Research Article

Visual Short-Term Memory Persists Across Multiple Fixations: An *n*-Back Approach to Quantifying Capacity in Infants and Adults

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Abstract

Visual short-term memory (STM) is a foundational component of general cognition that develops rapidly during the first year of life. Although previous research has revealed important relations between overt visual fixation and memory formation, it is unknown whether infants can maintain distinct memories for sequentially fixated items or remember nonfixated array items. Participants (5-month-olds, 11-month-olds, and adults; *n* = 24 at each age) from the United States were tested in a passive change-detection paradigm with an *n*-back manipulation to examine memory for the last fixated item (one-back), second-to-last fixated item (two-back), or nonfixated item (change-other). Eye tracking was used to measure overt fixation while participants passively viewed arrays of colored circles. Results for all ages revealed convergent evidence of memory for up to two sequentially fixated objects (i.e., one-back, two-back), with moderate evidence for nonfixated array items (change-other). A permutation analysis examining change preference over time suggested that differences could not be explained by perseverative looking or location biases.

Visual short-term memory (STM) is a critically important memory system that underpins cognitive functions such as interpreting incoming sensory information, performing mental operations, and acting on goals (Baddeley & Hitch, 1974; Luck & Vogel, 1997). Despite its central role in visual cognition, visual STM is highly capacity limited, with typical adult capacity estimated to be around three to four objects (Luck & Vogel, 1997). Visual STM is also highly volatile, decaying in seconds or even milliseconds in the absence of active rehearsal (Baddeley & Hitch, 1994; Baddeley & Logie, 1999; Posner & Keele, 1967). Though visual STM continues to develop over the first several years of life (Cowan et al., 2005; Ross-Sheehy et al., 2021; Simmering, 2016), research with infants has demonstrated rudimentary visual STM ability as early as 4 months of life (Ross-Sheehy et al., 2003). This is important, as some amount of visual STM may be necessary to facilitate important visual learning that occurs the first months of life (Oakes et al., 2013; Ross-Sheehy et al., 2003). As in

adults, infant visual STM appears to be highly capacity limited (e.g., Ross-Sheehy & Eschman, 2019; Ross-Sheehy et al., 2003; Feigenson & Carey, 2005; Rose et al., 2001), and this may influence the kinds of things that an infant can learn. For example, being able to hold the properties of one toy in mind while examining a second toy should facilitate the detection of both shared and unique features; important categorization and learning cues (Oakes et al., 2011).

Despite a growing literature in the study of infant visual STM, developing an infant paradigm that isolates STM from longer-term memory processes continues to pose a challenge. Thus, it is unsurprising that paradigms that differ in approach (e.g., looking vs. reaching, computer images vs. three-dimensional objects, one-shot

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paradigms vs. continuous stream paradigms) subsequently produce different developmental profiles (Buss et al., 2018; Kibbe, 2015; Simmering & Perone, 2013). However, results from these tasks also highlight several points of commonality and provide valuable insight for honing developmental theory (Cowan, 2016).

In general, researchers have attempted to limit contamination from long-term memory in infant visual STM tasks by carefully controlling the duration of memory arrays. For example, Ross-Sheehy et al. (2003) used a modified paired-comparison approach and presented infants with two arrays, each containing one, two, or three differently colored squares. For each 20-s trial, the left and right arrays (i.e., *streams*) blinked on and off continuously (500 ms on, 250 ms off, 500 ms on, and so forth). On one monitor, a single randomly chosen square changed color for each repetition, and on the other monitor, the colors stayed the same across all repetitions. If infants could encode the array items within the 500-ms sample array and retain that memory across the 250-ms retention array, they should notice the color change and prefer the changing array. Thus, a significant change preference was taken as evidence of change detection. Although this dual-stream approach precludes individual capacity estimates, this research demonstrated visual STM for object features by 4 months, with marked improvements over the first year of life. Additional follow-up research narrowed this window even more, suggesting that the bulk of this development occurred between the ages of 8 and 10 months (Kaldy et al., 2016; Káldy & Leslie, 2005; Oakes et al., 2006, 2009).

Although the dual-stream procedure helped to identify critical transitions in visual STM development, one limitation of this approach is the possibility that performance may be driven by memory for the nonchanging array (Simmering, 2011; Simmering & Perone, 2013). Recent approaches have eliminated this concern by incorporating a more canonical change-detection paradigm: a single brief sample array, followed immediately by a single test array. Findings using this "one-shot" approach have revealed that infants rapidly respond to novelty, demonstrating a significant change preference within the first 300 ms of viewing (Oakes et al., 2013, 2017).

One-shot approaches have also been used to examine developmental changes in visual STM capacity. In one such task, infants and adults were shown arrays of one to four colored circles that appeared for 1,000 ms (*sample*), disappeared for 500 ms (*retention*), and then reappeared for 3,000 ms (*test*; Fig. 1, top row). Test arrays either were identical to the sample array or a single circled changed color. Change preference was calculated as the proportion of time spent looking to

Statement of Relevance

The amount of visual information we can keep in mind is limited to three or four objects, even for adults. This can make even simple tasks difficult, such as tracking other cars when driving, comparing apples at a grocer, or finding a friend in a crowded room. Limitations in this working memory may be even more critical for preverbal infants who learn through visual exploration. To measure visual working memory in adults and infants, we developed a new task (with a novel *n*-back manipulation) that tracked eye movements as participants viewed an array of four colored circles for 1.5 s. After a brief blank interval, we presented an array that was identical to the previous array or in which one of the circles had changed color. As expected, adults showed strong memory for all circles in the array. Surprisingly, infants showed a similar patten, with clear memory for the last two circles. This new approach provides strong evidence of visual working memory in infants, paving the way for assessment of individual differences in visual working memory over the life span.

the changed circle relative to total looking during the test array. Results revealed a significant change preference at Set Size 2 for both 5- and 8-month-old infants; Set Sizes 2 and 3 for 11-month-olds; and Set Sizes 2, 3, and 4 for adults (Ross-Sheehy & Eschman, 2019). Importantly, additional analyses revealed that change-preference scores were heavily influenced by incidental attention during the sample array. Specifically, if the color change during the test interval occurred at a location that infants had previously fixated during the sample interval, then change-preference scores were especially strong. If, however, the color change occurred in a location that infants had not previously fixated, then change-preference scores did not differ from chance (Ross-Sheehy & Eschman, 2019). This is consistent with recent research demonstrating that 8.5-month-olds appear to obligatorily encode overtly fixated items into visual STM (Beckner et al., 2020) and earlier research demonstrating that an exogenous attention cue can induce selective visual STM encoding for 5- and 11-month-old infants (Ross-Sheehy et al., 2011).

All of these findings suggest an important relation between overt fixation and visual STM encoding as early as 5 months of age. Although this finding is not unique to infants (Ross-Sheehy & Eschman, 2019), it is especially pronounced in infant paradigms, in which
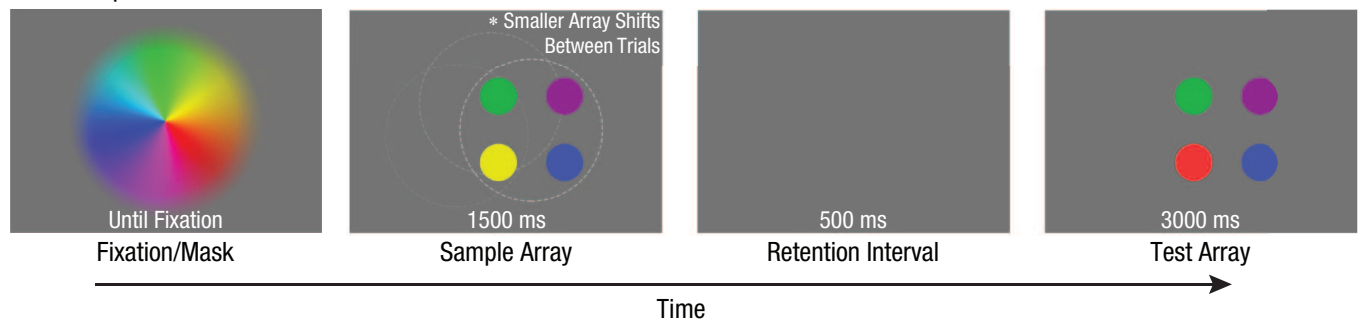
Ross-Sheehy & Eschman (2019)

Current Experiment

Fig. 1. Trial events for a previous infant change-detection study (Ross-Sheehy & Eschman, 2019; top row) and the current study (bottom row). Participants were presented with a brief sample array (previous study: 1,000-ms, current study: 1,500 ms), followed by a 500-ms retention interval, and finally a 3,000-ms test array that either was identical to the sample array (no-change condition) or varied by a single color (one-back, two-back, and change-other conditions). Condition was drawn randomly for each trial on the basis of infants' fixation behavior while viewing the sample array, with *n* corresponding to the sequence of fixated circles counting backward from the end of the sample-array interval. For the one-back condition, the circle that changed color was the last circle fixated during the sample array; for the two-back condition, the second-to-last circle fixated changed; for the change-other condition, one of the nonfixated circles changed; and for the no-change condition, the test and sample arrays were identical. Note that the test array for all change trials was followed by a brief audiovisual animation presented in the location of the color change (not pictured).

relatively long sample intervals (e.g., 1,000 ms) allow for multiple eye movements. This is typically not the case in adult paradigms, as sample intervals are often very short (e.g., 100 ms), preventing eye movements and reducing the confounding effects of obligatory encoding (Adam et al., 2017; Bays et al., 2009; Luck & Vogel, 1997; Wolff et al., 2017). Another key difference between tasks that have been designed for infants and tasks created for toddlers and adults is that infant tasks necessarily rely on visual responses. Thus, whereas toddlers and adults can perform an explicit memory task and speak, point, or press a key to indicate a response, infants can only passively view arrays, and responses are typically inferred on the basis of differences in look durations.

Clearly, visual STM performance is influenced not only by memory development and capacity but also by exogenous attention and overt fixation (Beckner et al., 2020; Cheng et al., 2019; Ross-Sheehy & Eschman, 2019; Ross-Sheehy et al., 2011), and these factors continue to interact in complex ways over the course of development (Kwon et al., 2013; Rose et al., 2001; Ross-Sheehy & Eschman, 2019; Ross-Sheehy et al., 2003). Despite these advances in our understanding of visual STM

development, several questions remain unanswered. For example, although overtly fixated array items are obligatorily encoded into visual STM, it remains unclear whether infants can remember multiple sequentially fixated array items and whether any nonfixated array items are encoded into visual STM. In addition, it is unclear whether developmental improvements in change detection are driven by improvements in visual STM mechanisms or whether orienting and/or attentional deficits contribute to developmental effects. Finally, it is currently unclear whether effects observed in infant tasks are unique to infants or whether adults tested in the same passive task would produce qualitatively similar effects, albeit with higher capacity.

In the current study, we explored these questions using a one-shot passive change-detection paradigm modeled after previous work (Ross-Sheehy & Eschman, 2019). However, unlike previous research, the current study incorporated a gaze-contingent color-change manipulation in which the change location was selected on the basis of the sequence of fixations observed during the sample array (e.g., last item fixated, second-to-last item fixated, or one of the nonfixated items). We tested infants when they were 5 and 11 months old to

capture performance both before and after key developmental improvements in visual STM. Adults were additionally tested in the same infant task. This allowed us to test passive change detection in a population with a known visual STM capacity (Luck & Vogel, 1997) and further allowed us to determine whether overt fixation effects are more or less pronounced when visual STM capacity has been exceeded, as is likely the case in infants.

We hypothesized that obligatory encoding would produce relatively strong STM representations for the fixated circle colors, as long as the number of circles fixated was within capacity limits. We further hypothesized that memory for nonfixated circles should vary as a function of STM capacity. We tested these hypotheses using change preference and run count. Change preference has been used in several infant visual STM tasks (e.g., Oakes et al., 2013; Ross-Sheehy & Eschman, 2019; Ross-Sheehy et al., 2003) and reflects relative preference for the color-changed circle, a location-specific measure of change detection. A score similar to run count has also been used previously ("switching"; Ross-Sheehy & Eschman, 2019) and provides a more general measure of change detection that may not require location-specific memory.

Open Practices Statement

The study reported in this article was not preregistered. The data and scripts for this study have been made publicly available via OSF and can be accessed at https://osf.io/vfd2n/. Requests for additional information can be sent to the corresponding author.

Method

Our task incorporated a modified *n*-back manipulation to assess memory for sequentially viewed array items. However, rather than presenting items one at a time, we presented array items all at once and used the order of sequential fixations observed during the sample array as a proxy for the serial presentation approach. In this way, it was possible to manipulate the location of the color change on the basis of the order in which each circle was fixated during the sample array (i.e., fixation sequence). Following the classic *n*-back paradigm, we hypothesized that memory for the most recently fixated item would be strongest, with memory decreasing with increasing *n*-back values, presumably because of limits in visual STM capacity. In addition to allowing us to examine the development of visual STM for sequentially fixated items, this paradigm allowed us to determine whether participants form memories for nonfixated array items.

Participants

Sample sizes were chosen on the basis of both previous research (Ross-Sheehy & Eschman, 2019) and a previously conducted power analysis that suggested that a minimum of 22 participants were required for moderate power (Ross-Sheehy & Eschman, 2019). Infant age groups were chosen to capture performance before and after key developmental milestones in visual STM and attentional development (Ross-Sheehy et al., 2011). Adults were additionally included to ensure that our task parameters (e.g., long sample array, large array eccentricity) produced similar capacity estimates as in other adult paradigms and to examine the influence of sequential fixations on visual STM representations. The final sample consisted of twenty-four 5-month-olds (*M* = 157.38 days, *SD* = 7.11 days; 10 females, 14 males), twenty-four 11-month-olds (*M* = 338.33 days, *SD* = 7.84 days; 13 females, 11 males) and 24 adults (*M* = 19.33 years, *SD* = 2.03; 19 females, 5 males). All infants were full term and had no reported birth defects, vision problems, or familial history of color blindness. Infant race was reported as follows: White (*n* = 37), Black (*n* = 1), biracial (*n* = 8), Native American (*n* = 1), and Pacific Islander (*n* = 1). An additional 15 infants were tested but excluded from analysis because of fussiness (i.e., agitation, distress, or crying; *n* = 3), sleepiness (drowsy with bouts of dozing; *n* = 4), equipment failure (*n* = 1), inability to calibrate or loss of gaze on more than 50% of trials (*n* = 5), or failure to meet the minimum performance criterion on at least two trials in every condition (*n* = 2). Adult participants had normal or corrected-to-normal visual acuity and normal color vision (Kuchenbecker & Broschmann, 2013). Adult race was reported as follows: White (*n* = 20), Black (*n* = 3), and Asian (*n* = 1). Adult participants received course credit for participation, and all methods and procedures were reviewed and approved by the University of Tennessee Institutional Review Board (Approval No. UTK IRB-17-03501-XP).

Stimuli and procedure

Stimuli were presented on an ASUS 24-in. 144 Hz color monitor (native resolution = 1,920 × 1,080 pixels, viewable surface = 39.27° × 24.7°), and point of gaze was sampled continuously at 500 Hz using an EyeLink 1000+ remote eye-tracking system (SR Research, Mississauga, Ontario, Canada) with a 16-mm or 25-mm lens (infants and adults, respectively) and a 890-nanometer infrared illuminator for infants. Participants were tested in a dimly lit room. A black curtain hanging from ceiling to floor, with a single cutout for the display monitor, obscured participants' view of the observers and equipment.

Table 1. Color and Luminance Values of Circles and Background

Stimulus	Color	(x, y)	cd/m²
Circle 1	Red	(.6475, .3287)	61.26
Circle 2	White	(.3080, .3180)	298.30
Circle 3	Black	(.3175, .3044)	1.10
Circle 4	Yellow	(.4279, .5204)	249.10
Circle 5	Green	(.2790, .5570)	108.30
Circle 6	Magenta	(.3122, .1411)	34.48
Circle 7	Orange	(.5222, .4327)	103.00
Circle 8	Cyan	(.2218, .3122)	206.90
Circle 9	Brown	(.4647, .4012)	49.47
Background	Gray	(.3038, .3107)	65.05

Change-detection stimuli consisted of arrays of four differently colored circles presented 5.5° from central fixation at 45°, 135°, 225°, and 315° (Fig. 1, bottom). All circles measured 4.38° in diameter, and total array eccentricity was 12.02° (width) by 12.02° (height). Colors were selected randomly without replacement from a pool of nine highly discriminable colors (red, purple, blue, white, black, green, teal, brown, and yellow) and were presented on a gray background (Table 1).

Prior to testing, adults were informed that they would be helping to test a visual task designed for use in infants, and like infants, they would not be given any instruction other than to relax and allow their eyes to move freely. All participants were seated approximately 65 cm from the display monitor (infants sat on a caregiver's lap), and calibration was performed using a 5-point dynamic calibration stimulus. Testing commenced once gaze accuracy was validated to be within 1° for each of the 5 points.

Each trial began with a central fixation stimulus consisting of a multicolored spinning pinwheel. This fixation stimulus acted as an attention getter and a between-trials perceptual mask. The fixation stimulus was gaze contingent to ensure that participants were fixating centrally when each trial began. After 500 ms of accumulated looking, the fixation stimulus disappeared, and participants were immediately presented with a 1,500-ms sample array followed by a 500-ms blank retention interval, and finally a 3,000-ms test array that either was exactly the same as the sample array (no-change trials) or included a single color change in one of the four array locations (change trials). For change trials, the location of the color change was determined on the basis of fixation behavior during the sample array and could occur in the location of the last item fixated in the sample array (one-back condition), the second-to-the-last item fixated in the sample array (two-back condition), or one of the nonfixated sample array

items (change-other condition). Importantly, condition assignment at test was constrained by the number of circles fixated during the sample array. Specifically, if participants fixated two or more circles during the sample array, then the test condition was drawn randomly from the one-back, two-back, change-other, or no-change conditions (P = .25). If infants fixated only one circle during the sample array, then a two-back manipulation was impossible; thus the test condition was drawn randomly from the one-back, change-other, or no-change conditions (P = .33). If infants did not fixate a circle, the test condition was drawn randomly from the change-other and no-change conditions (P = .5). All change trials were followed by a 3-s audiovisual animation in the location of the change. This training stimulus was designed to increase the likelihood that participants would fixate the location of the color change. Although a Pearson's correlation analysis revealed that change-preference scores did not increase over time, $r(1547) = .003$, $p = .916$, the animation was nonetheless highly enjoyable for the infants and helped to keep task engagement high. Infants saw up to 96 trials ($M = 30.06$, $SD = 7.14$), and all adults saw 120 trials.

Data analysis

All trials were included in this analysis. To assess gaze, we drew 3° interest areas around the circles and derived dependent measures from fixations within those interest areas. Saccades, fixations, and blinks were recalculated offline using EyeLink's standard cognitive event parser (Stampe, 1993), which incorporates a velocity threshold algorithm to classify saccades with the following settings: saccade velocity greater than 30° per second and acceleration greater than 8,000° per second for a minimum duration of 4 ms. Samples that did not exceed these thresholds were classified as either fixations (pupil data present) or blinks (no pupil present for at least three consecutive samples). Nearby fixations were left unmerged. An examination of the trial counts for each condition revealed strikingly similar proportions by condition across all three age groups, suggesting that despite large presumed capacity differences, infants and adults displayed similar scanning behaviors during the sample array (Table 2). These between-ages and between-conditions similarities were also apparent when we examined the mean number of circles fixated during the sample array (Table 2). This is important and suggests that lapses in attention and scanning behavior did not result in the oversampling of low-scanning trials in our change-other and no-change conditions. Data for infant and adult participants were analyzed separately.

Table 2. Mean Trial Count and Objects Fixated During the Sample Array by Age and Condition

Measure and condition	5-month-olds		11-month-olds		Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
Trial count						
One-back	8.917	3.269	8.042	3.569	32.208	4.872
Two-back	6.333	2.548	5.333	2.444	23.208	6.413
Change-other	7.625	3.268	8.292	3.793	27.667	6.112
No-change	9.583	3.309	8.542	3.811	36.917	6.036
Number of circles fixated during the sample array						
One-back	1.931	0.396	1.799	0.490	1.699	0.464
Two-back	2.215	0.232	2.208	0.368	1.902	0.433
Change-other	1.980	0.374	1.763	0.307	1.601	0.358
No-change	1.831	0.411	1.687	0.354	1.627	0.552

Results

Run count

Run counts during the test interval were calculated, and each run reflected the number of times the participant visited or revisited individual circle locations. Importantly, multiple fixations within the same circle did not increase the run count, though looking away and then back to the same circle did. For example, looking to the blue circle, then the red circle, then away, then back to the red circle would result in a run count of three (Eye-Link Data Viewer, Version 4.1.1; SR Research, 2019). Run counts were analyzed using a repeated measures analysis of variance (ANOVA) with condition (one-back, two-back, change-other, no-change) as a within-subjects variable and age (5 months, 11 months) as a between-subjects variable. Results revealed a significant main effect of age, $F(1, 46) = 5.239$, $p = .027$, $\eta^2 = .102$, with 5-month-olds demonstrating significantly longer run counts than 11-month-olds (Fig. 2, top). This is important because it demonstrates that limited visual STM capacity in younger infants is not likely due to prolonged fixations or orienting immaturity. Analyses also revealed a significant main effect of condition, $F(3, 138) = 24.302$ $p < .001$, $\eta^2 = .346$, with the longest run counts for the one-back and two-back conditions and the shortest run counts for the no-change condition.

The simple effects of condition were next examined to determine whether the degree of scanning varied by condition (note that all reported simple-effects tests incorporated a Bonferroni correction for multiple comparisons). Results revealed clear evidence of change detection, as all three change conditions (one-back, two-back, and change-other) produced significantly longer run counts than the no-change condition (all $ps < .001$). In addition, memory was strongest when the color change occurred in a previously fixated location, with longer run counts for the one-back and two-back conditions relative to the change-other conditions ($p < .001$ and $p = .087$, respectively). Run counts for the one-back and two-back conditions did not differ from each other ($p = 1.0$), suggesting strong memory for at least two sequentially fixated circles.

Adults' run counts were analyzed using a repeated measures ANOVA with condition (one-back, two-back, change-other, no-change) as the within-subjects variable. Like the infants, adults showed a significant main effect of condition, $F(3, 69) = 22.206$, $p < .001$, $\eta^2 = .491$, with the longest run counts for the one-back and two-back conditions and the shortest run counts for the no-change condition (Fig. 2, top). Just as with the infants, an examination of the simple effects of condition revealed significantly longer run counts for all three change conditions relative to the no-change condition (all $ps \leq .001$). Memory was also strongest when the change occurred at previously fixated locations, with significantly longer run counts for the one-back and two-back conditions relative to the change-other condition ($p = .010$ and $p = .032$, respectively). Run counts for the one-back and two-back conditions did not differ from each other ($p = 1.0$), suggesting strong memory for at least two sequentially fixated circles. This pattern of effects was strikingly similar across infants and adults, with all groups showing increased between-circles scanning for all change conditions relative to the no-change condition, even when the change location was not previously fixated.

Change preference

Change preference during the test interval was calculated as the proportion of time spent looking to the change circle divided by total looking to all the circles. Infant change-preference scores were assessed using a
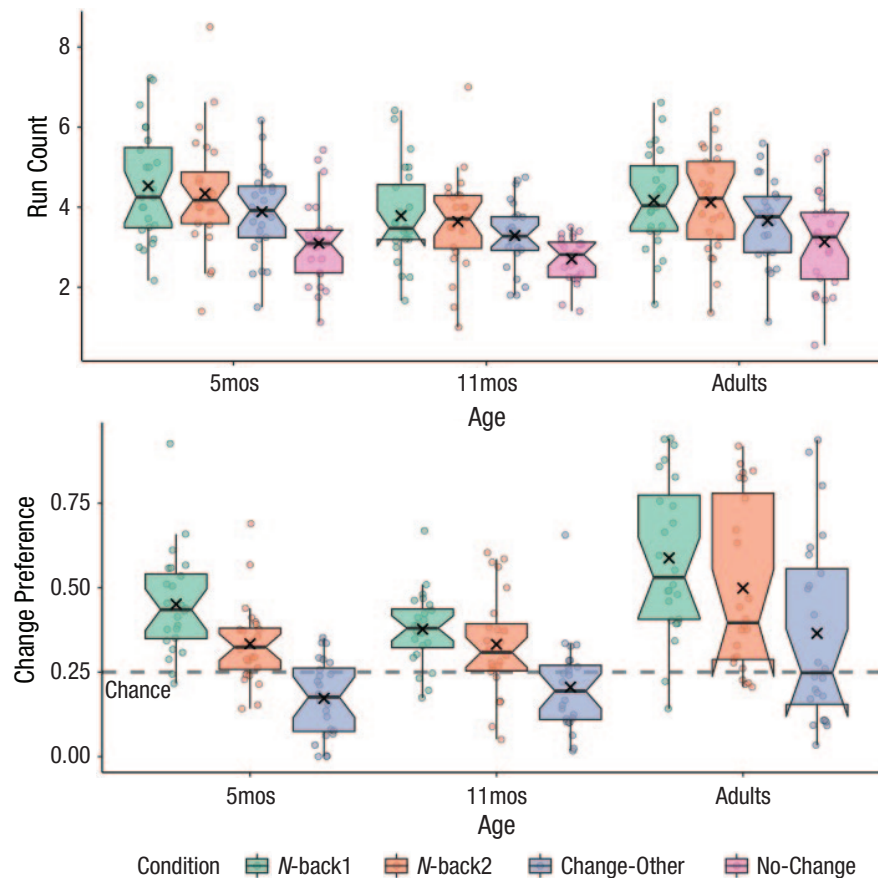
Fig. 2. Mean run count (top) and change preference (bottom) during the test array as a function of age group and condition. Boxplot edges mark upper and lower quartiles, and diagonal notches indicate 95% confidence intervals of the medians (center lines). The "X" represents the mean, and individual participant means are represented as dots.

repeated measures ANOVA with condition (one-back, two-back, change-other) as the within-subjects variable and age (5 months, 11 months) as the between-subjects variable. This analysis revealed only a significant main effect of condition, $F(2, 92) = 31.212$, $p < .001$, $\eta^2 = .404$, with the highest change-preference scores for the one-back condition and the lowest for the change-other condition (Fig. 2, bottom). An examination of the simple effects of condition revealed significantly higher change-preference scores for the one-back relative to both the two-back ($p = .025$) and change-other ($p < .001$) conditions. In addition, change-preference scores in the two-back condition were also significantly higher than those in the change-other condition ($p < .001$). As in the previous analyses, this pattern revealed (a) evidence of change detection for all conditions in which the change location had been previously fixated during the sample array and (b) significantly stronger memory for the most recently visited circle (one-back condition).

We next conducted a series of one-tailed t tests comparing change-preference scores with chance. We chose

a one-tailed t test because we predicted that change detection would produce change-preference scores that were significantly greater than chance (i.e., the probability of fixating one of the four circles, or .25). Results revealed evidence of change detection for the one-back condition at both 5 months, $t(23) = 6.389$, $p < .001$, Cohen's $d = 1.30$, and 11 months, $t(23) = 5.732$, $p < .001$, Cohen's $d = 1.17$, and evidence for change detection in the two-back condition at both 5 months, $t(23) = 3.380$, $p < .001$, Cohen's $d = 0.69$, and 11 months, $t(23) = 2.657$, $p = .007$, Cohen's $d = 0.54$ (Fig. 2, bottom). Neither 5- nor 11-month-olds demonstrated evidence of change preference for the change-other condition.

These same analyses were carried out with the adults' change-preference scores, and the repeated measures ANOVA with condition (one-back, two-back, change-other) as the within-subjects variable revealed a significant main effect of condition, $F(2, 46) = 23.512$, $p < .001$, $\eta^2 = .506$ (Fig. 2, bottom). Once again, an examination of the simple effects of condition revealed significantly higher change-preference scores for the

one-back relative to both the two-back (p = .029) and change-other (p < .001) conditions and significantly higher change-preference scores in the two-back condition relative to the change-other condition (p < .001). Lastly, t tests comparing adults' change-preference scores with chance (.25) revealed significant change detection for the one-back condition, $t(23)$ = 7.142, p < .001, Cohen's d = 1.46; two-back condition, $t(23)$ = 4.804, p < .001, Cohen's d = 0.98; and change-other condition, $t(23)$ = 2.054, p = .026, Cohen's d = 0.42.

Preference over time: Change detection or perseverative looking?

The previous analysis demonstrated strong evidence of visual STM for previously fixated array items, with the highest change-preference scores for the one-back condition, followed by the two-back condition. Although these findings are consistent with a recency effect, it is also possible that change-preference scores for the one-back condition may have been artificially high because of perseverative looking (e.g., Gliga et al., 2018). That is, it is possible that participants lingered longer in the one-back location not because of strong memory for that circle color but because they had a strong prepotent tendency to revisit previous array locations (i.e., *location bias*). Similarly, change preference for the change-other condition might have been artificially low not because of weak memory for the nonfixated circle color but, rather, because strong location biases pulled their gaze to previously fixated locations, reducing the likelihood that they would discover a color change within the 3,000-ms test interval. To address these possibilities, we examined change preference continuously throughout the entire test interval using a permutation analysis. This analytic approach has previously been used in both the infant and adult literatures (Cheng et al., 2019; Gaspelin et al., 2017; Oakes et al., 2013) and provides a robust assessment of moment-to-moment change over time.

Permutation approach. Raw data and scripts used to perform the permutation analysis are available at https:// osf.io/vfd2n/. First, we collected raw interest-area data from each 3-s test interval, resulting in 1,500-sample bins for each trial (3-s test interval × 500 Hz sample rate = 1,500 samples). Gaps shorter than 20 ms (10 samples) were filled with the nearest neighbor, and data were subsequently resampled at 50 Hz. We then indexed gaze for each sample as being either a look to the change location ("1"), a look to a nonchanging location ("2," "3," or "4"), or no look (e.g., saccades, blinks, looks away) and used this data to create our change-preference and location-bias scores (see Change Preference Over Time and Location Bias Over Time below). Next, we drew a new

random index for each observed circle from the set of all possible locations, P(change) = .25, and simply swapped the old circle indexes for the new ones. To illustrate using a simplified example, imagine that a participant fixated two circle locations and lingered at each location for four to seven samples, producing the following run sequence: [1 1 1 1 - - - 3 3 3 3 - - - 1 1 1 1 1 1 1]. For each permutation, every instance of a particular circle index was replaced with a new random circle index. So, for example, drawing a 4 and a 1 would result in the following permuted sequence: [4 4 4 4 - - - 1 1 1 1 - - - 4 4 4 4 4 4 4]. