

The Development of Visual Short-Term Memory Capacity in Infants

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Four experiments assessed visual short-term memory capacity in 4- to 13-month-old infants by comparing their looking to changing and nonchanging stimulus streams presented side by side. In each stream, 1 to 6 colored squares repeatedly appeared and disappeared. In changing streams, the color of a different randomly chosen square changed each time the display reappeared; the colors remained the same in nonchanging streams. Infants should look longer at changing streams, but only if they can remember the colors of the squares. The youngest infants preferred changing streams only when the displays contained one object, whereas older infants preferred changing streams when the displays contained up to 4 objects. Thus, visual short-term memory capacity increases significantly across the first year of life.

The short-term storage of information is important for acquiring new knowledge, solving problems, and acting on current goals. For example, effective comparison and categorization of items that cannot be simultaneously foveated requires visual short-term memory, and visual short-term memory is therefore critical for the online use of visual information. The present article examines the development of visual short-term memory capacity in infants, with an emphasis on understanding how infant short-term memory abilities are related to adult short-term memory abilities. We begin by discussing the general role of short-term memory in cognition and then turn to the development of short-term memory.

Short-Term Memory and Working Memory

Psychologists have distinguished between short-term and long-term memory systems for more than a hundred years (e.g., James, 1890). The common view of short-term memory systems is that (a) they can

create memory representations rapidly, (b) they can store only a handful of representations at any one time, and (c) they require active rehearsal to maintain the representations beyond a few seconds. In contrast, the common view of long-term memory systems is that (a) the memory representations are formed slowly, (b) storage capacity is essentially unlimited, and (c) the memories suffer from little or no decay of information.

Research in the 1960s and early 1970s failed to provide compelling evidence for separate short- and long-term memory systems (e.g., Crowder, 1982), but Baddeley and his colleagues (Baddeley & Hitch, 1974) revitalized the short-term/long-term distinction in the mid 1970s. They changed the direction of research on short-term memory by asking whether the memory system used in typical short-term memory tasks is a “working memory” system (i.e., a memory system that is used for the temporary storage and manipulation of information in the service of complex tasks). Because tasks such as reasoning and reading were impaired when short-term memory was filled to capacity by a concurrent task, these investigators concluded that short-term memory tasks do indeed tap into a working memory system. Moreover, they developed a model of working memory in which modality-specific slave systems are used for storing information, and a central executive is used to read, write, and manipulate this information. In this manner, Baddeley and his colleagues “rescued” the concept of short-term memory, demonstrating that it can be distinguished from long-term memory and that it plays an important role as a working memory system (Baddeley & Hitch, 1974).

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The Visual Cache

The visual cache is a subcomponent of Baddeley's model that is used to store information about visual object identities (Baddeley & Logie, 1999). This memory system is important for real-world tasks such as comparing objects that cannot be simultaneously foveated (Pomplun, Reingold, & Shen, 2001; Pomplun, Sichelschmidt, et al., 2001) and integrating views of the world separated by saccades (Hollingworth & Henderson, 2002; Irwin, 1991). These are tasks that are of fundamental importance for infants during almost every waking moment. Despite the importance of this system for infant development, little research has been directed at understanding the nature and development of the visual cache during infancy.

Studies of adults have explored the storage capacity of the visual cache by using change-detection tasks in which observers are presented with two arrays of simple shapes on each trial, separated by a delay of approximately 1 s (long enough to prevent the use of iconic memory), and must indicate whether the two arrays are identical (Luck & Vogel, 1997; Pashler, 1988; Phillips, 1974; Vogel, Woodman, & Luck, 2001). For example, the first array might consist of a red square, a green square, and a yellow square, and the second array would be identical to the first array or would differ in the color of one item (e.g., the yellow square in the first array might be replaced by a violet square in the second array). This procedure makes it possible to estimate the number of objects that can be stored in the visual cache. For example, if observers can maintain four objects in memory, they should be accurate at detecting changes with arrays containing one to four objects, and accuracy should decline systematically with arrays containing more than four objects. Using this approach, Luck and Vogel (1997) found that young adults can maintain three to four simple colors (or three to four multifeature objects) in short-term memory. Other studies have yielded similar capacity estimates (see review by Cowan, 2001).

Although short-term memory capacity has been extensively explored in adults over the past 100 years (see reviews by Blankenship, 1938; Cowan, 2001), little work has been done on short-term memory capacity in infancy. Thus, in the present study we assessed the development of visual short-term memory capacity across the first year of life, adapting Luck and Vogel's (1997) procedure for use in infants. The memory system isolated in our paradigm probably corresponds to the visual cache, but it is not yet possible to be certain that we have

isolated a component of Baddeley's working memory system. Consequently, for the present purposes we conservatively use the term *short-term memory* to describe the memory system we are studying.

Short-Term Memory in Infancy

Psychologists have intensively studied the memory abilities of infants for several decades (see Cohen & Gelber, 1975; Rovee-Collier & Hayne, 1987, for reviews). Many of these studies have used habituation or novelty preference procedures. In these procedures, infants are first shown one stimulus during a familiarization or habituation phase, and then their memory for that stimulus is tested by comparing how long infants look at the now-familiar stimulus in comparison to a novel stimulus. Researchers conclude that a memory has been formed for the familiarized item if infants look longer at the novel stimulus than at the familiar stimulus. Studies using these procedures have provided a foundation for our understanding of the early emergence and development of infants' memory for visually presented information. For example, 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).

This previous work does not allow firm conclusions to be drawn about the development of short-term memory systems, however. Recall that short-term memory systems are assumed to create memory representations rapidly, have a limited capacity, and require active rehearsal to maintain the representations beyond a few seconds. Although Rovee-Collier and Hayne (1987) argued that habituation and familiarization paradigms tap into short-term memory processes, most memory studies using these tasks do not seem to assess a short-term memory system that meets the criteria discussed earlier. There is no doubt that these paradigms evaluate memory over a relatively short period of retention compared with typical long-term memory procedures. However, infants tested in these procedures typically are presented with the familiarization stimulus for tens of seconds or more (thus, it is not clear that these procedures tap the rapid formation of memory representations), and in several studies infants have shown a reliable preference for a novel stimulus after seconds (Diamond, 1995), minutes (Courage & Howe, 2001), or hours and days (Fagan, 1970, 1973; Rose, 1981). For these reasons, it seems

that previous demonstrations of memory using these procedures likely reflect the use of both short- and long-term memory stores.

Rose, Feldman, and Jankowski (2001) recently reported a study using a variant of the novelty preference procedure that does seem to isolate more directly short-term memory systems in infancy. Specifically, this study addressed the relatively rapid formation of memory representations and the limited capacity of short-term memory. Rose et al. familiarized 5-, 7-, and 12-month-old infants with three-dimensional objects (small toys), one at a time, and allowed infants to study each item for a relatively short time (3 s to 10 s, depending on the infants' age). Infants' memory for each item was then probed by presenting it along with a novel item and assessing infants' looking to the novel and familiar items. Note that in most studies using the novelty preference procedure, infants are presented with only one item to study for 30 s to 2 min (e.g., Courage & Howe, 2001; Fagan, 1970), and then their memory for that item is assessed. Thus, the variation of the novelty preference procedure used by Rose et al. assessed infants' relatively rapid formation of a memory representation of the items.

To assess the capacity of infants' short-term memory, each infant was tested with spans of 1, 2, 3, and 4 items. For Span Length 1, infants were presented with 1 item during familiarization, and then their memory for that item was assessed. For longer span lengths, infants were presented with the items individually in a sequence (e.g., a sequence of 2 items for Span Length 2, a sequence of 3 items for Span Length 3), and then their memory for the items was tested by pairing each familiar item with a different novel item. Rose et al. (2001) reasoned that infants would only show a novelty preference for the number of items in the sequence that was within their short-term memory capacity. When a span included more items than infants could hold in short-term memory, they would show a novelty preference for only a subset of the items. Younger infants showed memory for only 1 or 2 items, but by 12 months infants showed significant memory for 3 or 4 items. Thus, these findings suggest that infants' short-term memory capacity is limited and undergoes significant change over the first year of life.

Two aspects of this study, however, make conclusions about short-term memory capacity from this study tentative. First, although infants were briefly familiarized with each stimulus only once, the exposure lasted between 3 s and 10 s, which may have allowed the formation of long-term memory representations. Indeed, adult short-term memory

capacity for complex multipart objects is substantially less than infants' apparent capacity of three to four objects reported by Rose et al. (2001; Alvarez & Cavanagh, in press). Second, there may have been demands on infants' memory for items in the larger spans beyond demands on short-term memory storage capacity. Specifically, as the size of the memory set increased, the delay that separated the initial exposure and the test increased. For example, when tested on spans of four items, 12-month-old infants had to hold the first item presented in memory for at least 25 s before their memory for that item was tested. They received three additional familiarization trials of 3 s (on which the subsequent items in the span were presented), each followed by a 4-s intertrial interval. Whereas, when tested on spans of two items, 12-month-old infants had to hold the first item in memory for only 10 s while fixating and remembering only one new item. Thus, infants were required to remember each item for increasingly longer durations as span length increased. In addition, as the size of the set increased there was an increase in the number of intervening test pairs (and thus additional novel items) between exposure and test. For example, before their memory for the last item in a span of four was tested, infants had to fixate (and encode) three old items and three new items. Consequently, performance may have been limited more by decay and interference than by storage capacity per se.

The Present Investigation

The present study sought to replicate the general developmental pattern reported by Rose et al. (2001) using a new experimental paradigm that more clearly isolates short-term memory, minimizes the contributions from long-term memory, and facilitates comparison with previous studies of visual short-term memory capacity in adults. This paradigm was based on the change-detection paradigm commonly used to study visual short-term memory in adults and is therefore well suited for studying the developmental origins of the adult short-term memory system. As shown in Figure 1, infants were shown two simultaneous displays of colored squares that blinked on and off repetitively. On one monitor, the colors of the squares remained constant from presentation to presentation. On the other monitor, one color was changed in each new presentation (the square that changed color on a given presentation was selected at random). The displays were presented for a brief period (500 ms) and were separated by a brief delay (250 ms). We measured the

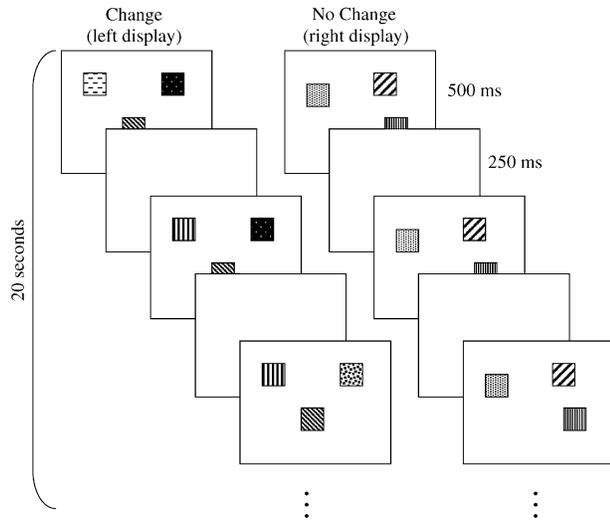


Fig. 1. Schematic representation of a trial used for Experiment 1 (Set Size 3). Trials for Experiment 1 consisted of 1, 2, or 3 colored changing or nonchanging squares. Items are not drawn to scale.

amount of time infants spent looking at the changing and unchanging displays.

This procedure is a variant of the paired-comparison procedure, which rests on the assumption that given the choice of two similar displays, infants will look longer to the display that imposes a greater information load (Richards, 1997). In the present context, one display remains constant, imposing a low load, and the other changes, imposing a higher load. Previous studies using other methods have shown that infants prefer to look at stimulus streams that vary compared with stimulus streams that remain the same (Cornell & Heth, 1979; Fantz, 1964). Thus, we expected that infants would prefer to look at the changing displays compared with the nonchanging displays, but only if they can form a memory of the colors and keep those colors active in memory across the 250-ms delay.

We evaluated memory capacity by varying the number of items in the arrays (the set size). We assessed infants' ability to detect a change with between one and six items in each display. If an infant's memory capacity is greater than or equal to the set size, the infant should detect the color changes and show a preference for the changing display. When the set size exceeds capacity, infants should be less likely to detect the change, and the changing and nonchanging displays will become functionally equivalent. Therefore, infants will exhibit significant preferences for changing displays that contain a number of items within or near to their visual short-term memory capacity, and they will not exhibit significant preferences for changing displays

that substantially exceed their visual short-term memory capacity. For example, an infant with a capacity of one item will show a strong preference for the change displays only at Set Size 1, whereas an infant with a capacity of three items will show strong preferences at set sizes up to 3. Some preference for the changing displays may be observed beyond an infant's capacity because some of the changes can be detected even if only a subset of the items are stored in memory. However, the degree of preference should decline substantially when capacity is exceeded. Thus, this procedure provides a means of assessing the capacity of short-term memory.

Several aspects of this paradigm were designed to emphasize the use of short-term memory systems and to minimize the contribution of long-term memory systems. First, each display was presented for only 500 ms, maximizing the need for rapid memory formation, especially for arrays containing multiple items. Second, although the stimulus arrays were presented for many cycles over a 20-s interval, a given color was not repeated very many times before changing to a different color. At Set Size 1, each item was presented only once before being changed. At Set Sizes 2 and 3, a given color was presented an average of two or three times, respectively, before being changed. The small total exposure duration before a change thus minimized contributions from long-term memory. In addition, the retention period was only 250 ms, which is long enough to minimize contributions from iconic memory and yet short enough to be well within the expected duration of short-term memory. Studies with adults have demonstrated that a 70-ms delay is sufficient to prevent the use of iconic memory for accurate change detection (e.g., Rensink, O'Regan, & Clark, 1997); therefore, the 250-ms delay used in the present study should be more than adequate to minimize any contributions from iconic memory. Finally, all of the items were simple colored squares and were therefore highly similar to each other. Such intra- and inter-trial similarity leads to substantial interference between long-term memory representations (Murdock, 1961), minimizing their contribution to performance.

