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Indexing Early Visual Memory Durability in Infancy

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The goal was to examine the scope and development of early visual memory durability. We investigated individual- and age-related differences across three unique tasks in 6- to 12-month-olds (M_{age} = 8.87, N = 49) by examining the effect of increased delay on memory performance. Results suggest longer-term memory processes are quantifiable by 8 months using a modified Change Detection paradigm and spatial-attention cueing processes are quantifiable by 10 months using a modified Delayed Response paradigm, utilizing 500–1,250 ms delays. Performance improved from 6 to 12 months and longer delays impaired performance. We found no evidence for success on the Delayed Match Retrieval task at any age. These outcomes help inform our understanding of infant visual memory durability and its emergence throughout early development.

Developmental theorists have long suggested that individual differences in memory abilities may underlie individual differences in fluid intelligence, a domain-general mechanism thought to underlie reasoning, problem solving, and novelty detection (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Conway, Kane, & Engle, 2003; de Abreu, Conway, & Gathercole, 2010; Deary, Strand, Smith, & Fernandes, 2007; McCall & Carriger, 1993; Sedek, Krejtz, Rydzewska, Kaczan, & Rycielski, 2016). Short-term memory (STM), a limited-capacity cognitive system used to temporarily store (but not manipulate) small amounts of information for short periods of time, is known to be available to infants by 4 months of age (Reznick, Morrow, Goldman, & Snyder, 2004; Ross-Sheehy, Oakes, & Luck, 2003). STM continues to develop and mature throughout childhood and into adolescence, forming a critical foundation that sets the stage for development of higher order cognitive processes, such as planning, reasoning, and problem solving (Collins & Koechlin, 2012). The development of these processes plays an important role across a variety of domains during childhood, including emotion regulation (Eisenberg, Hofer, & Vaughan, 2007), school readiness (Blair & Razza, 2007), and social cognition (Blakemore & Choudhury, 2006).

Shorter term memory processes are often operationalized in terms of capacity, such as how many discrete objects one can remember (Oberauer & Kliegl, 2006), but they can also be measured in regards to durability. Memory durability is defined as the maximum length of time that information can be successfully retained (Pelphrey & Reznick, 2003; Reznick, 2008). When information must be maintained over longer delay durations there is a demand increase placed on memory systems regardless of the number of discrete stimuli to be remembered. For example, adult studies have shown that increasing levels of cognitive demand via increased temporal delay can significantly restrict memory abilities (Barrouillet & Camos, 2012). Due to obvious constraints of testing infants, developmental researchers are often times limited in objective ways to test infant memory abilities. However, a body of literature described next provides evidence that early visual memory durability can be indexed over brief delay periods.

Infant Memory Assessments

Delayed Response

Delayed Response is a procedure used to assess frontal lobe function (Hunter, 1913). Participants are cued briefly with an auditory or visual stimulus until it is withdrawn, and after a short delay period, they attempt to identify the location where the stimulus appeared. In one popular developmental adaptation of the paradigm, infants are seated on a caregiver's lap, facing directly opposite an

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experimenter. In between the infant and experimenter is a table containing two hiding wells, and small cloths used to cover the hiding wells. A toy is first hidden in one of the two wells, and the infant is allowed to reach to the well to find the toy (Diamond & Doar, 1989). The task is similar to the Piagetian A-Not-B task, but differs because the side of hiding is varied randomly over trials, whereas in the A-Not-B task the toy is repeatedly hidden in the same well until the infant makes a correct reach, and then the side of hiding reverses (Piaget, 1955). Delayed Response has also been adapted to use oculomotor behavior as the dependent measure (Funahashi, Bruce, & Goldman-Rakic, 1989). Instead of coding reaching behaviors, oculomotor paradigms code the trial as a pass if the infant's first fixation or looking time is directed to the same target location as the previous cue stimulus.

Because the location of the cue stimulus randomly changes on a trial-by-trial basis, Delayed Response success requires maintaining representations of a previously cued visual stimulus over short delays. Studies utilizing Delayed Response procedures have found visual memory durability at 6 months of 1–2 s (Reznick et al., 2004) and 3–5 s delays (Gilmore & Johnson, 1995), with performance increasing to 10–20 s by 9 months (Schwartz & Reznick, 1999). Furthermore, memory durability was reported to undergo significant developmental improvement, linearly increasing by approximately 2 s each month of development from delays of 2 s at 7.5 months to 12 s at 12 months (Pelphrey et al., 2004). Another developmental study of Delayed Response reported success at 250 ms delays by 8 months, with performance improving to success at 9 s by 12 months (Brody, 1981).

Change Detection

The *Change Detection* visual memory task requires infants to assess changes across multiple-item arrays over a short delay. In a typical trial, infants are presented with a set of objects appearing in discrete positions on the screen that each contains a given number of specific stimulus features (e.g., size, color). Following initial array presentation, a delay is imposed in which the infant is meant to maintain information in memory. After the delay, the array re-appears, with one stimulus having changed features (e.g., color). During this phase, oculomotor fixations and looking times are recorded. If the infant's first fixation or total looking time is directed to the changed target stimulus, the trial is coded as a pass.

Studies using the Change Detection task in infancy have also reported notable developmental performance improvements. In one study, for example, 6- and 8-month-olds were shown a pair of two object arrays with a delay of 317 ms between arrays, 8-month-olds exhibited a preference for an item that changed color, evidence that memory for that item persisted across the delay. Six-month-olds exhibited no evidence for object memory under these conditions, but when the initial pair of squares was identical, they showed preference for the changed item, indicating successful memory (Oakes, Baumgartner, Barrett, Messenger, & Luck, 2013).

The *Change Preference* task was developed for younger infants and is thought to tap the same construct as the Change Detection task. In the Change Preference task, infants view two separate screens in alternation, one displaying constant stimulus arrays and the other displaying arrays with a color change. Set size is manipulated by varying the number of stimuli in each array. Six-month-olds were found to look significantly longer to changing streams of one object, and 10- to 13-month-olds looked significantly longer to changing streams with displays of up to four objects (Ross-Sheehy et al., 2003). A second Change Preference study found that 6.5-month-olds did not perform successfully on three-item arrays with 300 ms delays, but 7.5- and 12.5-month-olds were successful, with no improvement after 7.5 months. These results were attributed to development of an ability to bind features and store multiple objects between 6.5 to 7.5 months, a process mediated by the posterior parietal cortex and likely related to focused attention (Oakes, Ross-Sheehy, & Luck, 2006; Oakes et al., 2013).

Delayed Match Retrieval

The *Delayed Match Retrieval* task is an oculomotor-adapted delayed match-to-sample paradigm that assesses visual memory for object-location bindings by utilizing anticipatory gaze responses as the dependent measure (Kaldy, Guillory, & Blaser, 2016). Infants are initially presented with an array of three face-down virtual playing cards. Two cards are sequentially revealed, followed by a delay during which all cards are again face down, and then revealing of the third card. If infants look immediately to the corresponding face-down card that matches the remaining face-up card, the trial is coded as a pass. Kaldy et al. found that 10- month-olds, but not 8-month-olds, performed significantly above chance levels for delays of 1.5 s, indicating successful memory for object-location information.

Taken together, these findings demonstrate that early memory processes can be indexed by 6 months, as measured by a variety of unique tasks, and that performance improves with age. Notably, however, estimates of early visual memory durability are highly variable across different tasks for same-aged infants. For example, estimates of memory durability in 8-month-olds in Delayed Response studies ranged from 250 ms (Brody, 1981) to 2 s (Pelphrey et al., 2004). Furthermore, results across studies suggest infants are able to perform successfully at longer delays in Delayed Response tasks versus Change Detection and Delayed Match Retrieval tasks, presumably due to differences in task demands. For example, 12-month-olds showed evidence for retaining spatial information for a single object at delays up to 12 s in a Delayed Response task (Pelphrey et al., 2004), but in a Change Preference task, 12.5-month-olds failed to discriminate arrays of set size three for delays around 300 ms (Oakes et al., 2013). In a Delayed Match Retrieval task, 10.5-month-olds retained location information for two distinct stimuli in memory for only 1.5 s (Kaldy et al., 2016).

The goal of the present exploratory study was to examine infant performance in these three tasks to determine effects of age and delay duration, and to compare performance across tasks. Systematic investigations of the conditions under which early memory operates, including the scope and limits of its durability, will be important for understanding how memory comes to affect cognitive functions in later life. Here, we present a cross-sectional study examining developmental improvements in infant visual memory durability using a novel testing battery consisting of three tasks that have been previously investigated with infants: *Delayed Response* (Diamond & Doar, 1989), *Change Detection* (Oakes et al., 2006), and *Delayed Match Retrieval* (Kaldy et al., 2016).

Present Study

This study assessed infant memory using a battery of tasks to index the temporal boundaries and developmental growth of visual memory durability in the first postnatal year. Our novel testing battery utilized a gaze-contingent eye tracking method and recorded infants' first fixations to target stimuli as the principal measure of performance. The study sought to address three key aims:

1. Investigate the age-appropriateness of three unique infant memory tasks.
2. Investigate the impact of delay duration (i.e., increasing temporal delay) on performance.
3. Investigate age-related performance developments and correlations between performance on individual tasks.

Method

Participants

Forty-nine healthy full-term infants ranging from 6 to 12 months (M_{age} = 8.87 months, Median age = 8.80 months, SD = 1.75, male = 25) participated in the study. Infants were recruited from the greater Los Angeles area from birth record lists provided by Los Angeles County. Each infant made a single visit to the lab where their performance was assessed on Delayed Response, Change Detection, and Delayed Match Retrieval tasks. Infants were also assessed on two versions (eye tracking and experimenter-based) of the A-Not-B task (Piaget, 1955), results of which are not reported in this paper. An additional 10 infants were observed but not included in the final sample from loss of data due to fussiness. Infants included in the final sample completed all trials for all tasks in the testing battery (including the A-Not-B tasks). The dates of data collection were between September 2016 and September 2017. The age breakdown of the final sample was as follows: 6–6.9 months (n = 10), 7–-7.9 months (n = 9), 8–8.9 months (n = 6), 9–-9.9 months (n = 7), 10–10.9 months (n = 9), and 11–11.9 months (n = 8). The ethnic/racial background of the final sample was as follows: White (n = 17), Multi-Racial (n = 16), Latino (n = 9), Middle Eastern (n = 3), Asian (n = 2), and South Asian (n = 2). Families received a gift for their participation consisting of either a shirt, bottle, or small toy.

Eye Tracking Apparatus

An SR Eyelink 1000 eye tracking system with a 56 cm color monitor (SR Research Ltd., Osgoode, Canada) was used to display stimuli and collect oculomotor data. Infants were seated on a parent's lap approximately 60 cm from the monitor. Prior to testing, each infant's point of gaze was calibrated using the standard calibration routine provided by the SR Eyelink software. The five-point calibration process began by presenting an attention-getting stimulus at the middle of the screen, as well as at each of the screens' four corners, as the infant looked toward each of the five locations in a random order. The experimenter controlled the calibration's progression by advancing to the next fixation location upon the infant's successful fixation to the current location. If the calibration result was poor for a particular fixation location, that calibration point was repeated until successful. Calibration was validated by presenting the same five stimuli at each of the five prior locations. If the validated fixations were within 1° visual angle error from the calibration fixations, the calibration was considered acceptable and the experimenter advanced to presentation of the eye tracking test battery. If the validation fixations did not meet this criterion, the calibration was repeated until this threshold was met.

Tasks within the test battery were programmed with Experiment Builder, the proprietary stimulus presentation software associated with the SR eye tracker. A separate computer was used to control stimulus presentation and send time-dependent markers to be stored with the eye tracking data, allowing for the coordination of participants' eye movements with the respective stimuli. The eye tracking system recorded point-of-gaze coordinates (spatial resolution within 1.0° visual angle) at 500 Hz. Eye fixation locations and gaze durations to the whole scene as well as within specific areas of interest (AOIs) encompassing stimuli on the screen were recorded for each infant. We utilized fixation triggers in the SR Experiment Builder software to implement gaze-contingency (a fixation within a specified AOI for a certain amount of time) to advance individual trials, thus providing automated scoring of memory performance based on infants' fixations.

Eye Tracking Test Battery

Delayed Response

Each trial began with a salient "attention-getter" to re-center the infant's gaze on the screen (see Figure 1). Following this, a cueing stimulus appeared on either the left or right and remained on the screen for 1,500 ms. Next, the re-centering attention-getter appeared for a variable duration (500, 750, 1,000, and 1,250 ms), followed by two identical colored shape targets appearing at both peripheral sides of the screen. If the infant first looked to the same side as the previously cued stimulus, the trial ended (contingent upon the infant's gaze to that location) and it was coded as a pass; otherwise the trial ended after 1,500 ms. Following the end of the trial, an attention-getter appeared and the next trial began. Eye-gaze data after delay periods were recorded and analyzed to determine if infants successfully maintained memories for cue stimulus locations. Infants were tested using 16 total trials split into four blocks with delay intervals of 500, 750, 1,000, and 1,250 ms. Task success was determined by whether the infant's first fixation was to the AOI of the correct previously cued peripheral location, either on the left or right side of the screen. Thus, chance level performance in Delayed Response was 50% (left vs. right).

