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Visual Short-Term Memory for Complex Objects in 6- and 8-Month-Old Infants

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Infants' visual short-term memory (VSTM) for simple objects undergoes dramatic development: Six-month-old infants can store in VSTM information about only a simple object presented in isolation, whereas 8-month-old infants can store information about simple objects presented in multiple-item arrays. This study extended this work to examine the development of infants' VSTM for complex objects during this same period (N = 105). Using the *simultaneous streams* change detection paradigm, Experiment 1 confirmed the previous developmental trajectory between 6 and 8 months. Experiment 2 showed that doubling the exposure time did not enhance 6-month-old infants' change detection, demonstrating that the developmental change is not due to encoding speed. Thus, VSTM for simple and complex objects appears to follow the same developmental trajectory.

Visual short-term memory (VSTM) is a memory system in which visual input is rapidly encoded, briefly maintained, and used for maintaining perceptual continuity and for comparing multiple visual images that cannot be simultaneously foveated (Henderson, 2008; Hollingworth & Henderson, 2002; Irwin, 1991). Thus, VSTM must be important for many aspects of cognitive development. Indeed, individual differences in VSTM capacity are related to how quickly people store information into long-term memory (Nikolić & Singer, 2007), the ability to focus on relevant information while inhibiting irrelevant information (Fukuda & Vogel, 2009), and later academic achievement (Alloway & Alloway, 2010; Daneman & Carpenter, 1980; Fukuda, Vogel, Mayr, & Awh, 2010; Johnson et al., 2013; Kane, Bleckley, Conway, & Engle, 2001). It is likely, therefore, that VSTM in infancy is important for the emergence of many cognitive abilities such as successfully finding objects in the A not B task (Lange-Küttner, 2008) and discriminating displays containing different numbers of items, which also vary in many other continuous variables such as element size, contour length, and surface area (Mix, Huttenlocher, & Levine, 2002).

VSTM must emerge in infancy: In the 1st year, infants plan, execute, and correct eye movements (Hainline, Turkel, Abramov, Lemerise, & Harris, 1984; Richards & Hunter, 1998) and integrate information over temporal gaps (e.g., occlusion events; Arterberry, 1993; Spelke, Kestenbaum, Simons, & Wein, 1995). Indeed, research has revealed VSTM, and related memory systems, by 4 months of age (Ross-Sheehy, Oakes, & Luck, 2003). Moreover, there is evidence that this system undergoes rapid developmental change between 6 and 8 months of age (Oakes, Hurley, Ross-Sheehy, & Luck, 2011; Oakes, Messenger, Ross-Sheehy, & Luck, 2009; Oakes, Ross-Sheehy, & Luck, 2006; Ross-Sheehy et al., 2003). The goal of the present investigation was to provide deeper understanding of this developmental change.

Development of VSTM in Infancy

Because VSTM representations are formed within periods of stable gaze, which are often brief, VSTM operates over a very short timescale—information is encoded in a fraction of a second and is retained only briefly. Thus, traditional experimental procedures used with infants, in which response over a period of many seconds is examined, provide only indirect insight into the development of VSTM (see Oakes & Luck, in press, for review). Therefore, Ross-Sheehy et al. (2003) developed the *simultaneous*

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streams task, adapting the *change detection* task used to study VSTM in adults (e.g., Alvarez & Cavanagh, 2004; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). Several features of this task are designed to isolate VSTM: Items are only briefly available (500 ms), requiring rapid encoding; retention periods are short (250–300 ms), minimizing the influence of long-term memory; and stimulus values repeat frequently, leading to proactive interference that would minimize the usefulness of long-term memory. Moreover, the retention period of 250–300 ms is short enough to isolate VSTM from long-term memory and, at the same time, long enough to minimize contributions from iconic memory. Even for adults who may process information faster than infants, a delay as short as 70 ms is sufficient to avoid using iconic memory for change detection (Rensink, O'Regan, & Clark, 1997). These timing parameters are like those used in studies of VSTM in adults (Luck & Vogel, 1997) and have also been used to assess VSTM in older children (Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Riggs, McTaggart, Simpson, & Freeman, 2006). In the infant task, two stimulus streams—in which arrays of items repeatedly appear, disappear, and reappear—are presented side by side. In *changing streams,* a randomly selected item changes on each cycle (e.g., one of the items in the array is a different color on each reappearance). The logic is that infants will show a preference for such changing streams relative to a *nonchanging stream* (in which the items remain the same from cycle to cycle) only if they can rapidly store the items in VSTM.

Using this task, research has revealed evidence of VSTM by 4 months (Ross-Sheehy et al., 2003) and rapid developmental change in VSTM between 6 and 8 months (Oakes et al., 2006; Oakes et al., 2009; Oakes et al., 2011). Although infants 6 months and younger can detect the change in the identity of single items presented in isolation (Ross-Sheehy et al., 2003) and changes in some aspects of multiple-item arrays (e.g., number, overall configuration; Libertus & Brannon, 2010; Oakes et al., 2011), they are insensitive to changes in the identities (e.g., color) of individual items in multiple-item arrays (Oakes et al., 2006, 2009; Ross-Sheehy et al., 2003). Remarkably, when presented with multiple-item arrays, 6-month-old infants fail to encode the identity of *any* of the items—they did not prefer changing over non-changing streams with arrays of three items even *when every item changed color every time the array reappeared* (Oakes et al., 2006; Oakes et al., 2009). Detecting a change in such streams should be trivial because the infant needs only to attend to and remember a single item in the array. The fact that infants failed to prefer such changing streams suggests that they did not encode the information of any of the individual items in the array.

By 8 months, infants apparently do represent the identities of individual items in multiple-item arrays, responding to changes in item identities in such arrays (Oakes et al., 2006; Oakes et al., 2009). Unlike younger infants, 8- to 10-month-old infants prefer changing streams in multiple item arrays when involving changes in the identity of a single item (Ross-Sheehy et al., 2003) or the identities of every item (Oakes et al., 2006; Oakes et al., 2009). Thus, during this period infants appear to develop the ability to selectively represent the identity of the individual items in multiple-item arrays. For example, Ross-Sheehy, Oakes, and Luck (2011) found that supporting infants' selection of a single item in a multiple-item array—by having only that item rotate—helped infants younger than 6 months to encode the identity of that one item. Under these conditions, 5.5-month-old infants preferred streams in which the rotating item changed to streams in which the rotating item did not change. Young infants apparently lack the ability to selectively attend to and encode the features of individual items in multiple-item arrays.

These processes are closely tied to *object individuation* in multiple-item arrays, or the selection of items in arrays via their spatial location, a process that may be a necessary first step prior to encoding processes (Xu & Chun, 2009). In adults, capacity limitations on a number of different tasks, including VSTM and subitizing, appear to be related to such object individuation (Ester, Drew, Klee, Vogel, & Awh, 2012; Melcher & Piazza, 2011). Parietal cortical regions are important for both individuation processes (Xu & Chun, 2006, 2009) and capacity limitations in VSTM (Ester et al., 2012; Melcher & Piazza, 2011). These regions develop substantially during the first postnatal year (Chugani, 1999; Deoni et al., 2011). As a result, the observed developmental transition for infants' VSTM for simple objects may reflect the broader processes involved in object individuation, which implies that we should observe the same developmental transition for infants' VSTM of other types of objects.

Factors That Influence Infants' VSTM

All of the studies to date of infants' VSTM have used simple objects, such as colored geometric shapes, and have used precisely the same timing parameters (e.g., Oakes et al., 2006; Oakes et al., 2009; Ross-Sheehy et al., 2003). Thus, we know little about how infants' VSTM does or does not differ as a function of differences in stimuli or encoding durations. We addressed these gaps in this study.

First, we asked whether infants' VSTM for complex objects is similar to their previously established VSTM for simple objects. Previous studies have assessed infants' memory for complex objects (e.g., small toys or faces; e.g., Courage & Howe, 2001; Fagan, 1972; Rose, Feldman, & Jankowski, 2001) using tasks that tap long-term memory systems. Because the procedures in such studies used relatively long exposure periods (3 s to 2 min), the results reflect long-term memory processes in addition to VSTM processes (see Oakes & Luck, in press, for review). Therefore, we sought to isolate VSTM processes using the simultaneous streams task (Ross-Sheehy et al., 2003). This will also allow us to establish whether the previously observed developmental changes in infants' VSTM for simple features apply generally to a broad range of object types.

Here we define *complex objects* as objects with multiple parts and colors. Although little is known about VSTM for complex objects in infants younger than 12 months, many studies have examined the effect of object complexity on adults' VSTM (e.g., Alvarez & Cavanagh, 2004; Awh, Barton, & Vogel, 2007; Eng, Chen, & Jiang, 2005; Luck & Vogel, 1997; Wilken & Ma, 2004; Zhang & Luck, 2008). This work with adults was motivated by an interest in understanding the nature of VSTM representations and the relation between object complexity and VSTM storage capacity. Although this issue is beyond the scope of this investigation, the adult research underscores the need for extending our understanding of infants' VSTM to complex objects. Therefore, in this study, we examined infants' VSTM for complex objects and evaluated our findings in the context of previous work on infants' VSTM for simple objects.

Second, we asked how differences in VSTM are related to differences in encoding duration. We tested the possibility that observed developmental differences in VSTM reflect differences in the speed with which infants encode multiple items into VSTM. A general principle of cognitive development is that younger children are slower processors than older children (e.g., Fry & Hale, 1996; Kail, 1991; Rose, Feldman, & Jankowski, 2002) and slower processors require longer to encode information (Colombo, Mitchell, Coldren, & Freeseman, 1991). Thus, we varied exposure time between Experiments 1 and 2 to determine whether younger infants' difficulty at encoding multiple items in VSTM is related to speed of processing.

Experiment 1

Experiment 1 used the simultaneous streams task to investigate developmental changes in infants' VSTM for complex objects between 6 and 8 months, the period of rapid change in infants VSTM and related memory systems for simple objects (e.g., Kaldy & Leslie, 2003, 2005; Oakes et al., 2006; Oakes et al., 2009; Oakes et al., 2011).

Method

Participants. Participants were 72 healthy, full-term infants with no known vision problems or family history of color-blindness. There were thirty-six 6-month-old infants (20 boys and 16 girls; M = 181 days, SD = 9.36) and thirty-six 8-month-old infants (18 boys and 18 girls; M = 245 days, SD = 8.61). Fifty-three of the infants (twenty-nine 6-month-olds and twenty-four 8-month-olds) were Caucasian, 3 were Asian (one 6-month-old and two 8-month-olds), 14 were mixed race (six 6-month-olds and eight 8-month-olds), and race was not reported for two 8-month-old infants. Across these racial groups, nine 6-month-old and five 8-month-old infants were reported to be Hispanic. All of the mothers had graduated from high school, and 69% of them had earned at least a bachelor's degree. An additional thirteen 6-month-olds and twenty-one 8-month-olds were tested but excluded from the analyses due to fussiness (N = 26), parental interference (N = 4), equipment malfunction (N = 2), experimenter error (N = 1), and inattentiveness (defined as not looking at a monitor on at least three successive trials, N = 1). Names of infants were originally obtained from the State Office of Vital Records, and parents were sent informational mailings. Parents who wished to volunteer for studies contacted us and were included in our database. When infants reached the appropriate age for this study, we contacted them about participating. Infants received a small toy or T-shirt and a certificate in appreciation for their time.