Experiment 1

In Experiment 1, we tested infants in three age groups with approximate average ages of 6.5, 10, and 13 months. Short-term memory systems appear to be strongly dependent on the functioning of regions of the prefrontal cortex (Miller, Erickson, & Desimone, 1996; Rowe, Toni, Josephs, Frackowiak, &

Passingham, 2000; Smith & Jonides, 1997), and this range of ages brackets a period of dramatic development of prefrontal functioning (Bell, 1998; Johnson, 1995; Nelson, 1995). Thus, we expected to see large changes in short-term memory capacity across this age range, reflected in significant preferences for changing arrays at progressively larger set sizes.

Given that young infants have some ability to learn about and interact with the visual environment, we expected that the youngest infants would have some short-term memory abilities and would show significant preference for changing arrays at Set Size 1. Adult short-term memory capacity for simple colors is three to four objects, and this sets an upper bound for the capacity of the older infants. That is, if visual short-term memory capacity approaches adultlike levels by 13 months, the oldest infants should exhibit strong preferences for changing stimuli at all three set sizes. This pattern would provide converging evidence for the general developmental pattern observed by Rose et al. (2001).

Method

Participants. Participants were 144 healthy, full-term infants with no history of birth complications or vision problems, including 48 infants at each of three age groups. The infants in the youngest group of infants had an average age of approximately 6.5 months (average age 201.5 days, or 6.6 months, $SD = 9.71$ days, ranging from 174 days, or 5.7 months, to 225 days, or 7.4 months). The infants in the middle group had an average age of approximately 10 months (average age of 300.2 days, or 9.9 months, $SD = 9.38$ days, ranging from 288 days, or 9.5 months, to 321 days, or 10.6 months). The infants in the oldest group had an average age of approximately 13 months (average age 395.7 days, or 13.0 months, $SD = 8.57$ days, ranging from 381 days, or 12.5 months, to 416 days, or 13.7 months). Note that a small proportion of infants was first tested in Experiment 2 at 4 or 6.5 months and then tested again in Experiment 1 at 10 or 13 months. We conducted all the reported analyses both including and excluding the infants who had participated in both experiments. The results of these two analyses were identical. Therefore, we present the analyses with the full sample.

There were 25 boys and 23 girls at 6.5 and 10 months, and 23 boys and 25 girls at 13 months. Infants were predominately from White, middle-class homes. All of the mothers had graduated from high school, and 75% had completed at least a bachelor's degree. An additional 16 infants were

tested but were excluded from the final analysis because of fussiness (5 at 6.5 months, 3 at 10 months, and 4 at 13 months), sleepiness or inattentiveness (defined as not looking at both displays for a given set size; 1 at 10 months and 1 at 13 months), or experimenter error or equipment failure (1 at 6.5 months and 1 at 10 months). Infant names 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.

Stimuli and apparatus. A Macintosh G3 computer was used to present the stimuli on two 17-in. ViewSonic monitors each with a viewable surface of 18.26° (w) by 13.50° (h) at a distance of 100 cm. The two monitors were positioned side by side with a 22-cm gap between them, such that the total eccentricity of the two displays was approximately 88 cm (47.5°). (Previous research indicates that infants as young as 4 months can detect and make eye movements toward stimuli that are presented 75° from fixation in the temporal visual field; Maurer & Lewis, 1991. Thus, we were confident that while fixating one display, infants could detect that there was a stimulus on the other display, although given the total eccentricity it was unlikely that the squares on both displays were foveated while infants fixated one display.) A solid gray background (42.48 cd/m^2 , $x = .294$, $y = .283$) was continuously present on both monitors. Stimulus chromaticity was measured with a Tektronix J17 LumaColor chromaticity meter using the 1931 CIE (Commission International d'Éclairage) coordinate system.

As illustrated in Figure 1, the stimuli consisted of sequences of arrays that blinked on and off together on the two monitors; one monitor contained the change display and the other contained the no-change display. Each display contained one, two, or three colored squares that measured approximately 5 cm (w) \times 5 cm (h), subtending approximately $2.9^\circ \times 2.9^\circ$ per square. The set size (the number of squares on each monitor) was identical for the two displays and remained constant throughout a trial. Thus, for Set Size 3, an infant would see three squares on both the left and the right monitor; on one monitor the squares would be changing, and on the other monitor they would not be changing. The initial square colors were selected at random from a set of nine colors and were: green ($x = .311$, $y = .551$, 12.73 cd/m^2), brown ($x = .491$, $y = .410$, 8.48 cd/m^2), black ($x = .126$, $y = .166$, $.48\text{ cd/m}^2$), violet ($x = .279$, $y = .130$, 7.99 cd/m^2), cyan ($x = .254$, $y = .308$, 93.18 cd/m^2), yellow ($x = .429$, $y = .473$, 89.34 cd/m^2), blue

($x = .153, y = .061, 8.89 \text{ cd/m}^2$), red ($x = .644, y = .310, 27.14 \text{ cd/m}^2$), and white ($x = .295, y = .286, 92.97 \text{ cd/m}^2$). The colors within a display were always different from each other, but colors could be repeated across the two displays (i.e., the same color could appear on both monitors). It should be noted that the perception of color varies along three dimensions—hue, saturation, and brightness—and the nine colors used in this experiment varied along all three dimensions. Consequently, performance of the task reflects change detection across all three dimensions, not just hue. However, the three dimensions of color are perceived (and presumably remembered) in an integral manner, not as separate features (Garner & Felfoldy, 1970). Consequently, the use of stimuli that vary along all three dimensions does not significantly limit the conclusions that can be drawn.

The squares on the two monitors simultaneously appeared for 500 ms, disappeared for 250 ms, and continued appearing and disappearing in this manner for a total of 20 s per trial. For the no-change display, the colors of the squares remained constant for every onset within a trial (see Figure 1). For the change display, one square was changed to a new color before each onset; this square was selected at random for each presentation, and the new color was selected at random from the set of colors that was not currently present in that display.

Design and procedure. Infants were tested in a small experimental room, where they sat on a parent's lap. They faced a large black curtain that hung from ceiling to floor and obscured their view of the experimental apparatus. Openings in the curtain revealed the two computer monitors, a small black box positioned between the two monitors, and the lens of the video camera located directly beneath the black box. The black box produced a flashing light and audible tone at the rate of approximately 3 Hz at the beginning of each trial to ensure that infants were fixating between the two monitors when the stimulus sequences began. The parents wore occluding glasses during the testing session to minimize bias.

