multiple objects (Oakes et al., in press-a). One possible reason for this effect has to do with the relative immaturity of the attentional orienting system. It is possible, that at 6.5-months of age, infants are unable to attend to multiple objects in a given display. If this is the case, then performance on VSTM tasks would reflect not only the developmental state of the VSTM system, but also the developmental state of the visual attentional system.

Thus, it is important to consider the attentional demands of the task put to infants, in conjunction with the developmental state of the infant's attention systems. It has been demonstrated in adults that attention serves to constrain visual input by selecting what gets in to short-term memory (Schmidt et al., 2002). This strategy would be particularly useful for an infant, because visual attention can be flexibly driven by both external factors (e.g., movement of the mouth or gaze direction) or by internal factors (e.g., hunger, fear). In this situation, attention is beneficial because it selectively limits pool of potential targets to only the most likely candidates. Thus, attention can be an effective tool in reducing the VSTM load incurred by a particular display or object. For example, when presented with several relatively similar items, infants could attend only to the discrepant features (i.e., discrimination of a particular face), or alternatively, attend to only similar features (i.e., categorization based on a single, perceptually similar feature). Either way, attention serves an important function by limiting the set of possible items that must be encoded into VSTM, allowing infants to perform astonishingly complex cognitive tasks.

Attention and VSTM in 5.5- and 10-Month-Old Infants

The current experiments seek to determine if infants can use visual attention to overcome limits imposed by their VSTM systems, and under what conditions attention is beneficial. Recall that previous work in our lab has demonstrated a period of VSTM development from 6.5-10 months (Oakes et al., in press-a; Oakes, Ross-Sheehy, & Luck, in press-b; Ross-Sheehy et al., 2003a, 2004). In particular, infants are unable to demonstrate a preference for streams that include color-changing probes when embedded in arrays that exceed VSTM capacity. However, it is unclear what role, if any, visual attention played in these results. Thus, the goal of this thesis was to explore the relationship between VSTM and visual attention. In all of the experiments presented here, infants were shown memory displays similar to those used previously in our lab, with one important difference: every display included some means for helping infants to selectively attend to (an) individual object(s). In Experiments 1 through 3 the displays are identical to those used in our previous work except that they include a cue that orients attention to a single object in a multi-object display. The question addressed by these experiments is: does the addition of an attention cue induce infants to selectively attend to only a single item in an array? Furthermore, can infants subsequently form a VSTM representation for the attended item? Although perceptual cues are known to be effective elicitors of an orienting response in infants (Johnson, Posner, & Rothbart, 1994; Johnson & Tucker, 1996; Richards, 2001), the present experiments are the first to directly test if attention can mediate which items are encoded into VSTM in infants. To that end, Experiments 1-3 test the ability of 5.5- and 10-month-old infants ability to use a perceptual cue to selectively encode a particular item into VSTM, and if that ability is contingent on the properties of the stimulus, and/or the properties of the cue. Recall that previous work has demonstrated that 4- and 6.5-month-old infants are unable to represent more than a single item VSTM (Ross-Sheehy et al., 2003a), and that this liability is exacerbated when displays contain multiple objects (Oakes et al., in press-a). Therefore, Experiments 1-3 test the hypothesis that this failing might be partially due to constraints imposed by the immature attentional orienting system of the young infant. Experiment 4 extends these first three experiments by manipulating infants' attention to a collection of objects in a way that does not tax the attentional orienting system. By presenting each to-be-remembered item in seclusion and using a serial presentation, it will be possible to test infant VSTM capacity free from the attentional demands imposed by multi-item displays.

Figure 1. Schematic depiction of a single trial in Ross-Sheehy, Oakes, and Luck (2003) (above) and experimental apparatus from the infant's view (below).



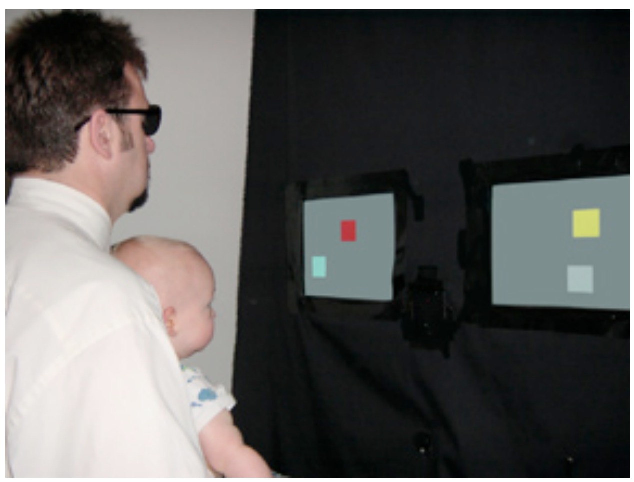


Figure 2. Change preference as a function of age and set size for Experiments 1, 2, and 3 (Ross-Sheehy, Oakes, & Luck, 2003).

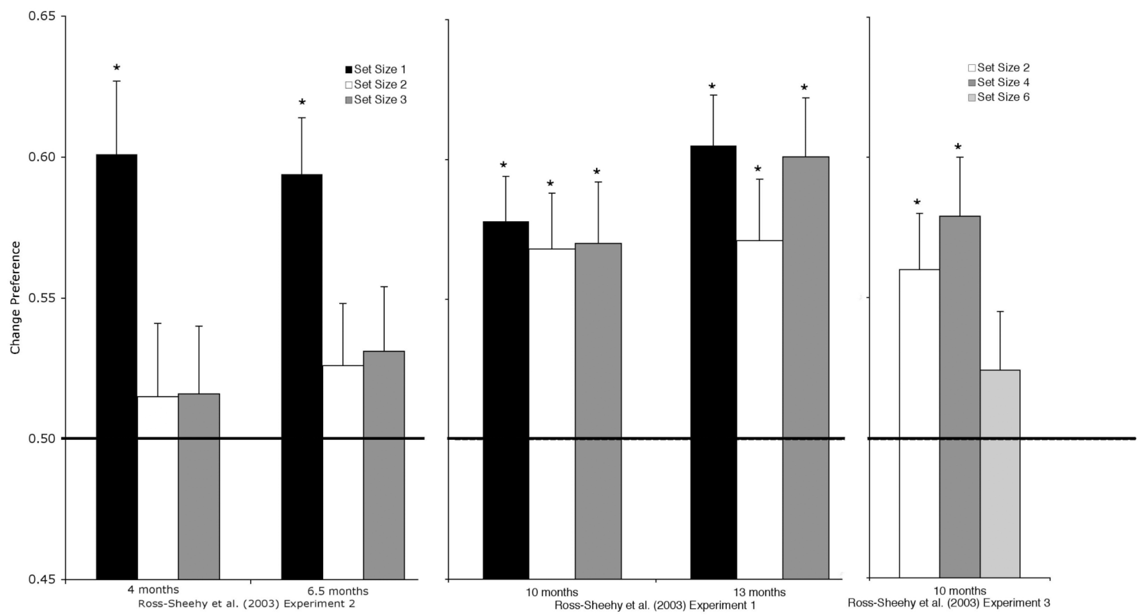
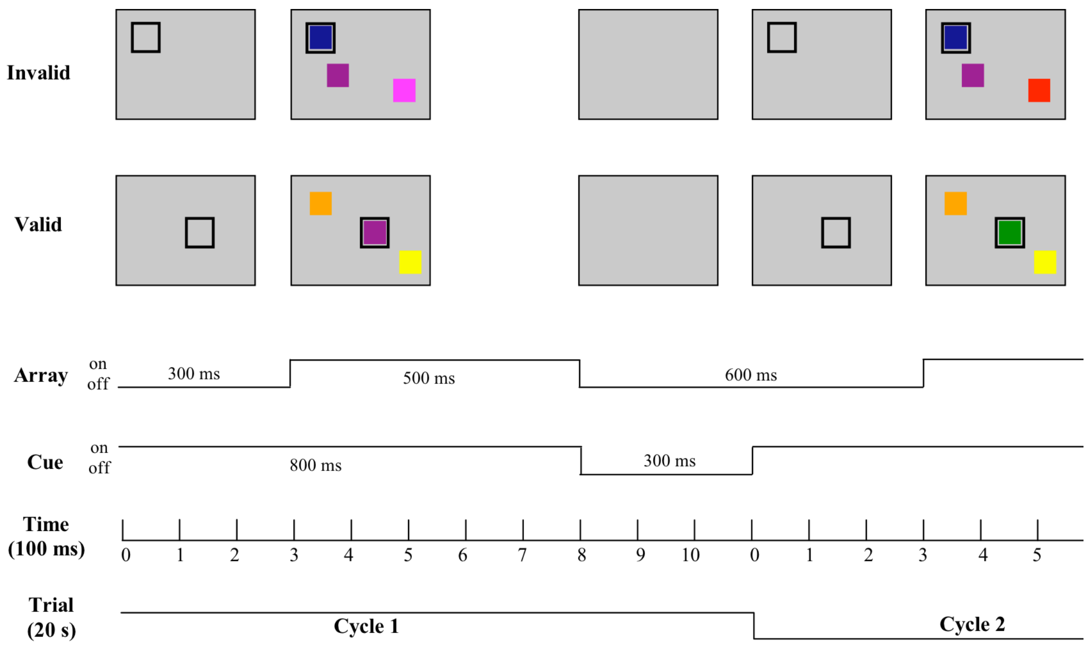


Figure 3. Schematic depiction of a Valid and Invalid stream for Experiments 1 and 2.



CHAPTER 2: EXPERIMENT 1

Attention and VSTM in 10-Month-Old Infants

Recall that infants have a very limited VSTM capacity until around 10 months, with dramatic increases occurring somewhere between the 6th month and the 10th month (Ross-Sheehy et al., 2003a). Specifically, 4- and 6.5-month-old infants failed to notice the color-change of a single square when embedded in an array of 2 or more squares, whereas 10-month-old infants only failed to notice the color-change of a single square when embedded in an array of 6 squares. However, previous work with adults demonstrates that when shown arrays that exceeded VSTM capacity, the addition of an attention cue was sufficient to enable participants to detect the color change (Schmidt et al., 2002; Sperling, 1960). It is possible that the addition of an attention cue to arrays that are otherwise impossible to encode might bestow the same benefit to 10-month-old infants as it does to adults. Attention therefore might also help infants to notice the changing square, even in arrays that exceed their VSTM capacity. However, it is also possible that perceptual attention cues like those used in adult studies, are not ideal for infants. Because 10-month-old infants have relatively underdeveloped visual attention systems, perceptual cues might not be sufficient to drive an orienting response. Furthermore, even if the cue is effective in eliciting an orienting response, infants may still fail to encode the target item into VSTM. Thus, the first step is to determine if infants can use a perceptual cue to selectively encode a single item into VSTM, and if this ability is dependent on the number of items in the test array.

To test this, we used blinking, dynamic streams of changing colored squares—the same types of stimuli infants at this age failed to encode in previous work (Ross-Sheehy, et al., 2003). However, there were a few important differences. First, these stimuli included an attention cue, which appeared before the onset of the array of squares, and remained visible the entire duration of the array. If infants can use attention to direct which items are encoded into VSTM, then infants in this condition should look longer to trials when the cue appears in the location where a color-change occurs (i.e., Valid streams), then when the cue appears in the location where no change occurs (i.e., Invalid streams). In addition, infants were tested with two different set sizes, one that exceeded their VSTM capacity (set size 6) and one that did not (set size 3). Finally, infants viewed a single computer monitor rather than two as before, thus the validity of the cue was varied randomly between trials.

The purpose of this experiment was twofold: First, it was important to determine if the addition of an attention cue could enable infants to selectively encode and remember the properties of a single square in arrays that exceed their VSTM capacity. It is possible that the attention cue will only be effective when the VSTM system is overloaded. This reliance on attention early in processing is known to be elicited by perceptually demanding tasks in adults (Lavie, 1995). If infants use the attention cue for the larger set size but not the smaller one, then this study will be the first to demonstrate that visual attention interacts with VSTM in predictable ways based on the nature of the visual input. It is also possible that infants utilize the attention cue regardless of set size. This pattern of results would be interesting, because it would be the first to demonstrate a strong and relatively inflexible sensitivity to perceptual-level attention cues in infants.

Participants

Participants were 36 (18 at each set size) healthy, full-term 10-month-old infants with no history of birth complications, vision problems, who were not at significant risk for color blindness (e.g., male infants with maternal uncles who were colorblind were excluded from the sample). Infants ranged in age from 41.86 weeks to 45.86 weeks, M = 44.00, SD = 1.03, and included 13 males and 23 females. All of the infants' mothers had graduated high school, and 69% had completed at least a bachelor's degree. An additional 10 infants were tested but excluded from the analysis due to fussiness or lack of interest (n = 8), means that were >2 SD from the group mean (n = 1), and looking for the entire duration of more than 80% of the trials (n = 1). Infant names in this study and in all subsequently reported studies were obtained from county birth records, and all parents were contacted by letter and received a follow-up phone call to schedule their appointment. Infants and parents were not paid for their participation, but infants received a small toy and parents' parking expenses were reimbursed.

Stimuli and Apparatus

A Macintosh G4 computer was used to present the stimuli on a single, 17-in. ViewSonic monitor with a viewable surface of 18.26° (w) by 13.5° (h) at a distance of 100 cm. As illustrated in Figure 4, the stimulus streams consisted of sequences of arrays that blinked on and off. Each array contained three or six colored squares measuring 3.6 cm x 3.6 cm, subtending 2.06° x 2.06° per square. In addition, an attention cue (an unfilled, black rectangle measuring 4.4 cm x 4.4 cm or 2.52° square with a line thickness of .2 cm or .11°) appeared briefly before the presentation of the array of squares in a single, randomly chosen location that was subsequently occupied by a square. This type of cue has been shown to automatically capture attention in both infants (Johnson et al., 1994) and adults (Jonides, 1981), and should serve to focus the infants' attention on a single item in the array. In adults, such cues automatically lead to the preferential storage of the cued item in VSTM (Schmidt et al., 2002). The question addressed here was whether the cue would also lead infants to preferentially store the cued item in VSTM.

The stimulus streams for this experiment contained the following sequence of events: The cue appeared prior to the onset of the array of squares, and remained visible for 300 ms. After this 300 ms pre-cue period, the colored-square array appeared, along with the cue, and together they remained visible for 500 ms, after which both the cue and colored-square array were removed and the screen was blank for a 300 ms delay period. Immediately after this delay period, the cue once again appeared for 300 ms (in the same location as before) followed by the presentation of the colored-square array. Within a stream, the location of the cue remained the same from onset to onset (i.e., it appeared in a particular location, remained there when the array appeared, and reappeared in the same location after the delay period). The cued location varied randomly between streams, and thus was different from trial to trial. It should be noted that the timing parameters for these stimuli closely resembled those used in previous work on VSTM in infants (Ross-Sheehy et al., 2003a).

Each time the array of squares reappeared, the color of one of the squares had changed color. For *valid* streams, the square within the attention cue changed color on each reappearance of the array. For the *invalid* streams, a square at one of the uncued locations changed color (the same square changed color on each cycle; see Figure 3). Thus, because both the valid and invalid streams contained a color change, infants would only discriminate these streams if the valid cue drew infants' attention to the changing square and allowed them to detect a change in that location. If the cue is effective, the invalid cue should presumably draw infants' attention to a square that does not change from location to location. This sequence repeated, without interruption, for the duration of the trial.

Three patterns of results are possible, depending on how attention influences infants processing of these stimuli. First, if like adults, attention is flexibly driven based on the complexity of the stimulus, then cues may be particularly useful when viewing arrays of six objects. In this case the cue will draw infants' attention to the changing square in the valid streams and to an unchanging square in the invalid stream, and infants will encode and remember only that cued item. As a result infants will prefer to look at the valid stream over the invalid one. This effect would be diminished or non-existent at set size three.

Alternatively, if attention is not flexibly driven by stimulus complexity, the cue may automatically capture infants' attention at both set size three and set size six. If this is the case, then infants will look longer to the valid than to the invalid streams regardless of set size.

Finally, it is possible that our cue will either not elicit a shift in attention, or that attention will not be selective enough to allow infants to encode on a single item. In either of these cases, infants will look equally to both the valid and the invalid streams for all set sizes. It should be pointed out that in addition to the cued item, some infants may be able to encode additional items. If this is the case, then it may decrease the difference between looks to the valid and looks to the invalid streams. However, this possibility is not worrisome, as its presence would not lead to a false conclusion, but rather would simply diminish our effect.

Design and Procedure

This experiment incorporated a 2x2x2 mixed design with Validity (valid and invalid) and Block (one and two) as within subject variables, and Set Size (six and three) as a between subject variable. Each infant saw two blocks of 6 trials. Each block contained three valid streams and three invalid streams, order randomly determined within each block, for a total of 12 trials. Infants were seated on a parent's lap approximately 100 cm in front of a large black curtain that hung ceiling to floor obscuring the infants' view of the experimental apparatus. Openings in the curtain revealed the computer monitor, a small grey speaker, and a video camera that was focused on the infant's face (see Figure 4). In another room, a trained observer viewed the infant via closed-circuit TV, and recorded the duration of looking by pressing and holding a computer key while the infant was judged to be looking at the monitor, and by releasing the key when the infant was judged to look away from the monitor. In addition to this online coding, 25% of all of the data reported in this thesis were recoded offline by a second trained observer. Average between-observer reliabilities were very good. Across the entire sample of infants (n = 156), the mean inter-observer correlation for the duration of looking on each trial was high ($r = .98$), and the mean absolute difference between observers for the duration of looking was low ($M = .53$ s).

Before each trial, the screen flashed from white to grey at a rate of approximately 2 Hz accompanied by a police whistle. The purpose of this flashing was to orient the infant's attention and gaze toward the monitor. Once the infant was judged to be looking the monitor, the experimenter pressed a button that simultaneously ended the attention-getting stimulus, and began the trial. During each trial, the stimulus stream was presented for 20 s, or until the infant had looked away for 1 consecutive s following 1.5 s of looking. Infant looks were measured and recorded using Habit 2000 (Cohen, Atkinson, & Chaput, 2000-2002).

Infants' ability to make use of the attentional cue and detect the color-change was assessed by measuring their duration of looking to both the valid and invalid streams. Because an array of six colored squares was known to exceed VSTM capacity at this age (Ross-Sheehy et al., 2003a), infants should look longer to the valid than to the invalid streams only if they can make use of the attention cue to remember the properties of the cued square. Thus, if the presence of an attention cue serves to focus the infant's attention on one part of the display (the cued item), then infants will look longer when that item changes color (Valid streams) than on trials in which that item does not change color (Invalid streams). Moreover, if the use of a perceptual attention cue is not dependent on the complexity of the stimulus, then we predict that infants will also look longer to the valid streams than to the invalid ones for displays that do not exceed VSTM capacity (i.e., set size 3).

Results

Mean infant looking times were calculated for each type of trial in each block, and these data were analyzed by means of a 2x2x2 mixed-model ANOVA with Validity (valid vs. invalid) and Block (one vs. two) as within subjects variables, and Set Size (three vs. six) as the between subjects variable. This analysis revealed several significant effects. First, there was a main effect of Set Size $F(1, 34) = 4.25$, $p < .05$. Infants looked significantly longer to the Set Size 6 streams ($M = 8.11$, $SE = .49$) than to the Set Size 3 streams ($M = 6.06$, $SE = .41$). The finding that infant looking times increase with complexity is a well-documented phenomenon (Brennan, Ames, & Moore, 1966), and simply indicates that infants look longer when displays contain more information, objects, or things to look at and process. There was also a main effect of Block, $F(1, 34) = 6.78$, $p = .01$. Overall, infants looked significantly longer to the first block ($M = 7.85$, $SE = .48$) than to the second block ($M = 6.32$, $SE = .44$). This finding suggests that infants were responding to the overall novelty of the stimuli, becoming increasingly familiar with the task and the stimuli in general by the second block. In addition, there was a marginal effect of Validity $F(1, 34) = 3.34$, $p = .08$ indicating that overall, infants tended to look longer to the Valid streams ($M = 7.33$, $SD = .47$) than to the Invalid ones ($M = 6.84$, $SD = .46$). Importantly, these effects were subsumed under a significant Block by Validity interaction $F(1, 34) = 4.68$, $p = .04$. An inspection of these means reveals that in general, infants looked longer to the Valid streams than to the Invalid streams in Block 2 ($M = 7.03$, $SE = .71$, $M = 5.62$, $SE = .49$, respectively) but not in Block 1 ($M = 7.63$, $SE = .63$, $M = 8.06$, $SE = .72$, respectively, see Figure 5). There were no other significant effects.

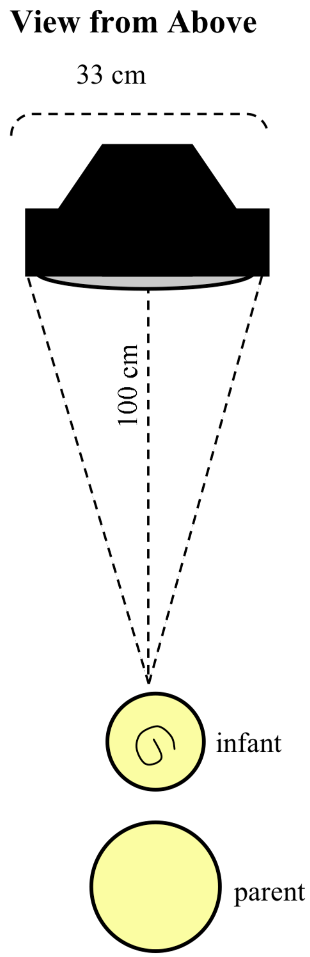
The Block by Validity interaction was followed-up with a series of paired t-tests comparing Validity (Valid vs. Invalid) and Block (One vs. Two). To account for multiple comparisons, the significance criterion was set at $p = .017$. These comparisons revealed that in Block Two, infants looked significantly longer to the Valid streams ($M = 7.03$, $SE = .71$) than to the Invalid streams ($M = 5.62$, $SE = .49$), $t = 3.47$, $p < .01$ (two-tailed). This effect was not observed in Block One, $t = -.74$, $p =$ ns (two-tailed). This null effect of Validity in Block One along with increased looking times observed for Block One relative to Block Two indicates that infants may have needed a period of familiarization with these blinking, dynamic stimuli before they could begin to discriminate the two conditions. In addition, for the Invalid streams only, infants looked significantly longer in Block One ($M = 8.06$, $SE = .72$) than in Block Two ($M = 5.62$, $SE = .49$), $t = 3.69$, $p < .001$ (two-tailed). This effect was not observed for the Valid streams $t = .79$, $p =$ ns (two-tailed) (see Figure 6). This pattern of responding indicates that the interaction was largely driven by a decrease in looking times to the Invalid streams from Block One to Block Two. Specifically, over the course of the experimental session, infants habituated only to the Invalid streams, where the attention cue repeatedly drew infant attention to the same non-changing square. This is strong support for the claim that attention was obligatorily deployed to the location of the cue, otherwise we would have expected the relative salience of the cue to compete with the relative salience of the test array leading to decreased differentiation between the Valid and Invalid streams over the course of the experiment. In other words, we would have expected that attention to the cued location would wane as a function of familiarity. This was clearly not the case. In addition, the lack of any set size effects is consistent with this interpretation.

Discussion

The results of Experiment 1 lead to the very important conclusion that 10-month-old infants are able to use an attentional cue to selectively encode items into VSTM. Moreover, this attentional cue had an extremely robust influence on infants' change detection at this age. Ten-month-old infants looked significantly longer to stimulus streams in which the change was validly cued than to streams in which the change was invalidly cued, even when the number of items in the array was presumably within their VSTM capacity. This finding is particularly impressive because the only difference between the valid and invalid streams was the predictive validity of the attention cue. That is, in order to succeed in this task, infants must have used the attention cue to preferentially encode the attended square into VSTM, because both the valid and invalid streams contained a color-change at every onset.

This study it is the first to demonstrate that attention can effectively mediate which items are encoded into VSTM in infants just as it does in adults. This ability may be a crucial component of an infant's learning repertoire, allowing them to quickly extract meaningful and relevant information about particular objects or events. This study also has important implications for researchers who rely on visual paradigms to study infant cognitive development. Specifically, any task involving memory, particularly short-term memory, for visual items would need to be closely examined to rule out the possible confounding effects of attention and VSTM capacity. For example, if attention were inadvertently drawn to one element in a memory array (either due to stimulus characteristics or task demands), one would expect the results to reflect the selective encoding of that item into VSTM. In other words, attentional factors (not perceptual or memorial factors) might cause infants to respond to the task as if they were unable to encode all of the objects into VSTM, a possibility that will be explored in subsequent experiments.

Figure 4. Experimental apparatus viewed from above, and from the point of view of the infant. Note: the black curtain hung from wall to wall, and ceiling to floor.



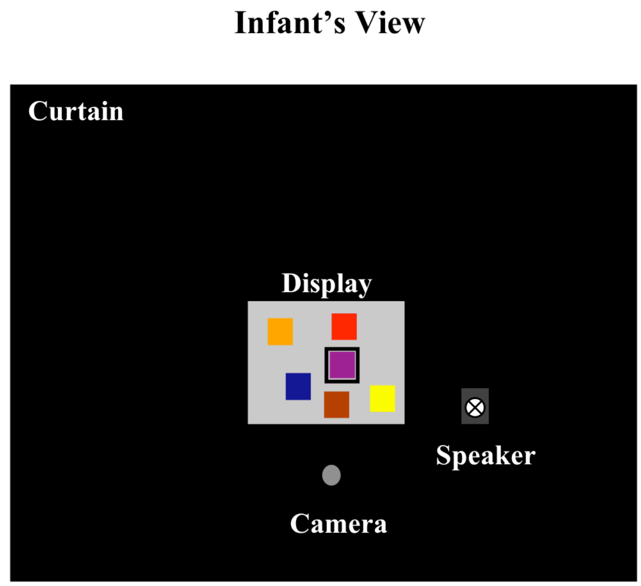


Figure 5. Experiment 1 (n = 36). Mean looking times to the Valid and Invalid streams as a function of Set Size (3 or 6) and Block (one or two).

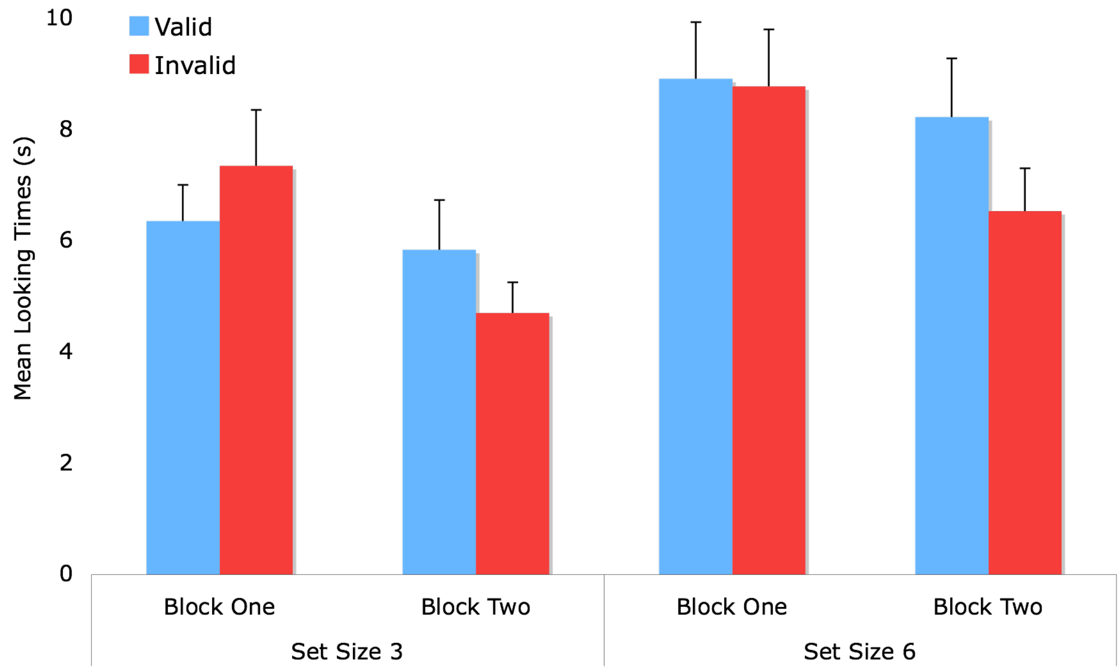
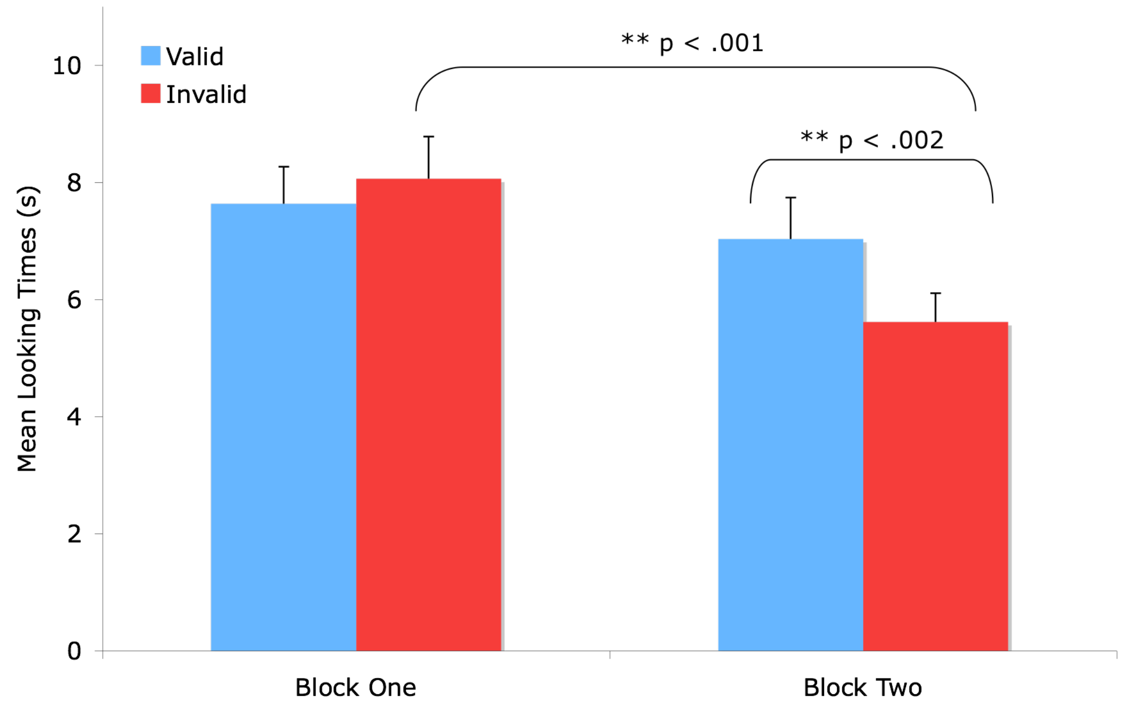


Figure 6. Experiment 1 (n = 36). Mean looking times to Valid and Invalid streams as a function of Block.



CHAPTER 3: EXPERIMENT 2

Attention and VSTM in 5.5-Month-Old Infants

Experiment 1 explored the effect of attention on VSTM in 10-month-old infants. Experiment 2 extends these findings by testing the same conditions in younger infants. Based on the results of Experiment 1, it appears that 10-month-old infants can use a perceptual attention cue to determine which objects are encoded in VSTM, an ability which appears to be obligatory, and independent of set size. Clearly, this sort of mediation provides infants with flexibility in processing the enormous amount of information they are faced with every day. However, the ability to use a cue depends on several factors including the ability to rapidly disengage, shift, and re-engage at the new location. To that end, Johnson and Tucker (1996) have demonstrated that at 4 months, but not at 2 months, infants are able to use a 100 ms pre-cue (SOA 200 ms) to facilitate processing of a stimulus that subsequently appeared ipsilateral to the cue location. These infants were faster to orient to the cued stimulus than to the uncued one. Clearly, by 5.5 months, infants are able to detect and orient to a briefly presented cue. However, in the Johnson and Tucker study (1996), facilitation was defined as correct orienting to the target location. In Experiment 1 of this thesis, facilitation required not only successful orienting of attention, but also successful encoding of the subsequent target into VSTM.

Moreover, in Johnson and Tucker's task, the cue disappeared 100 ms before the onset of the test array (1996) automatically disengaging infant attention from the cue. However, the cue used in Experiment 1 remained visible during the entire presentation of the stimulus array, which may have hindered the disengaging process. Therefore, it is critical to test younger infants using the exact same stimuli that we used for the older infants, in order to probe for developmental differences in cue efficacy. If the simultaneous aspect of the cue "captures" 5.5-month-old infant attention, then it is possible that the cue would not facilitate encoding of the target item into VSTM. One goal of Experiment 2 is to establish whether 5.5-month-old infants can use an attentional cue under the same conditions as do 10-month-old infants. If they can, then these younger infants in Experiment 2 will look longer to the valid cues than to the invalid ones. If, however, attention systems are insufficiently developed to support the rapid switching of attention and/or the competing aspects of the cue, then infants will look equally to valid and invalid trials. Because set size did not interact with validity preferences in Experiment 1, and because 5.5-month-old VSTM capacity is approximately one item, infants in this experiment were shown only set size three streams.

Participants

Participants were 18 healthy, full-term 5.5-month-old infants, with no history of birth complications or vision problems, including a significant family history of color blindness. Our sample of 5 infants ranged in age from 23.86 weeks to 27.00 weeks, M = 25.71, SD = .96, and included 8 males and 10 females. All of the infants' mothers had graduated high school, and 69% had completed at least a bachelor's degree. An additional 1 infant was tested but excluded from the analysis due to fussiness or lack of interest (n = 1).

Stimuli

The stimuli used in Experiment 2 were identical to the set size 3 streams used in Experiment 1.

Design and Procedure

As in Experiment 1, infants saw both Valid (n = 6) and Invalid (n = 6) streams. There was no between-subject variable. The procedure was identical to that of Experiment 1.

Results

As in Experiment 1, looking times to the Valid and Invalid streams were calculated and entered into a 2x2 ANOVA with the within subject variables of Validity (valid and invalid) and Block (one and two). As can be seen in Figure 7, there was a main effect of block, $F(1, 17) = 33.73$, $p < .001$. Overall, infants looked significantly longer to the first block ($M = 6.95$, $SE = .63$) than to the second block ($M = 4.51$, $SE = .44$). This finding is consistent with the results of Experiment 1, once again suggesting that infants were responding to the overall novelty of the stimuli, becoming increasingly familiar with the task by the second block. There were no other significant effects.

<u>Supplemental analyses:</u>

Comparison of the results from Experiments 1 and 2 suggest an important developmental transition from 5 to 10 months. In Experiment 2, 5.5-month-old infants showed no evidence of being able to use the attention cue, as evidenced by the total absence of any Validity effects. However, 10-month-old infants upon viewing the exact same stimuli, showed a significant Validity by Block interaction, indicating that they were indeed able to use the attention cue to facilitate encoding of the target item into VSTM. It is therefore important to directly test these developmental differences. To accomplish this, data from the 10-month-old infants in Experiment 1 (set size 3 trials only) were analyzed with data from the 5.5-month-old infants from Experiment 2 in an additional mixed-model ANOVA. As expected, results from this supplementary analysis reveal a main effect of Block $F(1, 34) = 19.79$, $p < .001$. Overall, infants looked significantly longer to the first block ($M = 6.90$, $SE = .43$) than to the second block ($M = 4.89$, $SE = .35$). However, this effect was qualified by a marginally significant Block by Validity by Age interaction, $F(1, 34) = 3.71$, $p = .06$. Although this interaction did not quite reach conventional levels of statistical significance, it does suggest that 10- and 5.5-month-old infants were responding differently to the attention cue. Recall that the main effects appear to be differential habituation to the valid and invalid streams. Therefore, to further understand the sources of this interaction we ran a series of t-tests exploring the decrement in looking times as a function of Block and Validity (once again using p = .0167 as the criterion for significance) (see Figure 8). Ten-month-old infants significantly decreased their looking to the Invalid streams, t (17) = 2.77, p = .01 but not the Valid streams, t (17) = .49, *ns*, whereas the 5.5-month-old infants significantly decreased their looking to both the Valid, t (17) = 4.03, $p < .001$ and Invalid streams, t (17) = 5.44, $p < .0001$. This pattern of responding clearly indicates that over time, the attention cue enables older infants to inhibit processing of the Invalid streams.

Discussion

This experiment tested the ability of young infants to use the same attentional cue that was successfully used by the older infants in Experiment 1 to selectively encode items into VSTM. The results of Experiment do not support that hypothesis. However, supplementary analyses comparing the 10-month-old infants from Experiment 1 to the 5.5-month-old infants in Experiment 2 yielded some very interesting results. In particular, older infants significantly decreased their looking to the Invalid streams while maintaining their interest to the Valid streams, whereas the younger infants decreased their looking to both trial types. This is important because it demonstrates that the ability to use a compound attention cue is developmental in nature, and may not be readily available until at around 10 months. However, failure on this tasks does not necessarily mean that young infants are unable to use attention to selectively encode items into VSTM. There are several possible reasons for the failure of young infants.

First, it is possible that the visual attention system of young infants is too immature to afford a processing benefit—either by not sufficiently enhancing processing of the attended square relative to the other squares, or by failing to inhibit processing to the distractor squares. Previous work has shown that even very young infants can benefit from the use of an attentional pre-cue (Johnson & Tucker, 1996), so this does not seem a likely explanation.

It is also possible that the task demands of our task were too high. To succeed in the present task, in addition to correctly orienting attention to the cue, infants had to encode the subsequently presented target into VSTM. To accomplish this, infants would need to disengage attention from the cue, and then shift it to the target before the offset of the target. Note that this type of disengagement is not required in tasks that measure orienting responses (e.g., target detection), as the targets in these types of studies need not be processed or encoded into memory (e.g., target identification). Because our attention cue appeared before the onset of the array, and remained visible during the entire presentation of the array, it is possible that these younger infants failed to encode the properties of the target because they were unable to switch attention from the cue to the target quickly enough. Recall that visual attention has been hypothesized to consist of at least three functionally distinct systems: the attentional engaging system, the attentional disengaging system, and the attentional orienting system (Posner & Cohen, 1984). Immaturity in any one of these systems could theoretically lead to a decrement in performance on tasks that contain of multi-object arrays. Indeed, several studies have shown that at around 6 months, infants have some difficulty orienting to the sudden onset of a peripheral stimulus (distracter) when the currently foveated stimulus remained on the screen (Hood, 1995). This drop in performance relative to conditions where the central stimulus disappeared prior to the onset of the distracter has been taken as evidence of an immature attentional disengaging system, as the infants apparent had difficulty disengaging from the central stimulus despite the sudden onset of the distracter (Frick et al., 1999; Hood & Atkinson, 1993; Richards & Casey, 1992). The hypothesis that the simultaneous component of the cue used in Experiments 1 and 2 made it particularly difficult for young infants to disengage and re-orient attention is tested in Experiment 3.