It is important to note that our implementation of Delayed Response had one significant departure from the traditional task. Delayed Response measures duration of memory for a hiding event through the use of hiding wells, but our implementation instead utilized a disappearing cue. We decided to forgo a hiding event as infants in our testing battery were already tested on two similar hiding event test procedures (implementations of the A-Not-B task using both real-world and virtual hiding wells).

Change Detection

Each trial began with an attention-getter centered on the screen (see Figure 2). Three same-sized, differently colored squares then appeared in random positions on the screen and remained visible for 5,000 ms. Next, an attention-getter appeared for a variable delay, after which the array of squares reappeared, one of which had changed color. The array remained on the screen for 5,000 ms, or until the infant first fixated on the changed square, whereupon the display ended (i.e., contingent upon the infant's gaze to that location). Following the end of the trial, an attention-getter appeared prior to the beginning of the next trial. The trial was coded as a pass if the infant's first fixation was to the changed square. Positions of squares within the arrays were randomized for each trial. Infants were tested using 16 total trials split into four blocks with delay intervals of 500, 750, 1,000, and 1,250 ms. Task success was determined by whether the infant's first fixation was to the AOI of the changed square. Thus, chance level performance in Change Detection was 33.3% (Square 1 vs. Square 2 vs. Square 3).

It is important to note that our implementation of Change Detection had one significant departure from the traditional task. The traditional Change Detection task typically uses 500–1,000 ms

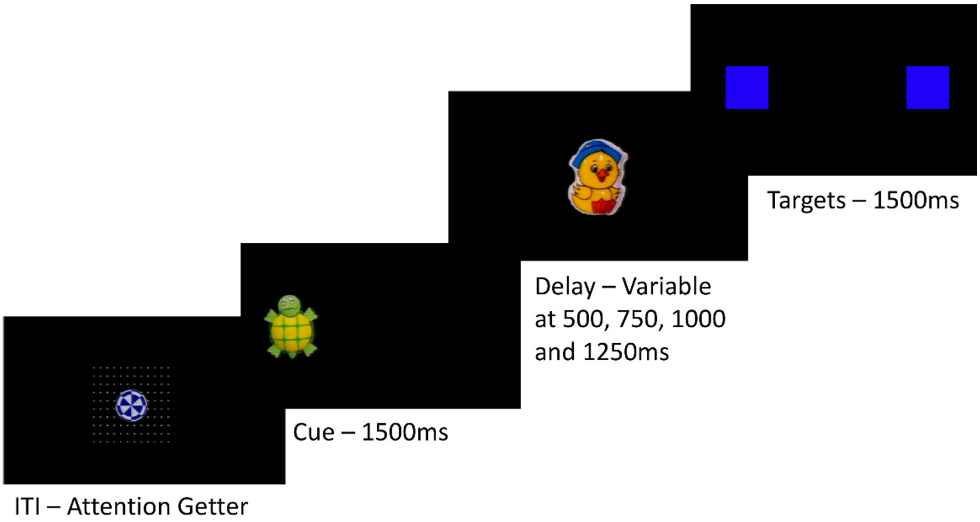

Figure 1. Delayed response. Infants are presented with a centering stimulus, followed by a cue presented in a peripheral location (left or right) lasting for 1,500 ms. Following the cue, a variable delay is imposed, consisting of delay periods of 500, 750, 1,000, and 1,250 ms. Following the delay, two identical targets are presented and remain on the screen for 1,500 ms. Task success is determined by whether the infant first fixates on the areas of interest of the target appearing on the same peripheral side of the screen that the cue was previously shown.

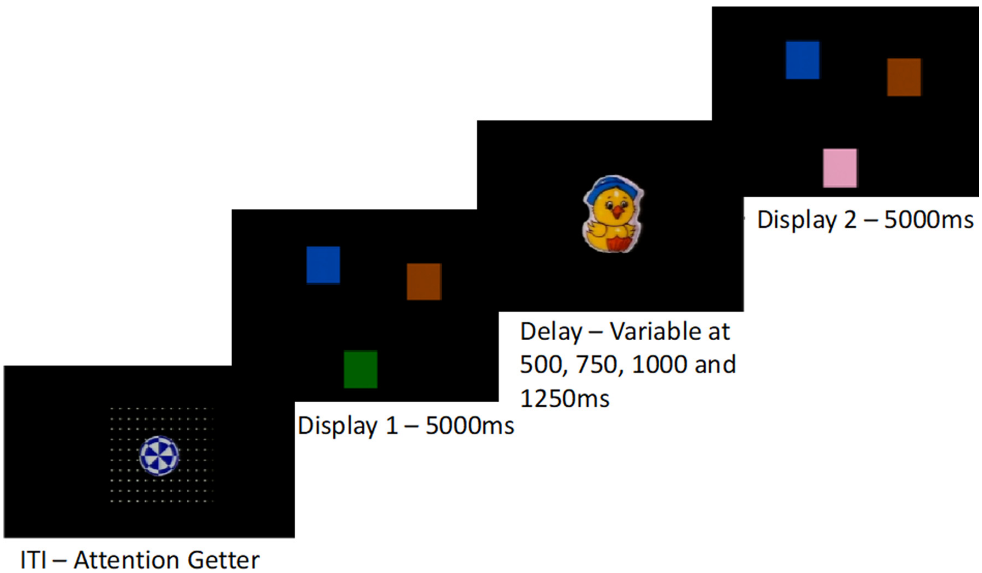

Figure 2. Change detection. Infants are presented with a centering stimulus, followed by an array of three differently colored squares remaining on the screen for 5,000 ms. Following the array, a variable delay is imposed consisting of delay periods of 500, 750, 1,000, and 1,250 ms. Following the delay period, the array of squares re-appears, except that one square's color changed. Task success is determined by whether the infant first fixates on the areas of interest of the square that changed color.

durations for encoding arrays, while our version utilized a 5,000 ms encoding duration. We decided to use a longer encoding period because infants did not perform successfully on the task in our piloting with brief encoding durations.