Apparatus and stimuli. The stimuli were presented on a 94-cm (diagonal) LCD monitor that was surrounded by a black curtain that obstructed the infants' view of the experimenter and other equipment. We used a Macintosh G5 computer and a custom program created in Adobe Director 11.5 to present the stimuli on this monitor and record the duration of infants' looking on each trial. The monitor displayed two virtual "screens": two 33.0 cm × 27.0 cm white rectangles (18.7° × 15.4° at a viewing distance of 100 cm), positioned on the left and right sides of midline, separated by a 15.3-cm (8.7°) gap. The center-to-center distance was approximately 48.3 cm (27.0°), which was far apart enough to prevent infants from fixating the stimuli presented on both "screens" at the same time, and allow them to focus on the stimuli presented on one "screen" at a time (Pelli, Palomares, & Majaj, 2004). The size of these virtual screens and the center-to-center distance were similar to those used in previous studies using the simultaneous stream task (Oakes et al., 2006; Oakes et al., 2009; Oakes et al., 2011; Ross-Sheehy et al., 2003).

Stimulus streams were presented in each of these "screens." There were eight digitized color images of novel, complex objects, taken from the NOUN object database (Horst, 2009). These objects were novel, consisted of multiple parts and varied in color (see Figure 1). The average size of the objects was approximately 14.8 cm wide (8.5°) × 20.0 cm high (11.4°). The stimulus streams involved the repeated presentation of one or two of these complex object(s) randomly chosen by our computer program, in the following cycle: The objects were presented for 500 ms, disappeared for 300 ms, and then reappeared again at the beginning of the next cycle (see Figure 2). This on–off cycle repeated continuously for 20 s (the duration of our trials) and each trial had 24 cycles, in total. Half of the streams included one object (Set Size 1) and the other streams included two objects (Set Size 2). The items could be presented on one of two locations—approximately 8.3 cm (4.4°) to the right of the center of the "screen" or 8.3 cm to the left of the center of the "screen." Regardless of the left or right positions, the centers of the objects were centered vertically within the "screens." For Set Size 2, the program randomly selected on each cycle within a trial whether the left or right item in the array would change on that cycle. For consistency across the trials with different set sizes, objects were placed in the same locations for Set Size 1 (rather than being placed in the middle of the screen). On each trial, the program randomly selected one of the two locations on each virtual screen, to present the item on each cycle within a trial. Thus, the only difference between Set Size 1 and Set Size 2 trials was how many objects were on the displays, and not where the objects were located in the display.

On each trial, one screen contained a *changing stream* and the other contained a *nonchanging stream*. In the changing stream, one randomly chosen item from the display on one cycle changed to a different item on the next cycle. In the nonchanging stream, the object(s) remained unchanged from cycle to cycle until the end of the trial. For changing streams at Set Size 1, the single visible object changed on every cycle, and for changing streams at Set Size 2, the changed item was selected at random on each cycle.

Procedure. Infants sat on a parent's lap, directly in front of and approximately 100 cm from the LCD monitor. To reduce parental influence, parents wore felt-covered sunglasses, preventing them from seeing the stimuli. Prior to the start of each trial, an attention getter was presented between the two "screens" to direct the infant's attention to a central location between the two stimulus streams. The

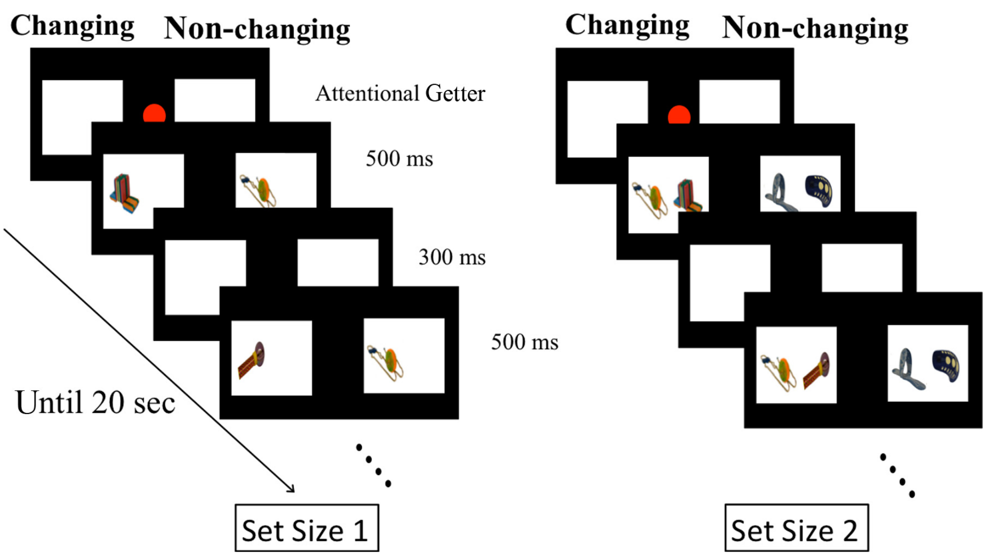

Figure 1. Depiction of procedure. On each trial, the program randomly selected one of the two locations (i.e., left vs. right) as the location for the changing stream.

Figure 2. Complex objects (the NOUN object database, Horst, 2009) used in Experiments 1 and 2.

attention getter consisted of a red circle, diameter of 7.5 cm, which blinked at a rate of approximately 2 Hz accompanied by a police whistle. As soon as the observer judged that the infant was looking at the attention getter, he or she pressed a computer key that simultaneously ended the attention getter and presented two stimulus streams—changing and nonchanging—side by side, on the rectangular "screens" on the monitor.

Infants received eight 20-s trials. On each trial, the number of objects in each stream (set size) was the same for the changing and nonchanging streams. Thus, the only difference between the two streams presented on each trial was that one involved a change and the other did not. Each infant received four trials at Set Size 1 and four trials at Set Size 2, order randomized across the eight trials. The set size was factorially combined with side that contained the changing stream, with two trials for every combination of set size and changing side.

In each trial, an observer, who was unaware of the set size or changing side, watched the infant on a monitor displaying live video feed from a concealed camera. For the duration of each 20-s trial, the observer recorded how long infants looked at each "screen" by pressing one computer key when he or she judged the infant was looking at the left screen and a second computer key when he or she judged the infant was looking at the right screen. This procedure yielded a record of how long infants looked in total at each stream during each trial. The looking times for 25% of the infants were recoded offline by a second trained observer, also unaware of the location of the changing stream. The average correlation between the two observers was .98, and the average between-observer difference on each trial was .55 s. The original data recorded online were used for subsequent data analyses.

Results and Discussion

Infants' total looking times. Before we discuss whether infants preferentially looked at the changing streams, we will describe how infants' looking *in general* varied across age and set size. For this purpose, we conducted an analysis of variance (ANOVA) on the total looking time (looking to the changed and unchanged streams combined) with age (6, 8) as the between-subjects factor and set size (1, 2) as the within-subjects factor. This analysis revealed a main effect of set size, $F(1, 70) = 8.85$, $p < .01$, $\eta^2_p = .112$ (see Table 1), indicating that infants looked longer when there were more items in each array. There was no significant main effect or interactions involving age, $ps > .30$. Thus, although infants in both age groups preferred arrays with more items, the overall looking patterns were indistinguishable in the two groups.

Infants' preference for the changing stream. To determine whether infants preferentially looked at the changing streams, we computed each infant's change-preference score for each set size. These scores were calculated by dividing the looking time for the changing display by total looking time, that

Table 1

Mean Total Looking Time in Seconds (Standard Deviations in Parentheses) for Each Experiment by Age and Set Size

	N	Set Size 1	Set Size 2
Experiment 1			
6 months	36	10.07 (2.65)	10.79 (2.81)
8 months	36	10.03 (2.82)	11.17 (3.00)
Experiment 2			
6 months	33	10.73 (3.13)	11.75 (2.94)

is, changing divided (changing + nonchanging). The maximum possible score was 1.0, which would indicate that the infant looked only at the changing side, and the minimum possible score was 0.0, which would indicate that the infant looked only at the nonchanging side. A score of 0.5 would be obtained if the infant looked equally long at the changed and nonchanged sides. Libertus and Brannon (2010) recently reported similar preference scores calculated in a different way, with a range from −1 to 1 and a chance level of 0. Their scores and those presented here are perfectly correlated and yield the same pattern of significance. Figure 3 presents individual change-preference scores for each combination of age and set size. Inspection of this figure suggests that one or more infant(s) may have an outlier response. In fact, all of the individual scores in each age group fell within 3 *SD* from the mean for each set size. Several infants, however, met more lenient criteria for outliers (e.g., 2 *SD* from the mean). We conducted all the analyses reported here excluding these "outliers" and the results were the same. Because no infants met the more conservative outlier criterion, we report only the analyses including the whole sample. The Shapiro–Wilk normality test revealed that the distributions of the change-preference score did not significantly violate the assumption of normality, $ps > .17$. Therefore, we used the untransformed raw preference scores in all the analyses.

We conducted two analyses on each change-preference score to determine whether infants preferred the changing side more than expected by chance. First, we conducted a one-sample t test (two-tailed) comparing the observed change-preference score for each set size at each age to .50 (chance), to test the null hypothesis that infants' response did not differ from chance. Second, we conducted a Bayes factor analysis (Rouder, Speckman, Sun, Morey, & Iverson, 2009) to indicate the relative likelihood of the null hypothesis versus the alternative hypothesis. Bayes factor analysis has been recently used in several studies to address such questions (see Beck, Hollingworth, & Luck, 2012; Kibbe & Leslie, 2011). According to Jeffreys's (1961) guidelines for interpretation, values > 3 are considered as substantial evidence to support one hypothesis (or model).

The results revealed robust preference for the changing streams at both Set Size 1 and Set Size 2 by 8-month-old infants. Their mean change-preference score was significantly greater than chance at Set Size 1, $t(35) = 4.32$, $p < .001$, $d = .72$, and Set Size 2, $t(35) = 3.74$, $p < .005$, $d = .62$. Bayes factor analyses also confirmed that 8-month-old infants preferred the changing stream: The hypothesis that infants' change preference was different from chance was 192 times more likely than the null hypothesis at Set Size 1 and 40.6 times more likely than the null hypothesis at Set Size 2.