Each infant was presented with six trials. There were two trials at each of the three set sizes, one with the change display on the left and the no-change display on the right, and one with the sides reversed. The order of trials was randomized across participants.

A trained observer sitting behind the curtain initiated each trial and timed the duration of infants' fixations to each of the two monitors using a program developed for the Macintosh (Cohen,

Atkinson, & Chaput, 2000). The observer was unaware of the set size or the side of the changing stimulus on each trial. The black box was turned on at the beginning of the trial, and the observer pressed a key once she judged that the infant was fixating the flashing light. This keypress simultaneously turned off the black box and initiated the changing and nonchanging displays on the two monitors. The observer recorded the duration of infants' fixation to each of the monitors by pressing two additional keys, one when the infant was looking toward the left monitor and the other when the infant was looking toward the right monitor. Neither button was pressed when the infant was not looking toward one of the two monitors. If an infant did not look at either monitor for the entire 20 s, the trial was repeated. Immediately on completion of a trial, the black box reactivated, and the observer once again waited for the infant to fixate the flashing light before initiating the next trial. This sequence continued until the infant received all six trials.

In addition to the online coding of looking times, 25% of each sample reported here were recoded offline from the videotapes of the sessions by a different trained observer. Average between-observer reliabilities were very good. The mean inter-observer correlation for the duration of looking to the left and right monitor on each trial was high for each sample ($r \geq .95$ for each sample) and the mean absolute difference between observers for the duration of looking was low ($M \leq .98 \text{ s}$ for each sample). Only the original online data are reported here.

Results

The data were analyzed in several steps. Preliminary analyses revealed no systematic effects of side of change (left or right) on looking time; subsequent analyses were therefore collapsed across this variable. The first analysis evaluated infants' total duration of looking on each trial. The mean looking times for each set size at each age are presented in Table 1. In general, infants looked longest at Set Size 3. This pattern was confirmed in a mixed-model analysis of variance (ANOVA) with age (6.5, 10, and 13 months) as the between-subjects factor and set size (one, two, and three) as the within-subjects factor. The increased looking times at larger set sizes yielded a significant main effect of set size, $F(2, 282) = 3.45, p < .05$. Post hoc comparisons using Tukey's honestly significant difference (HSD) test confirmed that looking times were significantly longer at Set Size 3 than at Set Size 1, $p < .05$, but the differences between Set Size 2 and the other set sizes

Table 1
Mean Total Looking Times by Age and Set Size

Experiment	<i>n</i>	Set size				
		1	2	3	4	6
Experiment 1						
6.5 months	48	9.94 (.45)	10.58 (.38)	11.41 (.38)		
10 months	48	10.44 (.40)	10.84 (.42)	10.83 (.39)		
13 months	48	11.32 (.41)	11.27 (.38)	11.52 (.43)		
Experiment 2						
4 months	48	9.81 (.64)	11.63 (.58)	11.97 (.56)		
6.5 months	48	11.52 (.50)	11.37 (.52)	11.63 (.45)		
Experiment 3						
10 months	48		9.82 (.47)		9.48 (.41)	9.22 (.50)
Experiment 4						
6.5 months	24	10.77 (.66)	11.20 (.73)	11.41 (.71)		

Note. Standard error is in parentheses.

were not significant. This finding is consistent with the general finding in the literature that infants look longer at displays that are more complex or contain more elements (Brennan, Ames, & Moore, 1966). The main effect of age was not significant, $p > .10$, nor was the interaction between age and set size, $p > .10$.

To evaluate differential looking toward changing versus unchanging arrays, we computed change preference scores, defined as looking time for the change display divided by total looking time (i.e., $\text{change} \div [\text{change} + \text{no-change}]$). A score of 0.5 indicates that an infant looked equally long at the change and no-change displays, and a score of 1.0 indicates that an infant looked only at the change display. For each infant, a preference score was computed at each of the three set sizes.

Mean preference scores are shown for each combination of age and set size in Figure 2. In general, younger infants preferred the changing side only at Set Size 1, whereas older infants preferred the changing side at all three set sizes. As is conventional in paired-preference studies, our main set of statistical analyses examined whether these preference scores were significantly different from chance (0.5). This was assessed with two-tailed t tests (two-tailed t tests were more appropriate than one-tailed tests because it was conceivable that infants might prefer the nonchanging display rather than the changing display). The values of these t tests are provided in Table 2. It can be seen that for the 6.5-month-old infants the change preference for Set Size 1 was significantly greater than chance. These infants did not show significant preferences for the changing stimulus at Set Size 2 or 3. The 10- and 13-month-old infants, in contrast, exhibited a significant

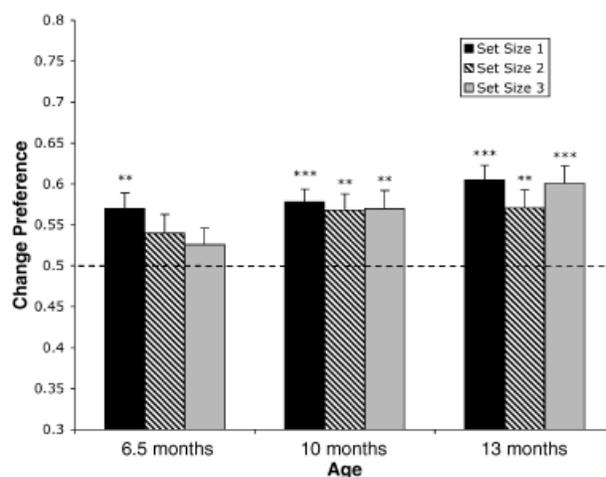


Fig. 2. Preference for the changing streams as a function of age and set size for Experiment 1. Chance (.50) is indicated by a dashed line. Error bars represent +1 SE. ** $p < .01$. *** $p < .001$.

preference for the changing stimulus at all three set sizes.

To determine whether the pattern of preferences differed reliably across age groups, we next entered the preference scores for all three groups into an ANOVA with age and set size as factors. This analysis revealed a significant main effect of age, $F(2, 141) = 3.75, p < .05$, but neither the main effect of set size ($p > .10$) nor the interaction between age and set size was significant ($p > .10$). Thus, although the overall pattern of means and individual t tests suggest that capacity increased across ages, the lack of a significant interaction between age and set size makes this conclusion tentative. However, this general pattern was replicated in the following

Table 2
T-Test Comparisons of the Preference Scores with Chance (.50) for Each Sample in Each Experiment

Experiment	<i>df</i>	Set size				
		1	2	3	4	5
Experiment 1						
6.5 months	47	3.86***	1.76 ^a	1.27		
10 months	47	4.92***	3.32**	3.14**		
13 months	47	5.78***	3.27**	4.85***		
Experiment 2						
4 months	47	3.89***	0.60	0.65		
6.5 months	47	4.79***	1.18	1.36		
Experiment 3						
10 months	47		2.98**		3.73***	1.17
Experiment 4						
6.5 months	23	5.75***	3.36**	7.51***		

** $p < .01$. *** $p < .001$. ^a $p = .09$.

experiments, increasing our confidence in this conclusion.

Discussion

Experiment 1 yielded two important results. First, infants as young as 6.5 months demonstrated significant memory abilities in a task that was designed to isolate visual short-term memory. That is, they significantly preferred a changing stimulus at Set Size 1, which required the rapid formation of a stimulus (i.e., within 500 ms) with no immediate repetitions, minimizing contributions from long-term memory. Second, these results point to the existence of large changes in the capacity of visual short-term memory in the second half of the first year of life. At 6.5 months, infants' visual short-term memory capacity appeared to be sufficient only to allow them to detect a change when one item was on the screen. At 10 and 13 months, infants' capacity had increased to allow them to detect a change in displays with two and three items. The time course of this developmental change accords well with the observations of Rose et al. (2001) in a different experimental paradigm, as discussed in the Introduction.

These conclusions, however, are based on the failure of the youngest infants to detect a change at larger set sizes, and we did not have sufficient power to observe a significant interaction between age and set size. Thus, in Experiment 2 we sought to replicate the findings with the 6.5-month-old infants so that we could have confidence that infants at this age indeed have a reduced visual short-term memory capacity. We also sought to extend this

finding to younger infants, and we made some minor changes to the paradigm (e.g., a smaller viewing distance) to make sure that it was suitable for young infants.

Experiment 2

Method

Participants. Participants were 96 healthy, full-term infants with no history of birth complications or vision problems. The infants in the younger group (25 boys and 23 girls) had an average age of approximately 4 months (average age of 121.9 days, or 4.0 months, $SD = 7.23$ days, ranging from 108 days, or 3.6 months, to 137 days, or 4.5 months). There were 22 boys and 26 girls in the older group, with an average age of approximately 6.5 months (average age of 191.33 days, or 6.3 months, $SD = 9.30$ days, ranging from 177 days, or 5.8 months, to 213 days, or 7.0 months). As in Experiment 1, the infants were predominately from White, middle-class homes, and all the mothers had graduated from high school (71% had earned at least a bachelor's degree). An additional 23 infants were tested but excluded from the final analysis because of fussiness ($n = 11$ and 7 at 4 and 6.5 months, respectively), sleepiness or inattentiveness ($n = 1$ at 4 months), or experimenter error or equipment failure ($n = 1$ and 3 at 4 and 6.5 months, respectively). All names were obtained as in Experiment 1, and infants were recruited as described for that experiment.

Procedure. All aspects of the stimuli, apparatus, design, and procedure were the same as those of Experiment 1 with a few exceptions. First, infants

were seated closer to the monitors (40 cm) because of relatively poor accommodation at 4 months of age (Atkinson, 1984). Second, the stimuli were modified in three ways. First, the individual stimuli were reduced in absolute size to approximately $2.8 \text{ cm} \times 2.8 \text{ cm}$ ($4.0^\circ \times 4.0^\circ$), so that the visual angle was closer to that of the stimuli used in Experiment 1. Second, the squares were constrained to appear on the interior 50% of the computer monitors, such that the combined eccentricity of both displays was approximately 55 cm (69°). Finally, the change and no-change displays had the same spatial configuration for a given trial and differed only in the colors of the squares.

Results

As shown in Table 1, looking times (averaged across change and no-change displays) increased as set size increased, leading to a significant main effect of set size, $F(2, 188) = 6.12, p < .01$. Post hoc comparisons revealed that infants looked for shorter durations at Set Size 1 than at Set Size 2 or 3, $p < .05$. This effect was more pronounced in the 4-month-old infants than in the 6.5-month-old infants, leading to a significant Age \times Set Size interaction, $F(2, 188) = 5.97, p < .01$. Separate ANOVAs conducted at each age revealed a significant effect of set size for the 4-month-old infants, $F(2, 94) = 11.41, p < .001$, but not for the 6.5-month-old infants, $F < 1$.

The preference scores at each age are presented in Figure 3 and the t values comparing each score with chance are presented in Table 2. Both 4- and 6.5-month-old infants in this experiment exhibited a significant preference for the change displays at Set Size 1. However, neither group of infants exhibited a significant preference for the changing stimulus at Set Size 2 or 3. Thus, this experiment replicated the pattern of results observed in Experiment 1 for 6.5-month-old infants and demonstrated the same pattern in 4-month-old infants. An ANOVA performed on the preference scores yielded a significant main effect of set size, $F(2, 188) = 7.15, p < .01$, but neither the main effect of age ($p > .10$) nor the interaction between age and set size ($p > .10$) was significant.

Discussion

In Experiment 1 we found statistically significant preferences for the changing displays at Set Sizes 2 and 3 in 10- and 13-month-old infants, indicating that they have a short-term memory capacity that is sufficient to distinguish between changing and unchanging displays of arrays with up to three

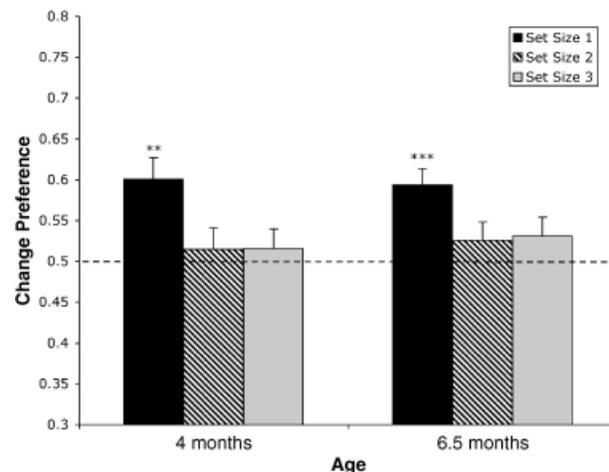


Fig. 3. Preference for the changing streams as a function of age and set size for Experiment 2. Chance (.50) is indicated by a dashed line. Error bars represent +1 SE. ** $p < .01$. *** $p < .001$.

items. In contrast, younger infants exhibited significant preferences only at Set Size 1 in both Experiments 1 and 2. These data are strongly suggestive of an increase in short-term memory capacity across the first year of life. Although we did not obtain a significant interaction between age and set size in Experiment 1 (presumably due to a lack of power), the overall pattern of results across the two experiments is compelling. In particular, two independent groups of older infants in Experiment 1 showed a strong and significant preference for change displays at all three set sizes, whereas three independent samples of younger infants across Experiments 1 and 2 showed a strong and significant preference at Set Size 1 but minimal preferences at Set Sizes 2 and 3. Together, these results demonstrate a replicable difference between younger and older infants.

Experiment 3

In Experiment 3 we began exploring the upper bounds of infants' visual short-term memory capacity. Precisely determining the upper bounds of infants' capacity would require testing a large number of age groups with a large number of set sizes, which is beyond the scope of the present study. However, as a first step toward this goal, we assessed 10-month-old infants' ability to detect changes at Set Sizes 2, 4, and 6.

Method

Participants. Participants were 48 healthy, full-term infants (26 boys and 22 girls) who had not

participated in the previous experiments and who had no history of birth complications or vision problems. These infants were on average approximately 10 months old (average age of 304.8 days, or 10.0 months, $SD = 9.68$ days, ranging from 290 days, or 9.5 months, to 326 days, or 10.7 months).

All the mothers had graduated from high school and 71% had earned at least a bachelor's degree. An additional 4 infants were tested but excluded from the final analysis because of fussiness ($n = 2$), or sleepiness or inattentiveness ($n = 2$). Infants were recruited as in the previous experiments.

Procedure. The stimuli, apparatus, design, and procedure were the same as those of Experiment 1, with the exception that the displays contained two, four, or six items.

Results

The analysis of the total looking time revealed no significant effects (see Table 1). Overall, looking times did not vary as a function of set size. Preference scores are shown in Figure 4, and the t tests comparing these scores with chance (.50) are provided in Table 2. Significant preferences were observed for the change displays at Set Sizes 2 and 4, but not at Set Size 6. However, an ANOVA performed on the preference scores yielded no significant main effect of set size, $F(2, 94) = 1.65, p > .1$.

Discussion

This experiment demonstrated that 10-month-old infants can reliably detect changes in arrays with as many as four items, but no evidence of reliable change detection was obtained at Set Size 6. The lack of a significant effect of set size in the ANOVA makes it impossible to conclude that change detec-

tion performance declined at Set Size 6, but the lack of a significant difference from chance at Set Size 6 makes it impossible to conclude that the changes were detected at this set size. Thus, we can positively say that 10-month-old infants can detect changes at Set Sizes 2 and 4, but we can draw no strong conclusions about Set Size 6.

Taken together, the results from Experiments 1 through 3 demonstrate that the capacity of visual short-term memory for object identity increases dramatically in the second half of the first year of life. Infants 6.5 months old and younger detected the change only when one item was on each display (Experiments 1 and 2), and by 10 months infants detected the change when there were between one and four items on each display (Experiments 1 and 3).

What is the capacity of visual short-term memory in these 10-month-old infants? To answer this question, we must make some assumptions about the relationship between change preference and memory capacity. If we simply assume that the degree of preference for the changing side reflects the probability that a change is detected, we would expect the degree of preference to be constant for set sizes that are less than or equal to the memory capacity (because the probability of change detection should be constant if all items are remembered). As the set size exceeds memory capacity, the probability that a given change is detected will decline, and so should the degree of preference for the changing side. The degree of preference for 10-month-old infants was approximately constant across Set Sizes 1 through 3 in Experiment 1, and was approximately constant across Set Sizes 2 and 4 in Experiment 4, with an apparent drop at Set Size 6. Thus, we tentatively conclude that memory capacity is approximately four items in these infants. This conclusion is tentative because our assumptions about the relationship between capacity and degree of preference may not be valid and because the observed preference scores have considerable variability. However, this seems like a good first approximation, and future studies may be able to refine this estimate.

Previous estimates of adult visual short-term memory capacity for simple colored squares are in the range of three to four items (Luck & Vogel, 1997). Thus, the present results suggest that infant working memory capacity for simple features approaches adultlike levels by 10 months of age. Adults can remember multiple-feature objects just as well as single-feature objects (Luck & Vogel, 1997), but we have not yet tested whether this is also true for infants. Thus, even if the memory capacity for simple features approaches adultlike levels by 10 months,

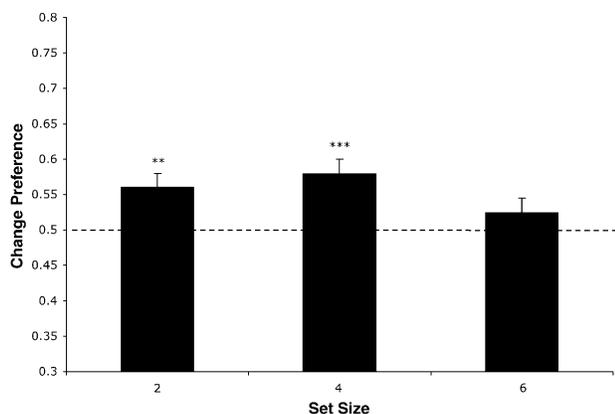


Fig. 4. Preference for the changing streams as a function of age and set size for Experiment 3. Chance (.50) is indicated by a dashed line. Error bars represent +1 SE. ** $p < .01$. *** $p < .001$.

capacity may not yet be adultlike for more complex objects.

It should also be noted the adult capacity estimates were obtained in a paradigm in which colors could repeat within a given array, requiring the observers to remember the location of each color. Different colors and briefer displays were also used, and these factors may have decreased the estimate of adult memory capacity. To measure adult capacity under conditions that more closely resembled those of the present study, we tested 14 young adults using the basic procedure of Luck and Vogel (1997), but with no color repetitions and with color and timing parameters similar to those used in the infant experiment. On each trial, a sample array of two, four, or six unique colors was presented for 500 ms, followed by a 250-ms blank period and then a 500-ms test array. The test array was either identical to the sample array ($p = .5$) or differed in the color of one item ($p = .5$). Participants pressed one of two keys to indicate whether the arrays were identical or differed; accuracy was the primary dependent variable. The next trial began after a delay of 1,000 ms. Each participant received 50 trials at each set size. Chromaticity and luminance values were within 5% of the colors used in Experiment 3 of the present study, and stimulus sizes and positions were matched exactly. We found that accuracy was nearly perfect at Set Size 2, fell slightly to 94% correct at Set Size 4, and fell further to 85% correct at Set Size 6. This corresponds to a mean capacity of 4.2 items (using the equation of Cowan, 2001), which is similar to our tentative estimate of memory capacity in the 10-month-old infants.

Experiment 4

We have concluded that the results from Experiments 1 through 3 demonstrate a significant change in the capacity of visual short-term memory in the first year of life. It is important to acknowledge that there is an alternative interpretation for lack of significant change-detection performance above Set Size 1 in the 4- and 6.5-month-old infants. Specifically, it is possible that this failure at set sizes larger than one was not caused by limitations in short-term memory capacity but was instead caused by limitations in perceptual or attentional abilities. That is, it is possible that the infants could not form perceptual representations of multiple simultaneously presented objects or that they could not attend to all of the items when storing them or when comparing them with the next array. There is no reason to suspect the existence of perceptual or attentional

limitations with arrays of one to three highly discriminable colored squares, but it is still worthwhile to rule out this possibility.

To rule out explanations based on perceptual or attentional manipulations, we conducted an experiment with the same displays used in Experiment 1, only without the memory component. That is, we presented 6.5-month-old infants with the same blinking displays presented in Experiment 1 but with no delay between subsequent presentations of the squares. This modified task has the same perceptual and attentional requirements as the task used in Experiment 1 because one to three colored squares must be perceived and attended whether or not a delay is present. Thus, if limits in perception or attention were responsible for the decline in performance at Set Sizes 2 and 3 in Experiments 1 and 2, eliminating the memory requirements of the task should not influence the pattern of results, and a substantial decline should again be observed at Set Sizes 2 and 3. If, in contrast, the decline was caused by limits in short-term memory capacity, eliminating the memory requirements should allow the infants to detect the changes very well at all set sizes.

We tested only 6.5-month-old infants in this experiment for two reasons: First, Experiments 1 through 3 showed that large developmental differences in visual short-term memory occur between 6.5 and 10 months. Thus, it is important to demonstrate that the effect of set size on younger infants' attention to changing displays is due to limits in short-term memory functioning, *per se*, and not to a developmental difference in perceptual or attentional abilities. Second, because the decline in performance at Set Sizes 2 and 3 has been replicated across two different samples of 6.5-month-olds, we can be confident that this finding is robust. Therefore, it is important to know whether performance in these infants was limited by perceptual or attentional factors rather than by memory capacity.

Method

Participants. Participants were 24 healthy, full-term infants (14 boys and 10 girls) with no history of birth complications or vision problems (average age of 194.8 days, or 6.4 months, $SD = 8.92$ days, ranging from 179 days, or 5.9 months, to 210 days, or 6.9 months). Again, all the mothers had graduated from high school and 71% had earned at least a bachelor's degree. An additional 6 infants were tested but excluded from the final analysis because of fussiness ($n = 3$), or sleepiness or inattentiveness ($n = 3$). All

names were obtained as in Experiments 1 through 3, and infants were recruited as described previously.

Procedure. All aspects of the apparatus, design, and procedure were identical to Experiment 1. The stimuli were the same as those of Experiment 1, with the exception that the delay between subsequent flashes of the squares was removed. Whereas the arrays in Experiment 1 were presented for 500 ms and separated by a 250-ms gap, the arrays in Experiment 4 were presented for 500 ms and not separated by any gap. As a result, the squares on one display appeared to be constant over the entire 20-s trial, and the squares on the other display appeared to remain constant except for a color change in a randomly selected item every 500 ms. Because the delay component was removed, the total number of color changes (per change trial) was slightly higher to maintain a trial length of 20 s.

Results

The analysis of the total looking time revealed no significant main effects or interactions (see Table 1). The analysis of the preference scores at each set size (see Figure 5) revealed that the infants exhibited a significant preference for the change displays at all three set sizes (see Table 2). The ANOVA performed on the preference scores yielded no significant main effect of set size ($p = .14$).

Discussion

In summary, the results of this experiment confirmed that when the memory component of these displays is removed (by eliminating the delay), 6.5-month-old infants can detect the change at all

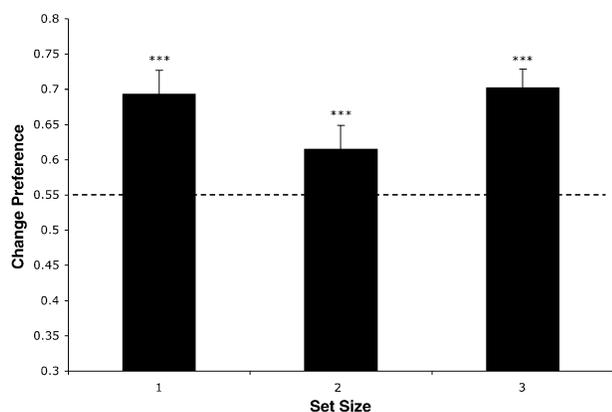


Fig. 5. Preference for the changing streams as a function of age and set size for Experiment 4. Chance (.50) is indicated by a dashed line. Error bars represent +1 SE. *** $p < .001$.

three set sizes. Consequently, the failure of these infants to show a significant preference at Set Sizes 2 and 3 in the previous experiments must be due to limitations in memory rather than limitations in perception or attention.

It should be acknowledged that eliminating the gap between the stimuli does more than simply eliminate the memory requirements of the task. For example, this manipulation also minimizes sensory transients in the stimulus sequences. Nonetheless, the no-gap version of the task does require that the infants perceive and attend to the same set of one to three objects as in the gap version; therefore, the excellent performance observed at all three set sizes in the no-gap version indicates that the infants can perceive and attend to three simultaneous stimuli.

General Discussion

The present study makes two significant contributions to our understanding of short-term memory in infancy. First, we have developed a task that appears to provide a relatively pure measure of short-term memory with minimal contributions from long-term memory systems. Our task accentuated the involvement of short-term memory systems by requiring the rapid formation of multiple memory representations from briefly presented stimuli with minimal repetition of a given stimulus. In addition, Experiment 4 showed that set size effects are eliminated when there is no delay and change detection does not require memory. Thus, we have confidence that the observed effect of set size on infants' preference for the changing stimuli is due to limitations in visual short-term memory capacity and not to limitations in perceptual quality or attention span.

The present results also are significant because they reveal substantial developmental changes in visual short-term memory capacity over the first year of life. Four- and 6.5-month-old infants showed strong and significant preferences for changing stimuli only at Set Size 1, whereas 10- and 13-month-old infants showed strong and significant preferences for changing stimuli at Set Sizes 1, 2, and 3. Ten-month-old infants showed significant preferences for changing stimuli at Set Size 4, but not at Set Size 6. Although we did not obtain a significant interaction between age and set size in Experiment 1, a highly replicable pattern was observed across experiments. That is, we found no significant change preferences beyond Set Size 1 in three separate samples of younger infants (Experiments 1 and 2) and significant change preferences at higher set sizes in three separate samples of older infants (Experi-

ments 1 and 3). Thus, the present study provides strong evidence that visual short-term memory capacity develops rapidly over the first year.

The results from the older infants also suggest that capacity for simple features reaches adult-like levels by 10 months of age. This conclusion depends on a variety of assumptions, as discussed in Experiment 3, and is therefore tentative. However, these assumptions are not required for the conclusion that short-term memory capacity increases dramatically between 6.5 and 10 months of age. That is, although the present procedure does not provide strong estimates of absolute short-term memory capacity, it provides excellent estimates of relative short-term memory capacity.

It should also be noted that we cannot be certain that the older infants remember a set of distinct, independent objects; they might instead retain a single gestalt impression of the entire array. However, this is also a possibility for visual short-term memory representations in adults (see Jiang, Olson, & Chun, 2000; Yantis, 1992). As discussed by Vogel et al. (2001), it is more precise to conclude that the visual short-term memory capacity of adults (and the older infants in the present study) is three to four items worth of information.

Developmental Changes in Visual Short-Term Memory Capacity

Capacity per se is only one potential source of development in the visual short-term memory system. For example, in addition to capacity improvements, it has been shown that the stability or duration of short-term memory improves with development (Diamond, 1990; Goldman-Rakic, 1983). Thus, younger infants may be able to represent multiple objects in short-term memory, but they may not be able to maintain this information as long as older infants. Similarly, younger infants may have a lower fidelity or less complex representation of the objects. However, it seems unlikely that these types of changes could account for our findings. Specifically, the retention interval was very brief (250 ms), minimizing maintenance requirements, and even the youngest infants demonstrated a significant preference for the changing square at Set Size 1, indicating that they can represent these extremely simple objects when storage capacity is not challenged.

It is also important to consider whether developmental changes in other systems might have influenced our results. First, it is conceivable that the observed results reflect developmental changes

in infants' perceptual or attentional abilities rather than developmental changes in short-term memory abilities. That is, the differences we observed may reflect changes in infants' ability to perceive and attend to the elements of the display. However, simple features appear to be processed in parallel without capacity limitations in infants (Quinn & Bhatt, 1998), just as in adults (Treisman & Gelade, 1980). Moreover, Vogel et al. (2001) found no perceptual or attentional limitations for arrays of up to 12 colored squares with a 100-ms exposure duration in adults. Thus, the 500-ms exposure duration used in the present study should have been more than adequate for the perceptual encoding of three highly discriminable colored squares. Indeed, the results of Experiment 4 confirm that 6.5-month-old infants can detect changes even in arrays of Set Size 3 when memory demands are minimized by eliminating the retention interval.

The developmental changes in memory we have observed occur at exactly the same time as several other documented changes in memory abilities. The changes in capacity reported here were nearly identical to those reported by Rose et al. (2001). In that previous study, 7-month-old infants remembered one item and 12-month-old infants remembered four items in a sequence. Thus, the present study suggests that some aspect of the developmental change observed by Rose et al. may have been due to changes in short-term memory abilities. Together, the present results and those reported by Rose et al. confirm that infants' ability to remember object identities changes rapidly during the second half of the first year of life.

Other studies have revealed significant developmental changes in other aspects of infants' memory during this time. For example, developmental changes in infants' memory for spatial location in the second half of the first year have been observed using delayed response and A-not-B tasks (Diamond, 1990, 1998; Reznick, Fueser, & Bosquet, 1998; Smith, Thelen, Titzer, & McLin, 1999). In these tasks, infants are shown one object placed at one of two (or more) locations; the locations are then occluded (either individually or collectively), and then after a brief delay, the occluders are removed and infants are allowed to look and or reach toward a location. Memory is inferred if the infant reaches and or looks to the location where the object was hidden. Studies using these procedures have revealed developmental changes between 6 and 10 months in the number of locations infants appear to remember (e.g., Reznick et al., 1998). It should be noted that these tasks rely on spatial short-term memory, which

appears to be functionally and neuroanatomically distinct from the object memory system that is the focus of the present study (Goldman-Rakic, 1983, 1987; Logie, 1995; Smith & Jonides, 1997). However, the present results taken together with these previous results demonstrate that there are general and robust changes in memory abilities in the second half of the first year of life.

Short-Term Memory or Working Memory?

We have conceived of the present results as assessing changes in the capacity of infants' visual short-term memory. There are several reasons to suspect that the developmental changes we observed are in fact changes in working memory abilities. The term *working memory* is commonly used to refer to either (a) any memory system that is used for the storage and manipulation of information in the service of complex tasks, (which may include both short- and long-term memory systems (e.g., Ericsson & Delaney, 1999), or (b) a memory system with the characteristics specified in the model developed by Baddeley and his colleagues (Baddeley, 1986). The memory system we have studied presumably corresponds to the visual cache sub-component of Baddeley's working memory model and is presumably used in the service of complex tasks. Because we do not yet have evidence for these assumptions, however, we have conservatively referred to this memory system simply as a short-term memory system even though it is likely a part of the working memory system.

In addition, the developmental changes described earlier are consistent with changes in working memory abilities late in the first year of life. That is, the correspondence in the timing of developmental changes for infants' visual short-term memory for object identities and for infants' memory for spatial location point to changes in more general memory abilities. It may be that during this time the working memory system undergoes developmental change, and changes in this system contribute to the present results, as well as the other developmental changes observed in previous studies.

Finally, a task that isolates working memory in infancy should reveal developmental changes during the period of rapid prefrontal development. In fact, our findings indicate that the most formative period of visual short-term memory development appears to occur between 6.5 and 10 months postnatally. This is exactly the time that researchers have suggested that prefrontal cortex undergoes rapid development (Bell, 1998; Nelson, 1995; Ri-

chards, 1998). Specifically, at around 8 months human prefrontal cortex undergoes a rapid phase of synaptogenesis that results in increased connectivity and stability (Bell, 1998; Goldman-Rakic, 1987). Thus, the developmental changes we have observed coincide with the time when prefrontal cortex appears to be developing. This is important because prefrontal cortex has been implicated in several studies as the primary locus of working memory (Baddeley, 1986; Baddeley & Hitch, 1974; Goldman-Rakic, 1987; Logie, 1995; Miller, 1999; Miller et al., 1996). This correspondence bolsters our confidence that the short-term memory system we are tapping is related to the visual working memory systems assessed in adults.

The question that remains is, have the present experiments assessed developmental changes in the visual cache? One of our main goals was to link short-term memory abilities in infancy to those abilities in adults. Thus, we have adapted a procedure that has been widely used to assess visual working memory, or the visual cache, in adults to assess the capacity of visual short-term memory in infancy. Although we cannot be certain that our task taps the same system as does the task used with adults (indeed, we cannot be certain that the adult system is functioning in 4- to 13-month-old infants), we do believe that the present results provide an important first glimpse into the origins and early development of the system assessed by those procedures used with adults. Our results show that infants can detect the same types of changes as do adults, and that the number of items on the display limits their detection of those changes. As in the adult procedure, our procedure requires that infants rapidly form memories of the displays. What we do not yet know is whether the memory system used in this procedure is a working memory as described by Baddeley and his colleagues (Baddeley, 1986; Baddeley & Logie, 1999). For the reasons just described, however, we do believe that the system infants use is the developmental precursor to the visual cache used by adults in change-detection tasks. Future studies may be able to show whether this system is a working memory system, as well as determine whether this system is similar to the adult visual cache in other ways.

Conclusions

In summary, the present results provide an important advance in our understanding of the development of memory in infancy and in our understanding of short-term memory in general. We

have developed a task that allows us to test definitively visual short-term memory abilities in infancy in isolation from longer term memory systems. Our procedure has revealed that there is significant change in visual short-term memory capacity in the first year of life, and infants' capacity appears to approach an adultlike capacity by the end of the first year (although this latter conclusion is tentative). Moreover, we observed a substantial developmental change in visual short-term memory capacity at a time that corresponds to rapid change in prefrontal cortex, adding support to the apparent link between those cortical structures and visual working memory.

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