In addition, it is possible that young infants could fail to encode the target even if they are able to switch attention from the cue to the target, if the cue itself is encoded as an object in VSTM. Consider the consequences of this shortcoming: If infants have a VSTM capacity of only a single item, then any item foveated by the infant would be encoded into VSTM. Moreover, any subsequently appearing item would necessarily displace the previous representation. In other words, the Valid streams and the Invalid streams would appear identical. Note that this would not be the case for infants whose capacity is greater than a single item, as they would likely be able to represent pairs of stimuli. This hypothesis is tested in Experiment 4.

Finally, it is possible that these young infants can orient attention, and are able to encode the target items into VSTM, but that the magnitude of this effect is too small to appreciate using looking time measures. It is possible that physiological measures such as ERPs or changes in heart rate might reveal sensitivity to the attention cue in our VSTM tasks in a way that looking time cannot. Unfortunately, these experiments are beyond the scope of this thesis.

In summary, before we can conclude that 10-month-old, but not 5.5-month-old infants can use attention to selectively encode items into VSTM, we need to rule out the two alternative hypotheses posited above. First, it is possible that the young infants failed because the simultaneous aspect of the cue made disengaging attention from the cue disproportionately difficult for young infants. To test this, we showed infants test displays that contained an attentional pre-cue only (Experiment 3). Second, it is possible that the cue itself competed for valuable VSTM resources in young infants. To test this, we showed infants displays in which the attention cue could not be encoded as an object (Experiment 4).

Figure 7. Experiment 2 (n = 18). Mean looking times to Valid and Invalid streams as a function of Block.

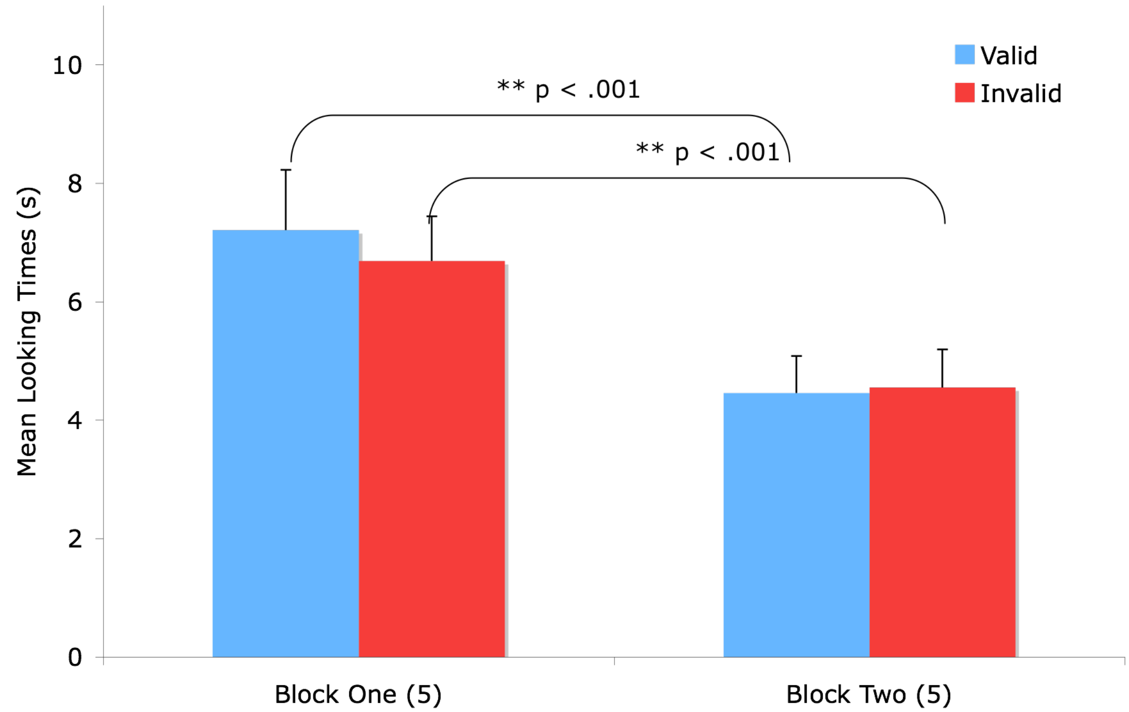
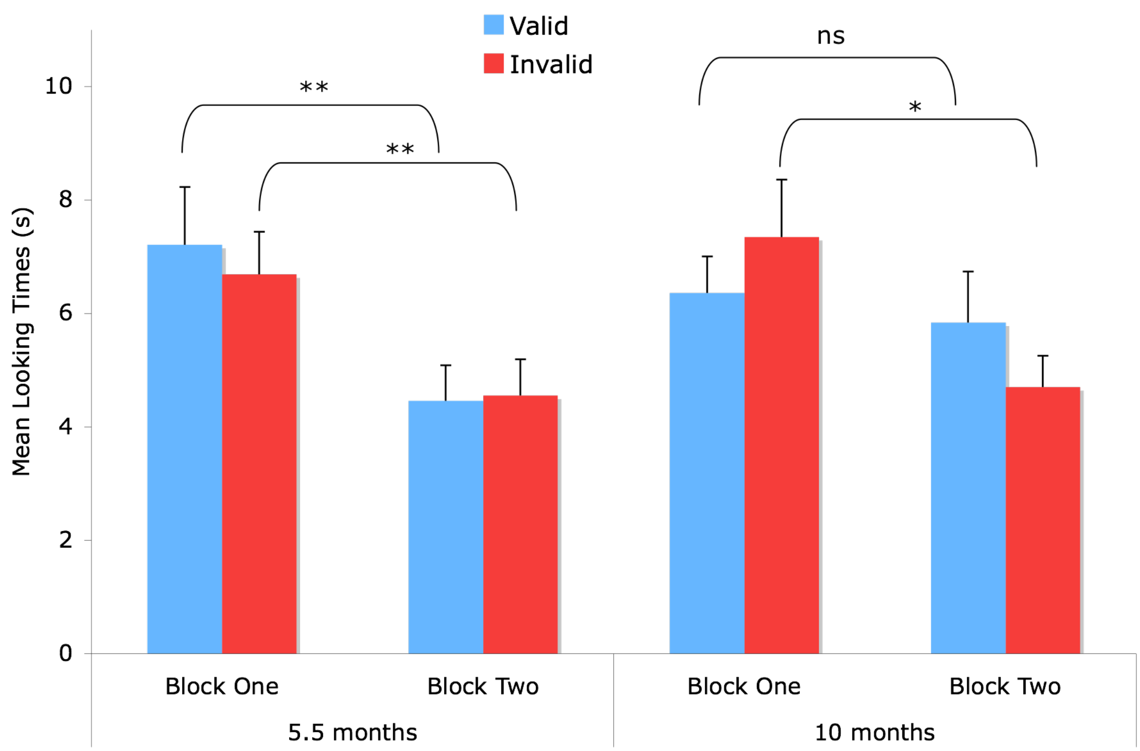


Figure 8. Experiment 2 Supplementary Analyses (n = 36). Mean looking times to Valid and Invalid streams as a function of Age (10-month-old infants from Experiment 1 and 5.5-month-old infants from Experiment 2) and Block.



** = p < .01, * = p < .05

CHAPTER 4: EXPERIMENT 3

Attentional Pre-Cue in VSTM in 5.5- and 10-month-old Infants

Based on the results of Experiments 1 and 2, it is clear that 10-month-old infants but not 5.5-month-old infants can use visual attention to direct which items are encoded into VSTM. However, because all of the infants in the previous experiments were tested using a compound attentional cue (i.e., pre-cue plus a simultaneous cue) it is important to rule out the alternative hypotheses that young infants failed to encode the VSTM displays either due to indirect competition from the attentional cue itself. (i.e., attention "captured" by the cue thereby making it difficult to orient to the target) or due to competition for VSTM resources (i.e., the cue itself was encoded as an object thereby filling VSTM to capacity).

In Experiments 1 and 2, infants were presented with stimuli in which multiple items were presented simultaneously; a situation that may particularly tax the attentional systems of the young infants. Work in adults has revealed that patients with bilateral parietal lobe damage are unable to perceive multiple objects presented simultaneously, and that this deficit may be due to the inability to rapidly switch attention from the currently foveated object (Moreaud, 2003; Woldorff et al., 2004). For example, if two objects are presented to a patient who has suffered bilateral parietal lobe damage, the patient will generally report the presence of only a single item. With some direction and "cueing" it is possible to get the patient to attend to or "see" the other object.

Work in infants has also revealed that at 6 months, objects may compete for attention (Hood & Atkinson, 1993) and that the parietal lobes are relatively immature until around 6 months postnatally (Johnson et al., 1994). The failure of young infants to detect a change at set sizes greater than one in our previous work, therefore, may reflect their inability to engage in such endogenous shifts of attention, and this failing might be due in part to the immaturity of the parietal lobes. In our own lab, we have demonstrated that infants at this age are unable to bind color and location in a VSTM task (Oakes et al., in press-a), an ability that requires visual attention in a multi-object context.

If attentional competition is responsible for the young infants' inability to encode the target items into VSTM, then the elimination of the simultaneous component of the attentional cue should allow these infants to demonstrate a relative preference for the Valid streams. Thus, Experiment 3 tested 5.5- and 10-month-old infants using the exact same types of stimuli used in Experiments 1 and 2, only this time, the cue disappeared when the target array appeared.

Participants

Participants were 36 healthy, full-term 5.5- and 10-month-old infants, with no history of birth complications or vision problems, including a significant family history of color blindness. Our sample of 5.5-month-old infants ranged in age from 23.71 weeks to 26.57 weeks, $M = 25.13$, $SD = .80$, and included 7 males and 11 females. Our sample of 10-month-old infants ranged in age from 41.57 weeks to 45.29 weeks, $M = 43.24$, $SD = 1.01$, and included 12 males and 6 females. All of the infants' mothers had graduated high school, and 64% had completed at least a bachelor's degree. An additional 2 infants were tested but excluded from the analysis due to fussiness or lack of interest ($n = 2$ at 5.5 months).

Stimuli

Stimuli were identical to those used for Experiment 2 with one exception; in Experiment 3, the cue disappeared simultaneously with the onset of the colored-square array (see Figure 9)

Design and Procedure

The design and procedures were identical to those used in Experiment 2 except that age (5.5 and 10 months) was the between-subjects variable.

Results

Once again, mean infant looking times were calculated for each type of trial in each block, and these data were analyzed by means of a 2x2x2 mixed-model ANOVA with Validity (valid vs. invalid) and Block (one vs. two) as within subjects variables, and Age (5.5 vs. 10) as the between subjects variable. This analysis revealed only the familiar main effect of Block, $F(1, 34) = 3.96$, $p = .05$. Overall, infants looked significantly longer to the first block ($M = 6.54$, $SE = .38$) than to the second block ($M = 5.66$, $SE = .36$). There were no other significant effects (see Figure 10).

Discussion

These results rule out the hypothesis that 5.5- and 7.5-month-old infants in Experiment 2 failed to use the cue to differentiate valid from invalid streams due to competition from the simultaneous component of our attention cue. In the present experiment, competition from the cue was reduced or eliminated by presenting a pre-cue only; however, infant performance did not improve. Thus, it is unlikely that competition from the cue led to the failures of the young infants in Experiments 1 and 2. However, the present failure of 10-month-old infants to differentiate Valid and Invalid streams might indicate that the pre-cue alone was insufficient to drive an orienting response. Thus, in Experiment 4, 5.5- and 10-month-old infants were shown displays that utilized the highly salient attentional cue of abrupt onset. In this manner, it was possible to probe the competition hypothesis, while providing infants with a strong attentional cue. Just as importantly however, these new displays enabled us to test the hypothesis that the 5.5-month-old infants in Experiment 2 failed due to the added VSTM burden imposed by the cue itself.

Figure 9. Schematic depiction of Invalid and Valid stream for Experiment 3.

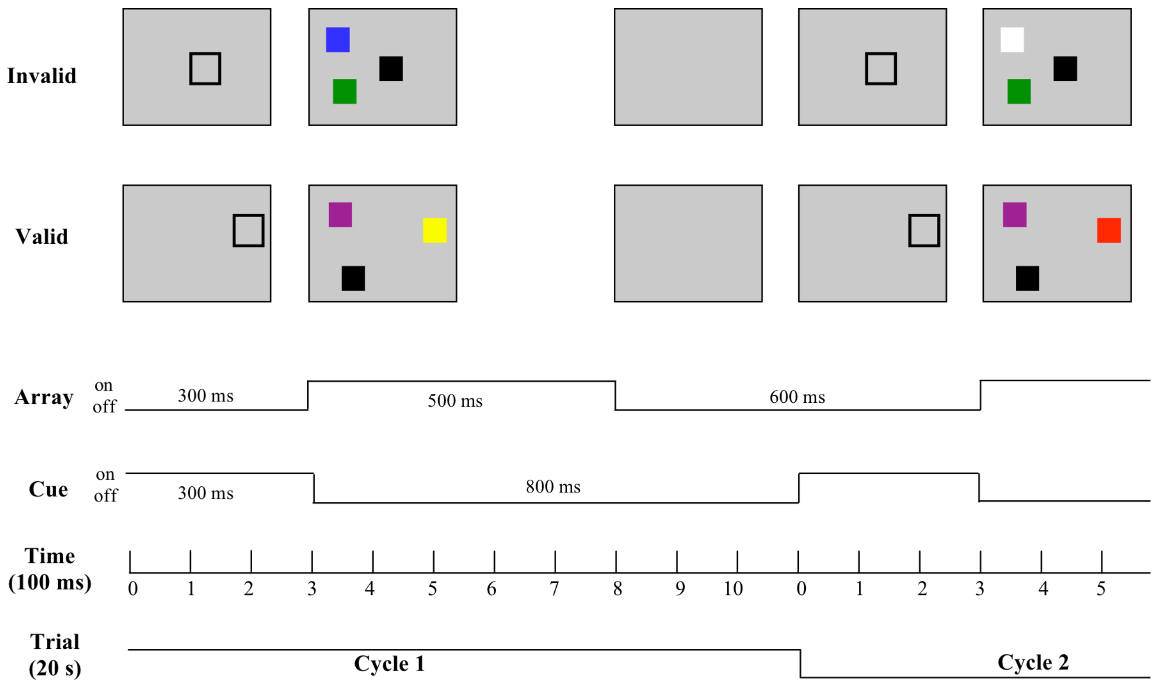
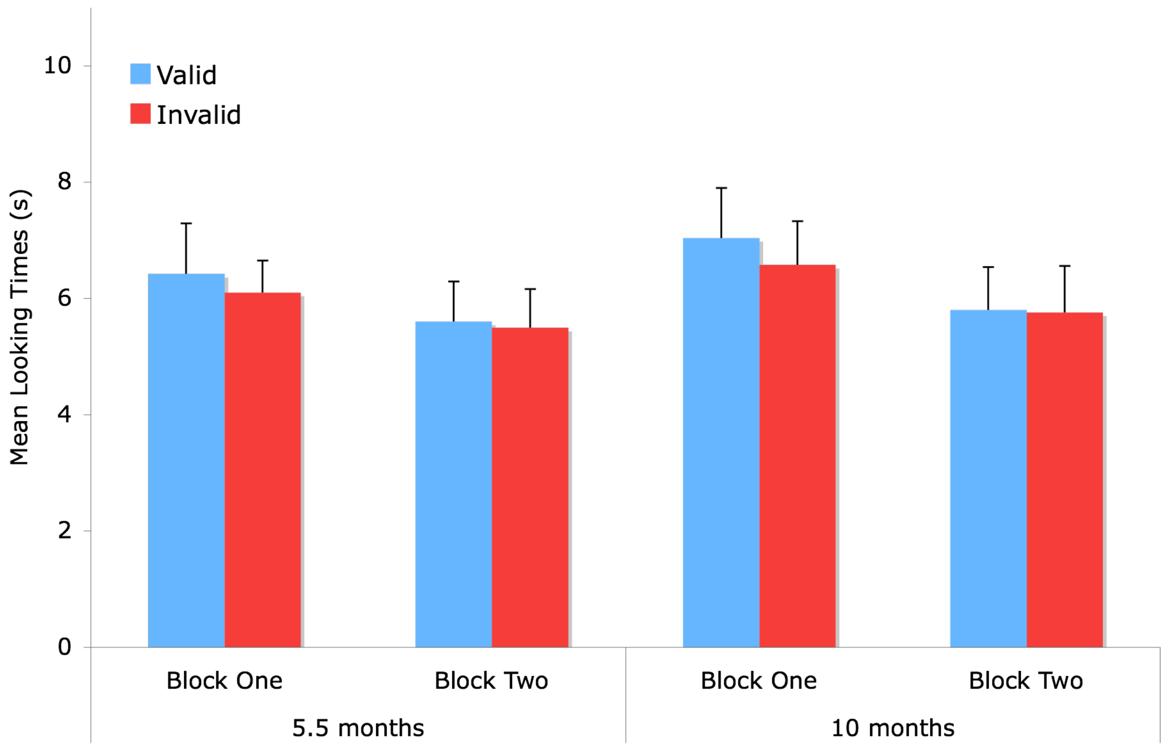


Figure 10. Experiment 3 (n = 36). Mean looking times to the Valid and Invalid streams as a function of block



CHAPTER 5: EXPERIMENT 4

Attentional Deficit or Capacity Limits

The previous experiments established that attention can influence which items are encoded into VSTM (Experiment 1) and under what conditions (Experiments 2 and 3). On the basis of these studies, it is clear that the some component of performance on this task develops between 5.5- and 10 months. What is not clear, however, is if the change in performance is a function of attentional development, VSTM capacity development, or both. On the basis of the results of Experiments 2 and 3, we can be reasonably confident infant performance is not hindered by immature attentional disengagement mechanisms. However, an even stronger test of this hypothesis would be to present multiple targets to infants in a way that allows us to make use of an extremely salient attention cue (i.e., abrupt onset), and allows us to present the items one at a time. By removing the attentional and VSTM competition effects, it may be possible for 5.5-month-old infants to demonstrate a relatively precocious VSTM capacity.

To achieve this, 5.5- and 10-month-old infants were shown colored squares, presented one at a time, in bursts of 2. This type of presentation eliminates the competition produced by multi-object displays (for both attentional and VSTM stores), and will allow us to directly test the confounding effects of attentional immaturity to sensitivity on VSTM tasks.

Participants

Participants were 48 healthy, full-term 5.5- and 10-month-old infants, with no history of birth complications, vision problems, or a significant family history of color blindness. Our sample of 5.5-month-old infants ranged in age from 23.43 weeks to 27.00 weeks, M = 25.35, SD = .92, and included 13 males and 11 females. Our sample of 10-month-old infants ranged in age from 41.43 weeks to 45.57 weeks, M = 43.77, SD = 1.16, and included 8 males and 16 females. All of the infants' mothers had graduated high school, and 71% had completed at least a bachelor's degree. An additional 2 infants were tested but excluded from the analysis due to fussiness or lack of interest (*n* = 2 at 10 months).

Stimuli

The stimuli for this study were based on the stimuli used in previous experiments. However, because the only cue in this study was the cue of abrupt onset, half of the streams depicted a change event, and the other half depicted a no-change event. As in previous studies, the stimuli were presented in streams, only this time, the infants saw pairs of squares, presented sequentially in the center of the monitor. Each pair was separated by a 600 ms delay period, in an attempt to make the test pairs more explicit (see Figure 11). So for example, on a given trial, one infant might see a blue square (300 ms), followed by blank period (100 ms), then a red square (300 ms), followed by a 600 ms inter-trial interval. This target, delay, target, long delay sequence was repeated over and over for 20 seconds. However, for half of the streams (Change streams) the color of one of the blocks in each pair (e.g., either the first or the second square, determined at random) changed, and for the other half of the streams, the colors remained the same from pair to pair (No-Change streams). Previous work has demonstrated that by 5 months, infants can represent the colors of objects even when trials involve only 250 ms of exposure to those objects (Catherwood, 1994). Thus, the 300 ms of exposure proposed here should be sufficient to allow for the encoding of each colored square. These test pairs were presented over and over until 20 seconds had elapsed. Note that the temporal parameters of these streams approximate the temporal parameters of the Ross-Sheehy et al. study (2003a) in which the 4- and 6.5-month-old infants were able to encode the identity of one object into VSTM that was visible for 500 ms, and remember that object across the subsequent 250 ms delay.

Because the stimuli used in this experiment did not contain an attention cue beyond the actual test items, the Change and No Change streams were presented side-by-side in a manner consistent with the procedure used in our previous work (Oakes et al., in press-a, in press-b; Ross-Sheehy et al., 2003a). This procedure is ideal because it has been shown to facilitate comparisons between concurrent displays (Cohen & Gelber, 1975; Oakes & Ribar, 2005), thereby increasing sensitivity to differences between the displays.

Design and Procedure

As is standard in this procedure (Oakes et al., in press-a), infants were presented with 2 warm-up and 6 test trials, each 20 s in duration. On each trial, infants were shown a Change stream on one monitor and a No-Change stream on the other (the left-right location of the Change and No-Change streams varied randomly from trial to trail). The dependent variable for this study was looking to the different stream types (i.e., Change vs. No-Change), and, because the paired-comparison procedure was used, we calculated the proportion of looking to the Changing stream as a function of looking to both the Changing and Non-Changing streams (i.e., change preference) on each trial. All other elements of the procedure were identical to previous experiments.

Results

Our primary measure was the change preference score averaged across the 6 test trials. This measure was obtained by dividing looking to the Change streams, by looking to both Change and No Change displays (Looking to Change/(Looking to Change + Looking to No Change)). We compared the average change preference scores at each age to chance (.50) by means of a two-tailed t-test. The ten-month-old infants had significantly higher change preference scores (M = .56, SE = .02) than would be expected by chance, $t\,(23) = 2.58$, $p < .05$, but 5.5-month-old infants did not (see Figure 12)

To directly test whether older infants performed differently than the younger ones in this task, mean change preference scores for the 10-month-infants were directly compared to mean change preference scores for 5.5-month-old infants. Though the difference did not reach conventional levels of significance, t (46) = -1.78, p = 08, it certainly does suggest that 10-month-old infants (M = .56, SE = .02) were performing differently on this task than the 5.5-month-old infants (M = .51, SE = .02).

It should be pointed out that we did not analyze infants' responding by block as we did in the first three experiments. Because this procedure incorporates warm-up trials that are not included in the analyses, the effects reported are similar to those observed in the later trials of the procedure used in the first experiments. In addition, because the side-by-side presentation procedure used in Experiment 4 may in fact be a more sensitive test of infants' memory abilities (Cohen & Gelber, 1975), changes over time may not be as dramatic as in the other procedure—because on each trial infants can *choose* whether to look at the changing or non-changing stream, habituation effects for the duration of looking should not have as significant an impact on the overall effects. Finally, by including all 6 preference scores in our mean, we reduced our variability and increased our power.

Discussion

The results of this Experiment reveal that 10- but not 5.5-month-old infants are able to represent two items in VSTM, even when the test items are presented in seclusion. This finding is significant for a number of reasons. First, it is the very first time a procedure such as this has been successfully used with infants. The addition of this potentially more sensitive procedure to the very limited pool of techniques used to measure VSTM and/or visual attention is a significant achievement. Using this task, it is now possible to probe for changes in attentional and VSTM development in ways that were previously impossible. For example, this task would be well-suited to probing for the presence of well-known adult memory/attentional phenomena such as order effects, the attentional blink, distinctiveness/complexity effects, interference effects, the amount of time necessary to encode an item into VSTM, and so on. Second, these results are the first to demonstrate that 10-month-old infants can encode and remember multiple, sequentially presented items in a VSTM task. This is an important finding because it indicates that at least by 10 months, infants are able to process stimuli individually, and do no need to rely on configural cues for multiple-item VSTM arrays. Third, this finding provides strong converging evidence for the claim that VSTM is relatively adult-like by 10 months (Oakes et al., in press-a, in press-b; Ross-Sheehy et al., 2003a). Fourth, the relative performance of the older versus the younger infants provides support for the claim that older infants respond to these arrays in a manner different that the younger infants, moreover that the ability to use attention to selectively encode items into VSTM develops somewhere between the 5th and 10th month of infancy. Finally, the failure of the 5.5-month-old infants to detect the changing streams even when the test items were presented in seclusion rules out the alternative hypotheses that young infants' failures in Experiment 2 were due either to competition from the attention cue itself or to competition from other objects.

Figure 11. Schematic depiction of a Change and No-Change stream for Experiment 4

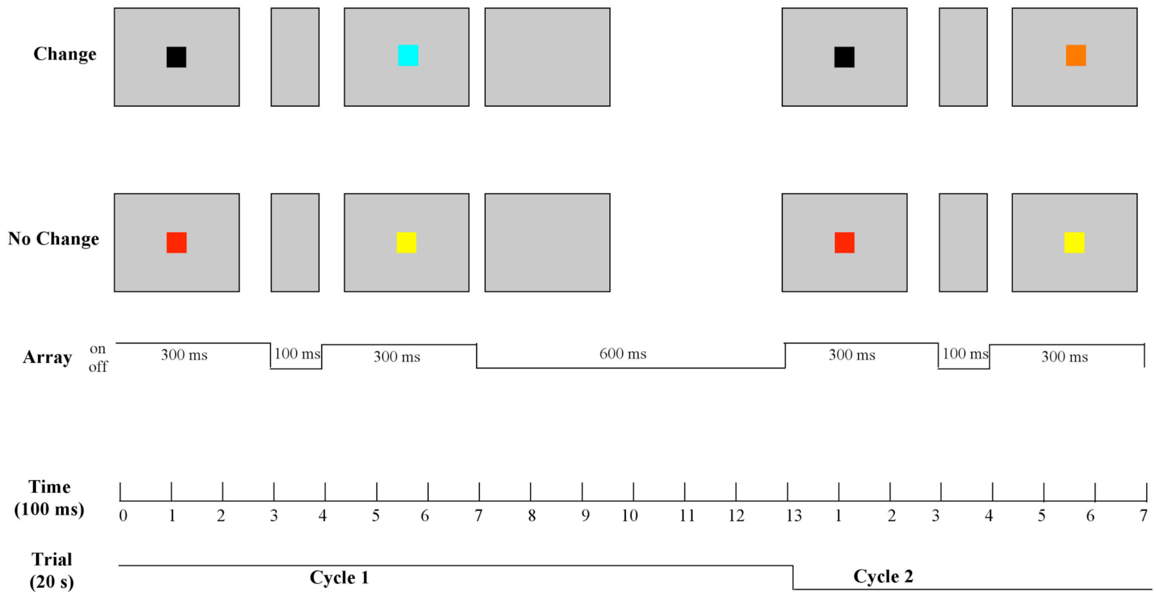
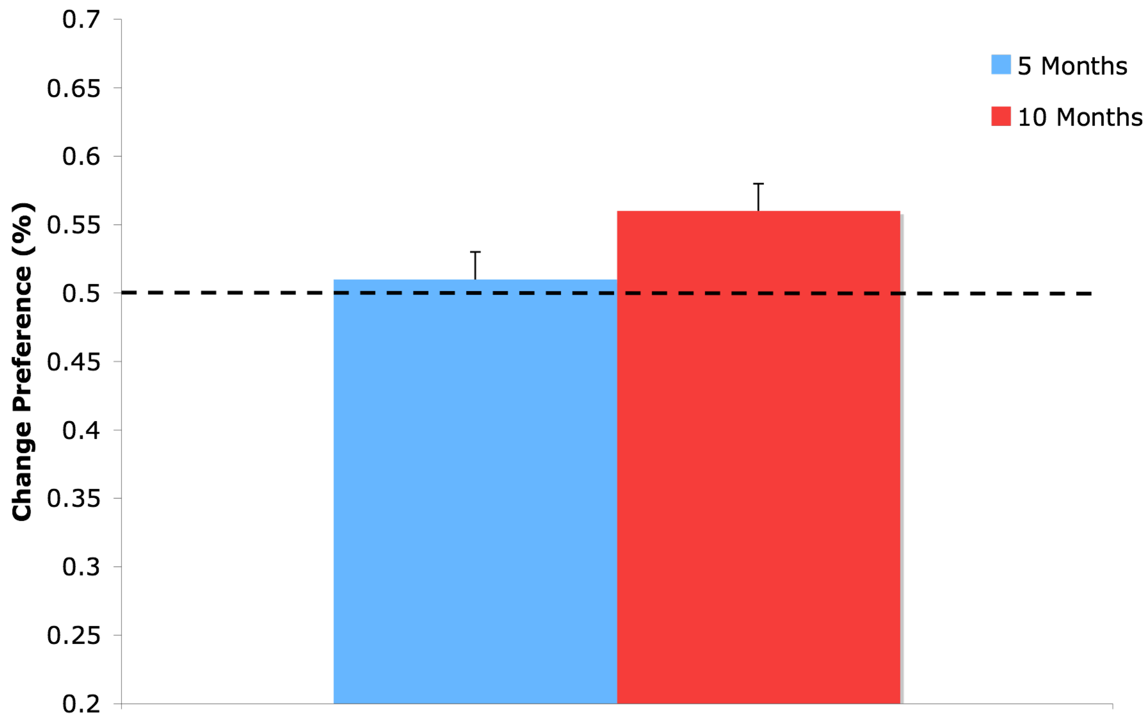


Figure 12. Experiment 4 (n = 48). Mean looking time to Change and No-Change streams as a function of Age and Block.



CHAPTER 6: GENERAL DISCUSSION AND CONCLUSIONS

Taken together, the results from these experiments contribute four significant and unique findings to the fields of infant cognitive development:

10-Month-Old Infants Can Use Attention in a VSTM Task

These results clearly demonstrate that 10-month-old infants can use attention to selectively encode particular items into VSTM. The interaction of attention and VSTM has never before been examined in infants, and these findings constitute a significant contribution. When 10-month-old infants were presented with a compound attention cue (i.e., pre-cue plus a simultaneous cue), attention was obligatorily oriented to the cue. As a result, infants were able to selectively encode the properties of the cued item into VSTM, allowing them to notice the color change of this square, despite the presence of multiple distracter squares. This finding, particularly for the infants who saw arrays of six items, stands in stark contrast to previous work demonstrating that without an attention cue, 10-month-old infants were unable to detect the color change of a single square embedded in arrays of six squares (Ross-Sheehy et al., 2003a).

Furthermore, the response to the cue appeared obligatory in nature. We can have confidence in this statement for two reasons. First, in Experiment 1, ten-month-old infants responded to the cue regardless of set size. That is, even when the test array was small enough that infants could encode every item into VSTM, infants continued to respond to the cue, looking significantly longer to the Valid streams than to the Invalid ones.

Second, the response to the cue seemed obligatory because this orienting response did not diminish over the course of the experiment. Quite to the contrary, infants became increasingly sensitive to the differences between the Valid and the Invalid streams over the course of the experiment. This sensitivity was manifested as diminished looking to the Invalid stream for Block 2 relative to Block 1. This "selective habituation" effect was robust and replicable, appearing in every sample of 10-month-old infants that demonstrated memory for the target item. If infants were simply responding to the novelty or distinctiveness of the attention cue, we would expect interest in the cue to wane over the course of the experiment, and we would further expect the Validity preference to decline as infants begin to pay attention to the distracter squares. Recall that in both Valid and Invalid streams, the color of a single block is changing at every onset—thus the only difference between the two streams is the predictive validity of the attention cue. If attention to the cue were endogenously driven, then we would expect habituation to the cue leading to shorting looking times across the board. Though in our sample of 10-month-old infants overall looking did decrease, it decreased significantly more so only for the Invalid streams.

Cue Efficacy Can Be Driven By the Properties of the Cue

In addition to the previous findings, we were able to demonstrate that the effectiveness of the attentional cue was at least partially driven by the properties of the cue itself. In other words, the cue was only effective when it consisted of both a pre-cue and simultaneous cue (Experiment 1), or if the cue consisted solely of the abrupt onset of the test item (Experiment 4). In both cases, we found evidence that 10-month-old infants were able to first orient their attention, then encode the subsequently appearing item into VSTM. Again, this effect manifested as longer looking to the Valid or Changing streams than to the Invalid or Non-Changing streams. It should be noted that it is currently unclear what particular aspect of the compound cue is useful for the 10-month-old infants. Though the results of Experiment 3 indicate that the pre-cue alone is insufficient to drive an attentional effect, we are currently running studies to examine the efficacy of a simultaneous only cue. Thus, it will be possible to determine if infants require a compound cue, or if the simultaneous component of the cue used in Experiment 1 was sufficient to drive the observed effect. Somewhat surprisingly, the effectiveness of this orienting response did not appear to be qualified by the perceptual load of the test array. Infants were just as likely to use the cue for arrays of three squares as they were for arrays of six squares. This particular finding indicates that by 10 months, there is a relatively inflexible perceptual processing hierarchy that favors processing of the attended item, even in situations where that level of selectivity is not necessary or even advantageous (e.g., set size three arrays). This is a very interesting possibility, suggesting a separate trajectory for the development the kind of attentional flexibility that we see in adults (Lavie, 1995). This possibility warrants further study.

Attentional Mediation of VSTM Develops

Another major contribution of these studies is that the ability to use an exogenous cue to selectively attend to and successfully encode that item into VSTM appears to develop between 5.5 and 10 months. In the present studies, 5.5-month-old infants showed no sensitivity to the color-change of a single item when given compound attention cues (Experiment 2) or attentional pre-cues (Experiment 3). This is particularly intriguing given that previous work indicates infants are able to detect a color-change when presented only a single item (Ross-Sheehy et al., 2003a). Why do infants fail when given an additional cue? There are several possible reasons, most of which have been directly addressed in this thesis. First, it is possible that the cue itself competed for attention, making it disproportionately difficult for these young infants to disengage attention from the cue and deploy it to the target. However, in Experiment 3, we removed the competitive, simultaneous component of the cue, and still found no sensitivity to cue validity.

Second, it is quite possible that the lack of a gap between the offset of the cue and the onset of the target array was insufficient to allow for the process of disengagement, and/or that that infants simply did not have enough time to encode the properties of target before the offset of the target array. This is quite possible, as previous research has shown that infants of this age are quicker to orient to a target in conditions where a gap exists between the offset of the cue, and the onset of the target (Hood & Atkinson, 1993; Matsuzawa & Shimojo, 1997). It is interesting to note that work with adults has demonstrated a marked attentional blink that occurs during a period of VSTM consolidation, which can persist for approximately 400-600 ms and can delay the encoding of subsequently presented items into VSTM (Vogel & Luck, 2002). It is quite possible that this VSTM refractory period is developmental in nature, contributing to the performance of the younger, but not the older infants. Note that an attentional blink could also hinder performance on our serial presentation tasks, if the items are presented within the refractory period of VSTM consolidation. This very interesting hypothesis warrants further study.

A third possibility for the failure of 5.5-month-old infants is that the cues were simply insufficient to drive an attentional orienting response, particularly in Experiment 3 where performance was poor for both the 5.5- and 10-month-old infants. In support of this hypothesis, most studies examining orienting of attention have relied on cues that incorporated motion or apparent motion (Dannemiller, 2000; Hood & Atkinson, 1993; Johnson et al., 1991; Richards, 2001; Ross & Dannemiller, 1999; Vogel & Luck, 2002).

10-Month-Old Infants Can Encode Serially Presented Items into VSTM

The final major conclusion of these studies, and perhaps the most exciting one, is that by 10 months, infants appear able to encode multiple rapidly presented items into VSTM. The purpose of Experiment 4 was to determine if young infants could encode more than a single item into VSTM if the theoretically confounding effects of attentional development were more explicitly controlled. Based on previous work, it was clear that young infants (i.e., 4 and 6.5-months) had dramatically diminished VSTM capacity relatively to older infants (i.e., 10 months) (Ross-Sheehy et al., 2003a). However, subsequent work revealed something even more dramatic: Six-month-old infants were unable to remember the color of even a single block if that block was embedded in a multi-object array. What was particularly startling about this finding was that these infants failed to detect a difference between streams in which the same three items were presented over and over, from streams in which *every single item changed color at every onset* (Oakes et al., in press-b). This remarkable inability to remember the color of even a single square when embedded in an array of squares seems to indicate a failure to bind the features of objects in a meaningful way. This type of binding has historically been thought to require attention (Oakes et al., in press-b; Treisman & Gelade, 1980).

Thus, Experiment 4 was designed to test the possibility that attentional liabilities were responsible for the capacity effects demonstrated in previous work, by essentially forcing the infant to attend to each and every item relatively free from the burden imposed by immature attentional orienting and disengaging mechanisms. However, even under these conditions of extreme attentional support, 5.5-month-old infants still failed to differentiate the Change from the No-Change streams. This finding strengthens the claim that the primary performance-limiting factor in tasks that require VSTM is indeed the development of VSTM.

It should be noted that this is a completely novel task, and that nothing like this has ever before been used to test infant memory. As such, it was a distinct possibility that this task might simply be ineffective. Fortunately, however, the 10-month-old infants showed a very robust preference for the Changing streams, indicating not only that this task was effective, but also that by 10 months, infants are able to encode and demonstrate memory for rapidly presented items.

General Conclusions

The results of these studies inform models of developing infant attention and VSTM. Clearly, visual attention is tied to VSTM capacity in complex and dynamic ways, particularly in infancy. Currently, models of the development of visual attention are maturational and descriptive in nature (Atkinson et al., 1992; Frick et al., 1999; Hood & Atkinson, 1993; Johnson, 1990; Johnson, 1998; Posner & Petersen, 1990), and models of the development of VSTM have yet to be posited. One interesting theory of infant memory is based on the object files account (Kahneman et al., 1992). Specifically, infant researchers have noted parallels between the development of infant memory, capacity and sensitivity to the features of objects, and the adult object files literature (see Carey & Xu, 2001 for a review). The results described in this paper fit nicely within the framework of object files. In their paper, Kahneman et al (1992) claim that attention might act at the level of the object file, essentially binding information from the attended dimension (e.g., color, shape, conjunction, etc.) to the object file. That information is then used to facilitate object recognition, and the subsequently resolved object identity is stored in the object file itself. In the present work, the use of an attention cue in Experiment 1 appears to allow infants bind the color of the attended square to the location of the square, thereby allowing infants to detect a change, even when six items were present in the display. This finding is entirely consistent with an object files account of memory.

This attentional element is significant for the study of infant cognition, because it allows us to make predictions as to what specifically infants will remember about briefly presented objects, as attention itself might be the primary determinant of which dimension (e.g., shape or color) infants will remember. For example, if one could instruct infants to attend to a particular dimension, then one would predict memory for that dimension if infants were using object files to track briefly presented stimuli. Thus, this type of an account can reconcile work demonstrating developmental differences in infant memory for shape verses color, (Feigenson et al., 2002a; Káldy & Leslie, 2003, in press; Xu, 2003) by demonstrating that memory for a particular dimension can be pushed around based on the attention demands of the task.

The results of the experiments presented here lay the groundwork for a new model of VSTM development, one that includes increasing attentional sensitivity and/or flexibility, as well as increasing capacity. Attention is a particularly important component in VSTM tasks, because the speeded nature of these tasks requires infants to rapidly encode items into VSTM. The consideration of attention and its role in determining which items are to be encoded into VSTM will become increasingly important, as the field continues to move toward characterizing infant development in a manner consistent with adult research. This continuity is vital to developmental research, and grounds our theories within the constraints of contemporary visual cognition.

In conclusion, these studies demonstrate that 10-month-old infants can use attention to selectively encode particular items into VSTM, and that this ability appears to develop somewhere between 5 and 10 months post-natally.

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