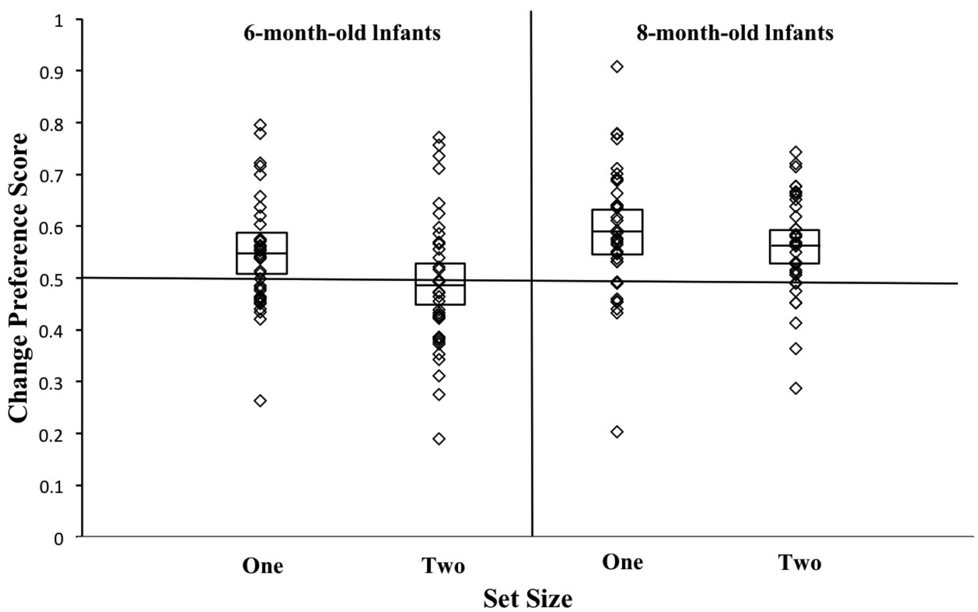

Figure 3. Preference for the changing streams in Experiment 1. Each individual diamond represents the change preference for a single infant. The bar bisecting the boxes reflects the mean and the boundaries of box reflects the 95% confidence interval for that mean.

The pattern of change preference was somewhat different at 6 months. The mean change-preference score of 6-month-old infants was significantly different from chance only at Set Size 1, $t(35) = 2.67$, $p < .05$, $d = .44$ (see Figure 3); their change preference did not differ from chance at Set Size 2, $p = .58$. Bayes factor analysis again corroborated these results: At Set Size 1, the hypothesis of a difference from chance was 3.1 times more likely than the null hypothesis, but at Set Size 2, the *null* hypothesis (that the change-preference score was not different from chance) was 6.6 times more likely than the alternative hypothesis. Thus, Experiment 1 provides evidence that, unlike the 8-month-old infants, the 6-month-old infants failed to detect a change in streams involving two complex objects.

We next directly compared the pattern of change preferences across age groups by conducting an ANOVA with set size (1, 2) as a within-subjects variable and age (6, 8 months) as a between-subjects variable. The main effect of set size was significant, $F(1, 70) = 4.83$, $p < .05$, $\eta^2_p = .065$, reflecting the greater preference scores observed across age at Set Size 1 ($M = .57$, $SD = .12$) relative to Set Size 2 ($M = .52$, $SD = .12$). The main effect of age was also significant, $F(1, 70) = 9.67$, $p < .005$, $\eta^2_p = .121$, reflecting a greater mean preference score for 8-month-old infants ($M = .57$, $SD = .12$) than for 6-month-old infants ($M = .52$, $SD = .12$). However, the interaction of set size and age effect was not significant, $p = .44$.

This lack of a significant interaction appears to be inconsistent with the conclusions just described in which *t* test and Bayes factor analyses comparing infants' response to chance demonstrated that both 6- and 8-month-old infants exhibited significant preferences at Set Size 1, but only 8-month-old infants exhibited a significant preference at Set Size 2. The lack of a significant interaction despite differences in the comparisons to chance is similar to that observed previously (e.g., Ross-Sheehy et al., 2003) and likely reflects the low power of a non-cross-over interaction.

However, on the basis of the existing body of research, we had specific hypotheses about differences between 6- and 8-month-old infants. That is, we predicted that 6- and 8-month-old infants would not differ in their response at Set Size 1 but would differ in their response at larger set sizes. Other studies using the simultaneous streams tasks have shown that 8-month-old infants have significantly greater change-preference scores than do 6-month-old infants in multiple-item arrays (Oakes et al., 2006; Oakes et al., 2009). We therefore conducted two planned *t* tests, comparing 6- and 8-month-old infants' change-preference scores at each set size. At Set Size 1, 6- and 8-month-old infants' change-preference scores did not differ significantly, $p = .12$. At Set Size 2, however, 8-month-old infants' change-preference score was significantly greater than the 6-month-old infants' score, $t(70) = 2.68$, $p < .01$, $d = .64$. Thus, although 8-month-old infants generally had higher change-preference scores than did 6-month-old infants, leading to a main effect of age in the omnibus ANOVA, these planned comparisons revealed a significant age difference only for Set Size 2. Bayes factor analyses corroborated these results. At Set Size 2, the hypothesis that 8-month-old infants' change-preference score is different from the 6-month-old infants' score was 4.3 times more likely than the null hypothesis (that the change-preference score does not differ); at Set Size 1, the hypothesis that the scores differed was only 0.5 times more likely than the null hypothesis. According to Jeffreys's (1961) guidelines, values < 1 are considered negative evidence.

Thus, despite the lack of a significant Age × Set Size interaction in the ANOVA, the results taken as a whole are consistent with the conclusion that there is a rapid developmental change in infants' VSTM for complex objects between 6 and 8 months. We make this conclusion based on several observations from Experiment 1: (a) comparisons of change-preference scores to chance revealed different patterns in 6- and 8-month-old infants—infants at both ages significantly preferred changing streams at Set Size 1, but only 8-month-old infants significantly preferred changing streams at Set Size 2; (b) the ANOVA yielded a significant main effect of age, suggesting that 8-month-old infants were generally more responsive to changing streams in this experiment than were 6-month-old infants; and (c) focused comparisons between 6- and 8-month-old infants—motivated by predictions derived from the results of previous studies—revealed no difference in change-detection scores at Set Size 1, but 8-month-old infants had a significantly greater change-preference score than 6-month-old infants at Set Size 2. Thus, the lack of a significant Age × Set Size interaction in the ANOVA likely reflects a lack of power to detect the kind of non-cross-over interaction in this experimental design, rather than a lack of a true developmental difference.

Experiment 2

Experiment 2 sought to rule out an alternative explanation for the failure of 6-month-old infants to significantly prefer the changing stream; specifically, that their apparent inability to store items in multiple-item arrays is actually a side effect of the need for more time to encode the items in VSTM. In general, younger children are slower processors than older children (e.g., Fry & Hale, 1996; Kail, 1991; Rose et al., 2002), and slower processors require longer to encode information (Colombo et al., 1991). Thus, it is possible that observed developmental differences in VSTM reflect differences in the speed with which infants encode multiple items.

To test this possibility, we replicated Experiment 1 with 6-month-old infants, except that we doubled the exposure durations to 1,000 ms. Because in Experiment 1, 6-month-old infants could encode the identity of a single complex object in 500 ms, we reasoned that if their main limitation at Set Size 2 was an insufficient amount of time to encode the two items, they should better encode the two items in that array with increased exposure time.

Method

Participants. Participants were 33 full-term 6-month-olds (15 boys and 18 girls; M_{age} = 183 days, SD = 8.10) with no known vision problems or family history of color-blindness, recruited as in Experiment 1. Twenty-five of the infants were Caucasian, seven were mixed race, and race was not reported for one infant. Across these racial groups, six infants were reported to be Hispanic. All of the mothers had graduated from high school, and 66% of them had earned at least a bachelor's degree. An additional 18 infants were tested but excluded from the analyses due to fussiness (N = 11), inattentiveness (defined as not looking at a monitor for at least three successive trials, N = 3), experimenter error (N = 1), equipment malfunction (N = 2), and falling asleep during the study (N = 1).

Apparatus, stimuli, and procedure. All aspects of the apparatus, stimuli, and procedure were identical to Experiment 1 except that the arrays were visible for 1,000 ms on each cycle (i.e., the array was visible for 1,000 ms and the screen was blank for 300 ms on each cycle). It should be pointed out that because we kept trial durations the same across experiments, increasing exposure time on each cycle in Experiment 2 decreased the number of cycles per trial relative to Experiment 1. That is, each trial had 24 cycles in Experiment 1, whereas each trial had only 15 cycles in Experiment 2. If doubling the exposure time allowed infants to encode the information about the two items, they should find the changing streams in Experiment 2 more compelling than those in Experiment 1 despite the reduced number of cycles during a trial. However, it is also possible that reducing the number of cycles (i.e., having fewer number of changes per trial) would result in less overall attentiveness in Experiment 2. To test this possibility, we compared infants' total looking times in Experiments 1 and 2 to determine whether infants were generally more attentive in one experiment than in the other.

As in Experiment 1, a second trained observer recoded looking times for 25% of the infants in Experiment 2. The average correlation between the two observers was .96, and the average between-observer difference for the duration of looking on each trial was .76 s.

Results and Discussion

Infants' total looking time. First, we address the question of whether infants' looking in general was influenced by the different exposure times (and frequency of visual streams). We compared the total looking of 6-month-old infants in Experiments 1 and 2 with an ANOVA conducted on the total looking time (looking to the changed and unchanged streams combined) for each set size, with experiment (1 vs. 2) as the between-subjects factor and set size as the within-subjects factor. This analysis revealed only a main effect of set size, $F(1, 67) = 10.31$, $p < .01$, $\eta^2_p = .133$, (see Table 1); infants looked longer during Set Size 2 trials than during Set Size 1 trials (collapsed across the changing and nonchanging streams). There were no significant effects of or interactions involving exposure time, ps > .267. Thus, regardless of exposure time, infants looked longer when there were more items in each array. Moreover, infants did not look differently when the change occurred more frequently or when the exposure duration was longer. Thus, the stimuli in the two experiments led to comparable levels of overall attentiveness.

Infants' preference for the changing stream. We computed the change-preference score for each set size as described in Experiment 1. The average change-preference score (with 95% confidence intervals) and individual scores for each infant are presented in Figure 4. The pattern was identical to that observed in Experiment 1—infants once again showed a preference for the changing stream only at Set Size 1. This impression was confirmed with one-sample t tests comparing infants' change preference to chance—6-month-old infants' change-

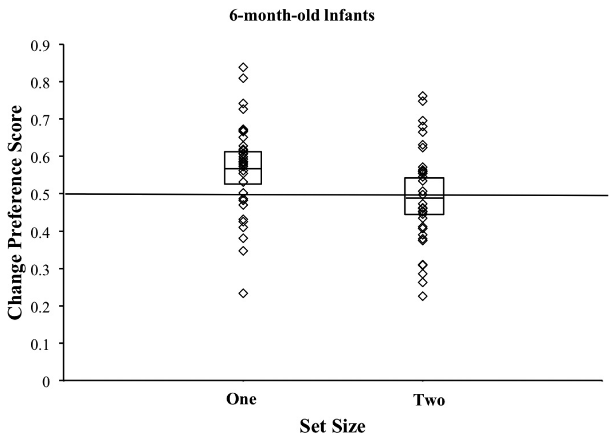

Figure 4. Preference for the changing streams in Experiment 2. Each individual diamond represents the change preference for a single infant. The bar bisecting the boxes reflects the mean and the boundaries of the box reflects the 95% confidence interval for that mean.

preference score for Set Size 1 was significantly greater than chance, $t(32) = 3.07$, $p < .005$, $d = .535$, whereas their score for Set Size 2 did not differ significantly from chance, $p = .74$. The Bayes factor analysis confirmed these patterns of the results; for Set Size 1, the hypothesis that infants' change-preference score is different from chance was 7.6 times more likely than the null hypothesis. For Set Size 2, the *null* hypothesis (that infants' score did not differ from chance) was 7.0 times more likely than the alternative hypothesis. Thus, we replicated the pattern observed in Experiment 1.

Next, to confirm that 6-month-old infants responded in the same way in Experiments 1 and 2, we conducted an ANOVA with set size (1, 2) as a within-subjects variable and Exposure time (500 ms vs. 1,000 ms) as a between-subjects variable. This analysis revealed only a significant main effect of set size, $F(1, 67) = 12.02$, $p < .005$, $d = .152$; infants' change preference scores were significantly greater at Set Size 1 ($M = .57$, $SD = .13$) than at Set Size 2 ($M = .49$, $SD = .14$). There were no significant effects of or interactions involving exposure time, ps $> .60$. Thus, doubling the exposure time did not enhance 6-month-old infants' change detection.

Recall that increasing exposure time on each cycle in Experiment 2 decreased the number of cycles per trial relative to Experiment 1, to keep trial durations the same across experiments. That is, each trial had 24 cycles in Experiment 1 and 15 cycles in Experiment 2. To ensure that reducing the number of cycles from 24 (Experiment 1) to 15 (Experiment 2) per trial did not change infants' change preferences, we recalculated infants' change-preference scores for Experiment 1 including only looking times for the first 15 cycles in each trial (i.e., how long they looked during the first approximately 12.5 s of each trial). The results were identical to those reported above: Eight-month-old infants' mean change-preference score was significantly greater than chance at Set Size 1 ($M = .60$, $SD = .13$), $t(35) = 4.72$, $p < .001$, $d = .79$, and Set Size 2 ($M = .58$, $SD = .11$), $t(35) = 4.35$, $p < .001$, $d = .73$, whereas 6-month-old infants' mean change-preference score was significantly greater than chance only at Set Size 1 ($M = .55$, $SD = .12$), $t(35) = 2.25$, $p < .05$, $d = .37$.

To summarize, Experiment 2 shows that 6-month-old infants' failure to store the individual items in multiple-object arrays in Experiment 1 did not reflect an insufficient period of encoding time. Our analyses also ruled out the possibility that the longer durations used in Experiment 2 somehow weakened the change preferences by reducing the overall attentiveness of the infants, because overall looking times were comparable across experiments. Moreover, we again found a very robust change preference at Set Size 1 in the present experiment. Our findings confirm previous results showing a limited ability to store information from multiple-item arrays in VSTM in the first half of the postnatal year.

General Discussion

This study yielded two primary findings. First, we replicated the developmental change in VSTM between 6 and 8 months with complex objects, illustrating the generality of this rapid development of VSTM. Second, we found that 6-month-old infants' failure to respond to changes in multiple-item arrays in the simultaneous stream task is not due to short exposure time. The significance of these findings for our understanding of VSTM in infancy is discussed in the following paragraphs.

Development of VSTM for Complex Objects in Infancy

Our first goal was to examine VSTM for complex objects in the first postnatal year, using a task that isolates this memory system. In Experiment 1, both 6- and 8-month-old infants exhibited significant change preferences for arrays containing a single complex object, but only 8-month-old infants exhibited a significant change preference for arrays containing two complex objects. Experiment 2 revealed this same pattern for 6-month-old infants, indicating that it is robust and replicable. Thus, by 6 months infants can store information about a single complex object in VSTM, and the ability to store information in VSTM about complex objects in multiple-element arrays develops rapidly between 6 and 8 months. This is exactly the same pattern that we have observed for simple objects in several previous experiments (e.g., Oakes et al., 2006; Oakes et al., 2009; Ross-Sheehy et al., 2003). Thus, this developmental pattern appears to be highly robust and general.

One might expect that VSTM performance would be poorer for complex objects than for simple objects. In adults, VSTM performance is often worse for complex objects than for simple features (e.g., Alvarez & Cavanagh, 2004; Eng et al., 2005). However, this pattern is observed only when the complex objects are highly similar to each other and does not reflect an intrinsic difference in working memory capacity for simple and complex objects (Awh et al., 2007). Even pigeons can perform change detection with complex objects that are highly discriminable (Gibson, Wasserman, & Luck, 2011). The close correspondence between the present results in which we assessed infants' VSTM for highly discriminable complex objects and previous experiments using simple objects suggests that performance in this task—and the developmental changes in performance—are determined by the number of objects and not the complexity of the objects. Thus, infants' VSTM does not appear to be intrinsically different for complex objects compared to the simple objects we had studied previously. However, we did not directly compare infants' VSTM for complex objects with that for simple objects within the same study. This is one goal for future studies.

The pattern of results across studies indicates that infants' VSTM undergoes a rapid change in the middle of the first postnatal year, for both simple and complex objects, allowing infants to rapidly encode the identities of items in multi-item arrays. This developmental shift may be related to emerging abilities to individuate the items in such displays, an ability that is thought to be critical for encoding information in VSTM (Xu & Chun, 2009). Such individuation in adults relies on activity in posterior parietal cortex (Cusack, 2005; Xu & Chun, 2006, 2009), a region that undergoes significant development during infancy (Chugani, 1999). The present results are consistent with broad developmental changes in VSTM coinciding with the development of individuation abilities. Although there has been significant interest in infants' developing ability to individuate objects (e.g., Wilcox & Baillargeon, 1998a, 1998b; Wilcox & Schweinle, 2002; Xu, Carey, & Quint, 2004; Xu, Cote, & Baker, 2005), there has been little work examining infants' emerging ability to individuate individual items in cluttered visual scenes. This is an important direction for future work.