Delayed Match Retrieval

Each trial began with an attention-getter centered on the screen (see Figure 3). Three face-down cards then appeared. Each card slid in from the

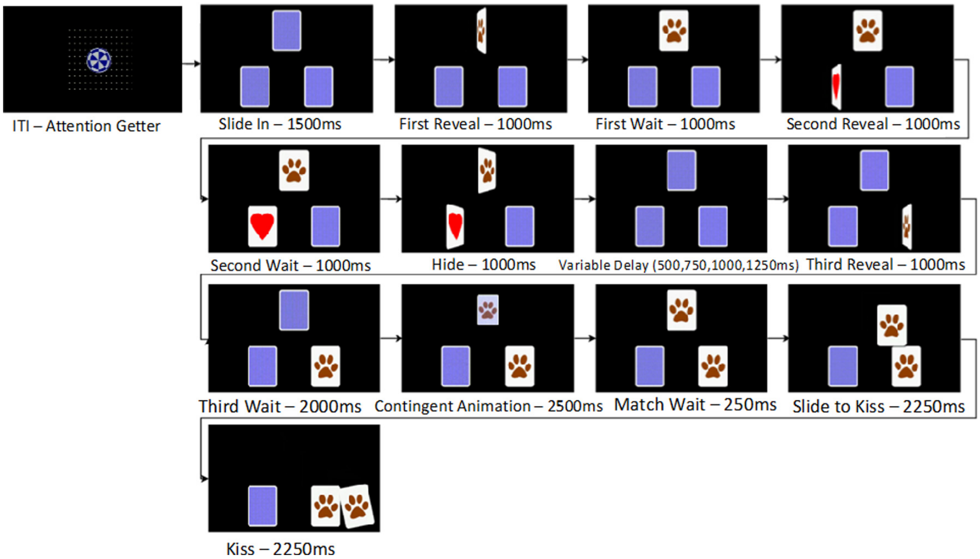

Figure 3. Delayed match retrieval. Infants are presented with a centering stimulus, followed by three face-down cards. One of the cards flips over to reveal its pattern and remains flipped-up while a second card on the screen also flips over to reveal its pattern. Following the flipping of these first two cards, the cards flip back downward, hiding the card's pattern. While the cards remain face-down, a variable delay period was introduced consisting of delay durations of 500, 750, 1,000, and 1,250 ms. Following the delay period, the third card that was previously unexposed flips face-up to reveal its pattern and remains flipped up for 2,000 ms. Task success is determined by whether the infant first fixates on the areas of interest of the face-down card that matches the pattern of the exposed card on the screen.

side and remained face-down for 1,500 ms. The first card was then flipped face-up and remained on the screen for 2,000 ms, followed by the second card in the same fashion. Next, the two face-up cards were flipped back face-down for 1,000 ms. Once the cards were flipped face-down, they remained face-down for a variable delay, after which the card that was previously unexposed was flipped face-up and remained on the screen for 2,000 ms. If the first fixation was to the corresponding face-down card, the infant was "rewarded" with a small salient animation over the correct card, followed by an animation that brought the two cards together in a kiss, accompanied by a kissing sound (Kaldy et al., 2016), and the trial was coded as a pass. The kissing animation lasted for 5,000 ms. If the infant's first fixation was not to the matching face-down card, the two cards still "kissed" to reinforce the rule for future trials, but the infant did not receive a salient animation. Following the end of the trial, the attention-getter appeared, and the next trial commenced. The Delayed Match Retrieval task requires observers to encode and maintain two relevant features (color, shape) for two cards, as well as their spatial locations, in memory. Therefore, infants are required to encode three stimulus features (color, shape, location) to succeed on the task. Infants were tested using 16 total trials split into four blocks with delay intervals of 500, 750, 1,000, and 1,250 ms. Task success was determined by whether the infant's first fixation was to the AOI of the matching face-down card. Thus, chance level performance in Delayed Match Retrieval was 50% (Face-up card 1 vs. Face-up card 2).

It is important to note that our implementation of Delayed Match Retrieval had one significant departure from the traditional task. The traditional Delayed Match Retrieval task utilizes training trials, but our implementation did not. We decided to forgo training trials to standardize the testing battery, as none of the other tasks in the battery utilized them.

General Eye Tracking Method

The eye tracking assessment was presented in a blocked fashion. Each block consisted of a single task and the order of tasks was counterbalanced for all infants (including the A-Not-B tasks not reported here) using a balanced Latin square. Each task was composed of 16 total trials, testing infants with four trials for each delay duration (500, 750, 1,000, and 1,250 ms). Thus, for each task, infants completed four trials for each delay in a randomized order.

Individual trials across all tasks were composed of three segments. The first segment introduced the stimuli to be encoded and stored in memory. The second segment served as a delay period: a black screen with a centered stimulus to re-orient attention (Delayed Response, Change Detection), or an interval during which cards were face-down (Delayed Match Retrieval). This variable delay period allowed us to test for maintenance of memory traces when delay duration is increased (see below). During the final segment, stimuli re-appeared and the infant's first fixation (100 ms minimum fixation duration) to the target stimuli was recorded. A time limit was imposed for each trial during the final segment (Delayed Response—1,500 ms, Change Detection—5,000 ms, Delayed Match Retrieval—2,000 ms) in which infants' responses were recorded and coded for one of three possible outcomes:

1. The trial was coded as a *pass* if the infant's first fixation was to the correct target stimulus' AOI (within the allotted time).
2. The trial was coded as a *fail* if the infant failed to make a first fixation to the correct target stimulus' AOI.
3. The trial was also coded as a *fail* if the infant never fixated on the correct target stimulus' AOI.

Memory Durability

Delay durations were directly manipulated within the tasks (500, 750, 1,000, and 1,250 ms) to assess temporal limits of early visual memory durability. Delay durations were randomized within each task. We hypothesized that average performance would decrease as delay duration increased.

Results

Each trial was binary-coded as either a pass (1) or fail (0), based on the infant's first fixation to the AOI of the correct target stimulus following the end of the delay period. Each task was composed of 16 trials split into four blocks, with each block consisting of four trials of each delay duration (500, 750, 1,000, and 1,250 ms). We utilized a combination of analyses—including chance level t-tests, correlations, and modeling—to test our different hypotheses.

Chance Levels

To compare against chance levels, performance was operationalized as a ratio computed using the total number of passes versus fails for each task and delay duration. For example, if an infant correctly fixated on three out of four 1,250 ms trials in a task, their performance score for that task would be 0.75 for 1,250 ms delays. For each task, average performance was computed across all ages for the various delay durations (see Figure 4). Deviations from chance level performance were computed for the effects of task type, delay duration, and age on performance using two-tailed one-sample t-tests with Bonferroni-adjusted p-values.

Task Type

First, we examined performance for each task by collapsing across age and delay, using a Bonferroni adjusted p-value of .0167 (three comparisons). Average performance was significantly higher than chance levels (50%) for Delayed Response (M = .579, SD = .161, $t(48) = 2.994$, $p = .004$, $d = 0.422$), significantly higher than chance levels (33.3%) for Change Detection (M = .545, SD = .184, $t(48) = 8.09$, $p < .001$, $d = 1.147$), and not different from chance levels (50%) for Delayed Match Retrieval (M = .451, SD = .250, $t(48) = -1.364$, $p = .179$, $d = -0.168$).

Delay Duration

Next, we examined the effect of increased delay duration on performance for each task, collapsed across age, using a Bonferroni adjusted p-value of .0125 (four comparisons). For Delayed Response,

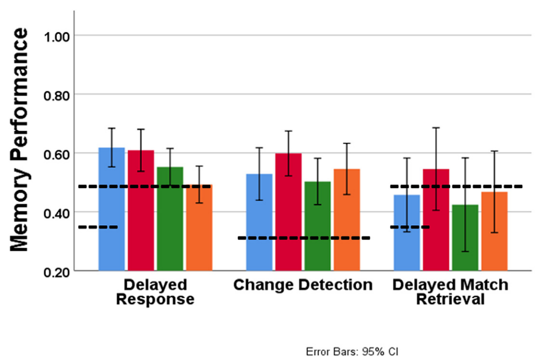

Figure 4. Average memory performance by task and delay duration. Memory performance was computed for all infants and separated by task and delay duration. Infants performed significantly above chance levels (denoted by a dotted line) in Delayed Response (50%) and Change Detection (33.3%), but performance did not differ from chance in Delayed Match Retrieval (50%). Chance level performance is shown by the dotted black line. Error bars are displayed with 95% confidence intervals.

infants performed significantly above chance levels (50%) for 500- (M = .618, SD = .230, $t(48)$ = 3.61, p = .001, d = 0.513) and 750 ms (M = .609, SD = .250, $t(48)$ = 3.063, p = .004, d = 0.436) delays, but performance did not differ from chance levels for 1,000- (M = .553, SD = .220, $t(48)$ = 1.675, p = .100, d = 0.241) and 1,250 ms (M = .493, SD = .220, $t(48)$ = −0.227, p = .821, d = −0.318) delays. For Change Detection, infants performed significantly above chance levels (33.3%) for 500- (M = .529, SD = .313, $t(48)$ = 4.395, p < .001, d = 0.626), 750- (M = .599, SD = .267, $t(48)$ = 6.96, p < .001, d = 0.996), 1,000- (M = .546, SD = .305, $t(48)$ = 4.324, p < .001, d = 0.698), and 1,250 ms (M = .503, SD = .276, $t(48)$ = 4.89, p < .001, d = 0.616) delay durations. For Delayed Match Retrieval, performance did not differ from chance levels (50%) for 500- (M = .458, SD = .430, $t(48)$ = −0.676, p = .502, d = −0.098), 750- (M = .505, SD = .426, $t(48)$ = 0.648, p = .521, d = 0.012), 1,000- (M = .468, SD = .421, $t(48)$ = −0.949, p = .350, d = −0.076), and 1,250 ms (M = .468, SD =.422, $t(48)$ = −0.461, p = .648, d = −0.076) delay durations.

Age

Lastly, we examined the developmental progression of task performance by collapsing across delays, using a Bonferroni adjusted p-value of .0083 (six comparisons). For Delayed Response, infants did not perform different from chance levels (50%) at 6 (M = .463, SD = .180, $t(9)$ = −0.660, p = .526, d = −0.206), 7 (M = .500, SD = .108, $t(8)$ = 0.000, p = 1.00, d = 0.000), 8 (M = .583, SD = .129, $t(5)$ = 1.581, p = .175, d = 0.643), or 9 months (M = .598, SD = .148, $t(6)$ = 1.754, p = .130, d = 0.662). However, performance improved to marginally greater than chance by 10 (M = .632, SD = .138, $t(8)$ = 2.873, p = .021, d = 0.957) and 11 months (M = .668, SD = .176, $t(7)$ = 2.708, p = .030, d = 0.955). For Change Detection, infants performed marginally above chance levels (33.3%) at 6 (M = .475, SD = .165, $t(9)$ = 2.729, p = .023, d = 0.861) and 7 months (M = .486, SD = .179, $t(8)$ = 2.567, p = .033, d = 0.855). However, performance rose to significantly greater than chance levels by 8 (M = .552, SD = .294, $t(5)$ = 1.824, p = .003, d = 0.745), 9 (M = .613, SD = .156, $t(6)$ = 4.741, p = .003, d = 1.795), 10 (M = .542, SD = .165, $t(8)$ = 3.786, p = .005, d = 1.261), and 11 months (M = .633, SD = .147, $t(7)$ = 5.757, p = .001, d = 2.034). For Delayed Match Retrieval, infants did not perform greater than chance levels at any age (6 months: M = .471, SD = .258, $t(9)$ = −0.357, p = .729, d = −0.113; 7 months: M = .338, SD = .262, $t(8)$ = −1.858, p = .100, d = −0.618; 8 months: M = .572, SD = .295, $t(5)$ = 0.596, p = .577, d = 0.244; 9 months: M = .441, SD = .288, $t(6)$ = −0.544, p = .606, d = −0.205; 10 months: M = .508, SD = .205, $t(8)$ = 0.114, p = .912, d = 0.039; 11 months: M = .459, SD = .175, $t(7)$ = −0.670, p = .524, d = −0.234).

Correlations

Correlations were calculated between age and individual task performance, as well as for performance between each task. Overall, infants' performance between individual tasks was not correlated. Specifically, Delayed Response performance was not correlated with Change Detection performance (r = .136, p = .352) or Delayed Match Retrieval performance (r = .145, p = .319), and Change Detection performance was not correlated with Delayed Match Retrieval performance (r = .038, p = .798). However, there were significant correlations between age and performance for two tasks: Delayed Response (r = .461, p = .001) and Change Detection (r = .309, p = .031). The correlation between age and Delayed Match Retrieval performance was not significant (r = −.001, p = .995). Scatterplots were produced to visualize the relation between age and performance (see Figure 5).

Correlations were also conducted between age and individual task performance for each delay duration (see Figure 6). Infants' Delayed Response performance was significantly correlated with age for 500- (r = .367, p = .009), 750- (r = .319, p = .025), and 1,250 ms (r = .373, p = .008) delays, but not for 1,000 ms (r = .208, p = .151) delays. Infants' Change Detection performance was significantly correlated with age for 500 ms (r = .312, p = .029) delays, but not for 750- (r = .007, p = .960), 1,000- (r = .182, p = .211) or 1,250 ms (r = .265, p = .065) delays. Infants' Delayed Match Retrieval performance was not correlated with age for 500- (r = .024, p = .871), 750- (r = .022, p = .884), 1,000- (r = −.035, p = .815), or 1,250 ms (r = .017, p = .908) delays.