Our approach here is similar to that adopted by Zosh and Feigenson (2012), who compared toddlers' memory for complex objects with previous findings from the same task with simple objects (Feigenson & Carey, 2003, 2005). However, our findings seem to differ from these previous findings. Specifically, Zosh and Feigenson reported that toddlers had smaller memory capacity for complex objects than for simple objects. Our results suggest that 6- and 8-month-old infants' VSTM capacity is the same for complex objects as was previously observed for their VSTM for simple objects. How do we reconcile our results with Zosh and Feigenson's findings? There are several possibilities. For example, VSTM may undergo a qualitative shift during the 1st year, and our finding of similarities in VSTM for simple and complex objects could reflect one developmental stage, whereas Zosh and Feigenson's finding of differences in toddlers' memory for simple and complex objects could reflect a different developmental stage. Although we cannot completely rule out this possibility, other explanations for the apparent discrepancy seem more plausible.

In particular, the two tasks used in these studies differed in a number of ways that might have contributed to differences in findings. Feigenson and her colleagues (Feigenson & Carey, 2003, 2005; Zosh & Feigenson, 2012) used a manual search task in which memory is inferred from differences in search durations when infants encounter a change (e.g., the search reveals a mismatch in the number or identities of the items that were hidden) versus when there is no change (e.g., the search reveals the expected number and identity of the items). This task likely engages multiple systems—their individuation and encoding of items in VSTM, their storage of the items during the delay period, their recognition of the mismatch during retrieval, their motivation to continue searching, and so on—and their effects may have reflected something other than the effect of complexity on VSTM different memory system. Moreover, our task and that of Feigenson and colleagues differ significantly in the duration of encoding time available (many seconds vs. 0.5–1 s) and the length of the retention periods (many seconds vs. 0.3 s). Thus, object complexity may have a different effect on infants' performance in these two tasks.

The discrepancy in results may also reflect differences in the magnitude of the changes infants were required to detect in the two tasks. It is possible that our unfamiliar complex objects were more discriminable to our 6- and 8-month-old infants than were the differences between Zosh and Feigenson's (2012) familiar objects to their 18-month-old infants. In support of this possibility, although Zosh and Feigenson found that 18-month-old infants did not respond to a change when one of three complex objects changed from one familiar solid object to another familiar solid object (e.g., a car to a shoe), they did respond to the change from a familiar solid object to an unfamiliar nonsolid object (e.g., a car to a blob of goo). Finally, the differences in results may reflect the use of two-dimensional (2-D) images in this study versus three-dimensional (3-D) objects in Zosh and Feigenson's study; it is possible that memory systems are differentially engaged when encoding 2-D versus 3-D stimuli. These issues can best be addressed by testing the same infants with both manual search and simultaneous stream tasks.

In summary, our results demonstrate that the rapid developmental change in VSTM—as isolated in the simultaneous streams task—is observed when the to-be-remembered items are complex objects, just as it has been observed when the to-be-remembered items are simple colored squares (Oakes et al., 2006; Oakes et al., 2009; Ross-Sheehy et al., 2003). Our findings suggest that this developmental transition is general and not specific to infants' VSTM for a particular type of stimuli, perhaps reflecting infants' emerging abilities to individuate items (and represent the identities of individual items) in multiple item arrays.

Exposure Time and Development of VSTM in Infancy

Second, this investigation showed that the failure of young infants to respond to changes in multiple-item arrays was not due to inadequate opportunity to encode the items in those arrays. Comparison of Experiment 1, in which encoding periods were 500 ms, and Experiment 2, in which encoding periods were 1,000 ms, revealed no effect of exposure time on 6-month-old infants' VSTM for multiple objects. Responses were indistinguishable in these two experiments, despite the fact that infants had twice as long to encode the individual items in Experiment 2 as in Experiment 1. Moreover, 8-month-old infants showed a robust change preference at Set Size 2 with a 500-ms encoding period, and it takes adults approximately 50–100 ms to encode individual objects in VSTM (Vogel, Woodman, & Luck, 2006; Vogel et al., 2001). It is implausible that 6-month-old infants would need more than twice as much time as 8-month-old infants and more than 10 times as much time as adults to encode items in VSTM. Thus, the developmental change between 6 and 8 months does not solely reflect age differences in encoding speed.

Our results also suggest that infants do not appear to require more time to encode complex objects than to encode simple objects despite the fact that complex objects contain more information to encode than simple objects (Eng et al., 2005). The response of the 6- to 8-month-old infants tested here was very similar to the response of other infants in previous studies examining VSTM for simple objects, using the same task and identical exposure time (Oakes et al., 2006; Oakes et al., 2009; Oakes et al., 2011; Ross-Sheehy et al., 2003). If encoding time was a significant factor limiting infants' VSTM, we would expect that 8-month-old infants' VSTM for complex objects would be limited in Experiment 1 compared to their VSTM for simple objects in previous studies.

Finally, although we cannot rule out the possibility that infants would perform differently given much longer encoding periods, several findings in the literature cast doubt on the notion that VSTM processes would be enhanced by encoding times of several seconds. For example, in a working memory task in which encoding occurred over several seconds, Kaldy and Leslie (2003, 2005) revealed the same developmental pattern as we observed here. In a procedure in which infants first were familiarized with two objects hidden sequentially behind two separate occluders, and then were shown test trials in which one or both items changed shape or color, 6-month-old infants remembered the location of only the last item object, whereas 9-month-old infants remembered both of the hidden items.

In summary, we have no evidence that infants' VSTM is influenced by encoding time. The difference between younger and older infants remains even when encoding time is increased, and infants' response is similar when the task involves simple and complex objects.

Conclusions

The results presented here add to our understanding of the development of VSTM in infancy, and contribute to a growing literature suggesting that there is a rapid and general developmental change in VSTM between 6 and 8 months of age. The present results show that this developmental shift is independent of the particular stimuli used, suggesting that this aspect of VSTM development is quite general. We speculate that this developmental transition reflects processes related to the ability to individuate items in multiple-item arrays and that these changes likely reflect the emergence of cortical processes that have been found to be important in adults' VSTM processes.

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