Generalized Linear Mixed Model

To compare performance across the different tasks, delays, and ages (i.e., to determine the extent to which task, delay duration, and age predicted performance), we modeled our data using a Generalized Linear Mixed Model (GLMM) with logit function. This analysis was most appropriate for

Figure 5. Developmental trajectories in memory performance by task. Developmental trajectories are plotted for individual tasks. Average performance for each task was collapsed across all delay durations and is plotted along the *Y*-axis, whereas age is plotted along the *X*-axis. The resulting R^2 linear values are given for the following tasks: Delayed Response ($R^2 = 0.213$), Change Detection ($R^2 = 0.095$), and Delayed Match Retrieval ($R^2 < 0.001$). For Delayed Response, results suggest linear increases in average memory performance from above 40% at 6 months to above 60% at 12 months. For Change Detection, average memory performance also increased linearly from above 40% at 6 months to above 60% at 12 months. For Delayed Match Retrieval, average memory performance showed no age-related increases.

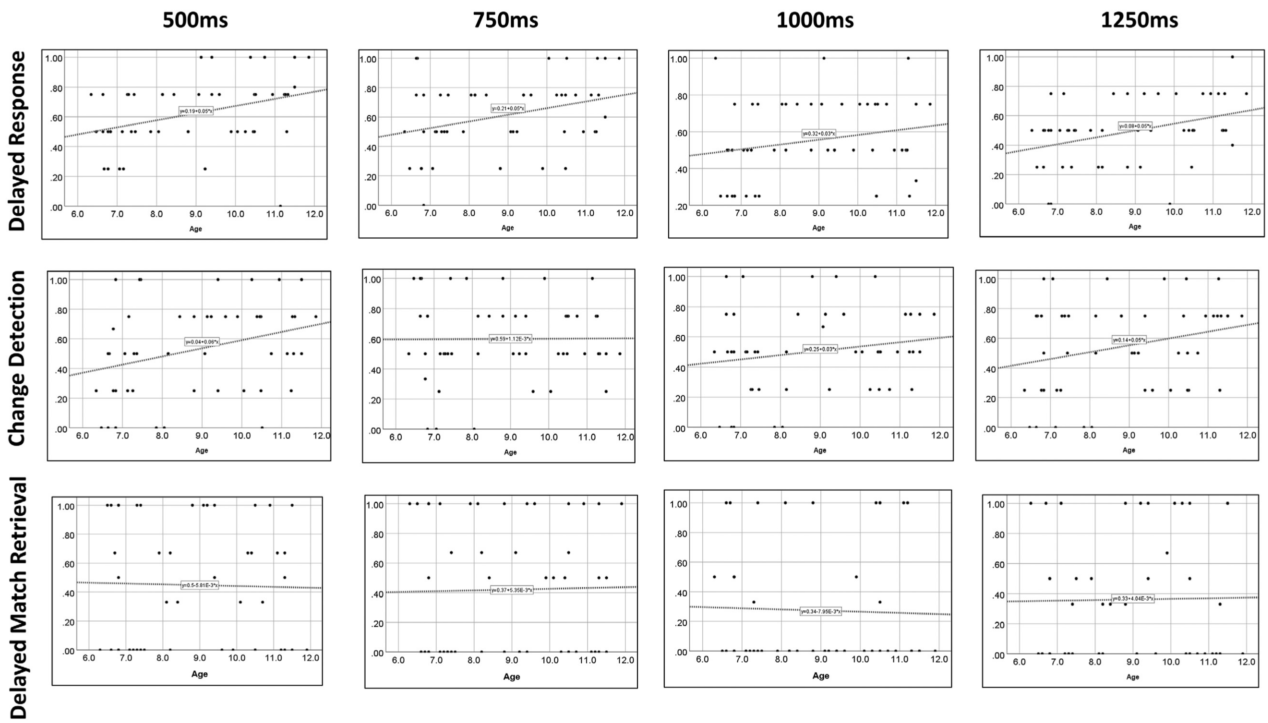

Figure 6. Developmental trajectories in performance by task and delay. Developmental trajectories are plotted by each delay period for individual tasks. Average performance for each task is plotted along the *Y*-axis, whereas age is plotted along the *X*-axis. The resulting R^2 linear values are given for the following tasks and delays: Delayed Response (500 ms: $R^2 = 0.135$, 750 ms: $R^2 = 0.102$, 1,000 ms: $R^2 = 0.043$, 1,250 ms: $R^2 = 0.139$), Change Detection (500 ms: $R^2 = 0.097$, 750 ms: $R^2 < 0.001$, 1,000 ms: $R^2 = 0.033$, 1,250 ms: $R^2 = 0.070$), and Delayed Match Retrieval (500 ms: $R^2 < 0.001$, 750 ms: $R^2 < 0.001$, 1,000 ms: $R^2 = 0.001$, 1,250 ms: $R^2 < 0.001$). For Delayed Response, results suggest age-related increases in average performance from 6 to 12 months across all delay durations. For Change Detection, average performance also increased linearly across age for all delays except for 750 ms. For Delayed Match Retrieval, average performance showed no age-related increases across any delays.

our data set because our dependent measure for each trial was a binary outcome and GLMM allows for use of both quantitative and qualitative predictor variables using logistic regressions. The predictor variables included were as follows: task type (Categorical: Delayed Response, Change Detection, Delayed Match Retrieval), delay duration (Categorical: 500 ms, 750 ms, 1,000 ms, 1,250 ms),

Table 1
Generalized Linear Mixed Model (GLMM) fixed Coefficients. The fixed coefficients output from the GLMM utilized task type, delay duration, and age. The reference variables for the analysis include delayed match retrieval (task reference) and 1,250 ms (delay reference). Log odds are noted in the column labeled "coefficient." Odds ratios are noted in the column labeled "Exp(Coefficient)." The intercept term is Included, but should not be meaningfully Interpreted

Model term	Coefficient	Exp(Coefficient)	*SE*	*t*	Sig.
Intercept	−1.583	0.205	1.253	−1.264	.207
Delayed Response	.483	1.621	0.146	3.320	.001
Change Detection	.390	1.477	0.155	2.521	0.012
Delayed Match Retrieval	0	Reference			
500 ms delay	.243	1.258	0.133	1.828	.068
750 ms delay	.388	1.474	0.136	2.851	.005
1,000 ms delay	.060	1.062	0.132	0.458	.647
1,250 ms delay	0	Reference			
Age	.136	1.145	0.028	4.775	< .001

and age (Continuous: months). The dependent variable, performance, was computed by the model using each infant's total number of binary-coded passes for each trial as the numerator and number of possible trials as the denominator. The results of the GLMM fixed effects output indicated that task type ($F(2,529) = 5.512$, $p = .004$), delay duration ($F(3,216) = 3.938$, $p = .009$), and age ($F(1,446) = 20.457$, $p < .001$) were all significant predictors of performance.

Task Type

Average performance across tasks was compared in terms of log odds from the logit distribution (see Table 1). Performance differences were most apparent when contrasting Delayed Match Retrieval and Delayed Response; specifically, performance significantly increased by log odds of .483 ($p = .001$, $SE = 0.146$, 95% CI [.197, .769]) when tested with Delayed Response. When comparing performance on Delayed Match Retrieval to Change Detection, performance significantly increased by log odds of .390 ($p = .012$, $SE = 0.155$, 95% CI [.086, .694]) when tested with Change Detection.

Delay Duration

Average performance across delays was compared in terms of log odds from the logit distribution (see Table 1). Performance differences were most apparent when contrasting delays of 750 ms and below and delays of 1,000 ms and above. Specifically, log odds increased by .243 when comparing performance on 1,250- versus 500 ms trials ($p = .068$, $SE = 0.133$, odds ratio = 1.275, 95% CI [−.018, .504]), and increased by .388 when comparing 1,250- versus 750 ms trials ($p = .005$, $SE = 0.136$, 95% CI [.121, .655]). In contrast, log odds only increased by .060 on 1,250- versus 1,000 ms trials ($p = .647$, $SE = 0.132$, 95% CI [−.198, .319]).

Age

The coefficient associated with the continuous age predictor revealed that for every 1 month increase in age, the log odds of passing a given trial significantly increased by .136 across all tasks and delays ($p < .001$, $SE = 0.027$, 95% CI [.081, .190]).

Discussion

This study is the first to assess infants' performance on a visual memory task battery with the goal of indexing the scope, temporal boundaries, and development of early memory abilities in the first postnatal year. We investigated two key components of infant visual memory—durability and developmental trajectories—using three unique tasks, and the results help inform our understanding of how memory durability improves in infancy and how it may be quantified in early development.

Age-Appropriateness

The first goal of this study was to assess the age-appropriateness of each task (Delayed Response, Change Detection, and Delayed Match Retrieval) by comparing relative performance against chance levels. We accomplished this using two-tailed one-sample *t*-tests with Bonferroni adjusted *p*-values to correct for multiple comparisons. The fixed effects GLMM output also indicated that task type significantly predicted performance across the entirety of the testing battery, over and above the other variables.

Collapsed across age and delay, average performance was significantly higher than chance levels for Delayed Response, and displayed a medium effect size. As suggested by previous literature, Delayed Response appears to be an appropriate test of early memory durability. For Delayed Response, infants must encode the spatial location of a single previously presented visual cue stimulus varying between one of two possible locations (left or right). Success also requires the inhibition of a prepotent response to look to the previously presented location, if it was different, and instead use memory to guide oculomotor behavior to the new location. However, at closer glance, our adaptation of Delayed Response can also be viewed as an attentional cueing task, requiring minimal memory demands (Fan, McCandliss, Sommer, Raz, & Posner, 2002) and instead reflecting exogenous cueing of spatial attention (Ross-Sheehy, Schneegans, & Spencer, 2015). As mentioned previously, this discrepancy stemmed from our decision to forgo using hiding wells and instead using a disappearing cue. Without the use of hiding wells, our implementation provides no information that the object continues to exist once occluded. On this account, infants do not necessarily have to bind a particular shape to a specific location for successful performance, rather, the abrupt cue onset may automatically capture attention to that spatial location. This may leave a lingering attentional trace at that location, prime that location, or bring it into some privileged state where the infant finds it more interesting; thus, attention may have been captured at that location and it remained there. In this case it may not be the memory of the cue's location that fades away with time, but the extent to which it signals that something interesting will be presented on that side. An analogy is to consider when your cellular phone makes a noise when receiving an incoming message. You only have a few seconds to check the message displayed on the screen before it dims, but if you do not look at the message, it is not the result of having forgotten there was a noise. Therefore, although we believe that memory is still required to succeed on the task, the aforementioned attentional confounds cannot be ruled out as contributing to Delayed Response performance.

Collapsed across age and delay, average performance was also significantly higher than chance levels for Change Detection, and displayed a large effect size. As suggested by previous literature, Change Detection also appears to be an appropriate test of early memory durability. However, it is important to note that average performance (54.5%) was slightly lower (see Figure 4) when compared with Delayed Response (57.9%), perhaps because the Change Detection task was more cognitively demanding. For Delayed Response, the object's location is the only relevant stimulus feature to be encoded; therefore, maintenance of other stimulus features (such as the cue stimulus' color or shape) is not required for successful performance. However, during each Change Detection trial, infants are required to encode colors and spatial locations of three individually colored squares and retain that memory over the delay. Following the delay, infants must again encode the new array of three squares and identify the changed square by comparing new information with previously encoded information held in memory. Infants must encode the color of each square as well as their respective spatial locations in the array—two features (color, location) for each item—as opposed to one feature (location) in Delayed Response.

It is also important to note that we have emphasized the use of our testing battery for investigating shorter term visual memory processes, but the 5,000 ms encoding familiarization period utilized in our Change Detection task may have been long enough to tap longer term memory systems. Thus, successful performance may have also been driven by ensemble processing (e.g., mean color change across arrays) and allocation of global attention (Brady & Tenenbaum, 2013; Pailian & Halberda, 2015). The longer encoding period may have also allowed for two critical attentional processes that could both influence performance beyond just the use of STM: (a) fixation of each square in the encoding array and (b) sufficient time to encode the entire array (either piecemeal or holistically) into longer term memory. Since infants' developing attention skills may influence their ability to rapidly disengage and re-fixate in the context of virtual competition, and since fixations to specific items during encoding are likely to facilitate memory, these age-related findings may also represent a capacity-like pattern of visual attention. We addressed this possibility with a follow-up analysis. We calculated each infants' total number of fixations during the 5,000 ms encoding period and included it as the outcome variable in a regression model with age as the predictor. The overall regression model was significant ($R = .335$, $R^2 = .112$, $R^2_{\text{Adj}} = .095$, $df = 1$, $MS = 3{,}458.515$, $F = 6.327$, $p = .015$, $f^2 = .126$), with age significantly predicting the total number of fixations during the encoding period ($B = 4.386$, $SE = 1.744$, $t = 2.515$, $p = .015$). Thus, as infants age, they make significantly more fixations during the encoding period, providing evidence that attention and longer term memory may additionally influence infant performance in the Change Detection task, beyond just the use of STM abilities. (Due to the gaze-contingent nature of this measure we were unable to examine preference for the changed square as a function of looking to the entire test array, since the test interval ended if the first fixation was to the changed square.) Tasks aimed to investigate shorter term memory processes typically incorporate brief encoding durations of less than a second. As mentioned earlier, we chose to use a longer encoding period for this task because piloting in our lab revealed that infants often did not succeed until they were given 5,000 ms to respond. The range of delays over which we examined memory durability, therefore, may involve both short- and long-term storage mechanisms. This remains a question for future research.

Collapsed across age and delay, average performance did not differ from chance levels for Delayed Match Retrieval. This task was likely the most cognitively demanding in the battery, because infants must encode three relevant features (shape, color, location) of two cards to maintain in memory over a delay until the third card is exposed. Once exposed, the third card must also be encoded and compared with stored memories of the two face-down cards. In this respect, Delayed Match Retrieval may prove to be an exceptionally challenging task for infants, suggesting that more advanced memory processes may be needed for successful performance (such as planning or reasoning). For example, Delayed Match Retrieval requires infants to make online predictions over multiple locations based on remembered information (Kaldy et al., 2016, p. 897).

Notably, we obtained no evidence for successful Delayed Match Retrieval performance even in the oldest infants we observed (up to 12 months), in contrast to successful performance at 10 months as reported by Kaldy et al. (2016). Part of the explanation for this discrepancy may stem from our paradigm's requirement for participation in multiple assessments, which are likely to place additional demands on infants' attentional and cognitive resources, and thus perhaps impair overall performance. Nevertheless, results from our Delayed Response and Change Detection tasks reflect substantial differences in performance as a function of task and age, implying that our testing battery was not overly demanding. In addition, Kaldy utilized training trials in the original version of the task, while we did not. As mentioned earlier, we chose not to include these in order to keep the tasks standardized across the testing battery, but training may be necessary for the memory effect, due to the complex causal structure of the task. (Nevertheless, our adaptation of the task reinforced learning of the causal structure. The matching cards always kissed at the end, similar to the original task, and infants received a salient reward animation when they made a correct fixation.) Successful performance on the Delayed Match Retrieval task, therefore, may rely on cognitive resources other than memory for matching face-down cards because infants also presumably learn that the correct match will be followed by something interesting (the salient animation).

Memory Durability

Our second goal was to assess the scope of early visual memory durability by examining the effect of increasing temporal delay on performance across tasks. We accomplished this by comparing average performance across various delay periods to chance levels, as well as by examining the delay duration fixed effect output from the GLMM output.

For Delayed Response, infants performed significantly above chance levels across delay durations of 500 and 750 ms (displaying medium effect sizes), but performance did not differ from chance for the highest delays of 1,000 and 1,250 ms. However, for Change Detection, infants performed significantly above chance levels across all delay durations (displaying large effect sizes), suggesting that the range of delay durations chosen did not significantly impact performance. This performance discrepancy may stem from developmental timings within different brain regions. Change Detection performance may rely on the posterior parietal cortex (Tseng et al., 2012), whereas Delayed Response performance may rely more on frontal regions (Diamond & Doar, 1989), which generally mature at a slower rate than the parietal regions. Therefore, memory durability is stronger for Change Detection than Delayed Response in part because posterior parietal cortex is relatively more functional in infants than the frontal lobe. For Delayed Match Retrieval, performance did not differ from chance levels across all delay durations.

Performance Across Tasks

Performance across tasks was not correlated for individual infants. As noted earlier, this may be due to the possibility that Change Detection and Delayed Response performance relies on maturation of different brain regions. The Change Detection, Delayed Response, and Delayed Match Retrieval tasks thus may test distinct kinds of visual memory, though their precise nature remains to be discovered. As noted, the three tasks may also pose distinct cognitive demands over the same four delay durations.

Developmental Trajectories

Our final goal was to quantify the development of visual memory durability between 6 and 12 months. We accomplished this by (a) comparing age-related performance across individual tasks to chance levels, (b) examining GLMM output related to age, and (c) examining R^2 linear values between age and performance obtained via correlation analyses.

For Delayed Response, infants' performance was not marginally different from chance until 10 months (displaying large effect sizes). For Change Detection, performance was marginally above chance starting from 6 months (displaying large effect sizes), was significantly greater than chance by 8 months (displaying larger effect sizes), and continued to improve. For Delayed Match Retrieval, infants did not perform different from chance levels at any ages. Regarding the GLMM output, the fixed effect associated with age revealed that for every 1-month increase in age, the odds of passing a given trial across the testing battery significantly increased, suggesting that older infants were more likely to perform successfully across the task battery.

Developments in performance were also examined by collapsing across delays and examining the relation between age and individual task performance based on R^2 linear values obtained from the correlation analyses. Examining these values allowed us to determine the percent of variability that age accounted for in performance for each task. For Delayed Response, collapsed across delays, there were linear increases in average performance from above 40% at 6 months to above 60% at 12 months. For Change Detection, average performance also increased linearly from above 40% at 6 months to above 60% at 12 months. For Delayed Match Retrieval, average performance showed no age-related changes from 6 to 12 months. As shown in Figure 5, the percent of variability accounted for by age in each task was as follows: Delayed Response (21.3%), Change Detection (9.5%), and Delayed Match Retrieval (< 0.01%). Our results provide evidence, therefore, for significant age-related improvements in Delayed Response and Change Detection performance, but not in Delayed Match Retrieval, between 6 and 12 months of age. Furthermore, significant correlations were found between age and performance for Delayed Response and Change Detection (indicating age-related improvement in both), but not for Delayed Match Retrieval.

Finally, age-related developments in performance were examined for individual delays between tasks as shown in Figure 6. We examined R^2 linear values obtained from the correlation analyses to determine the percent of variability that age accounted for in performance for each delay duration between tasks. For Delayed Response, age was significantly related to performance on 500, 750 and 1,250 ms delays, but not for 1,000 ms delays. For Change Detection, age was significantly correlated with performance for only 500 ms delays, but not for higher delays. For Delayed Match Retrieval, age was not correlated with performance for any delay periods.

Conclusion

This study provides new insights about fundamental memory abilities in infancy. We provided evidence that infants begin to perform marginally above chance on memory paradigms beginning from 6 to 7 months with robust improvements across tasks by 10 months. We also provide evidence regarding infant memory durability: longer delays between 500 and 1,250 ms significantly hindered performance. In addition, this study provides important tools for future research of infant memory durability. For example, the distinct nature of infants' performance in Delayed Response and Change Detection tasks may help shed light on development of different brain systems that subserve memory, in this case posterior parietal cortex and frontal areas. Despite the methodological departures we highlighted when creating the tasks limit our ability to draw firm conclusions regarding the use of STM mechanisms, results nonetheless make a substantial contribution to the literature, by providing the first-ever cross-task assessment of the joint influence of attention, STM, and long-term memory as a function of delay interval.

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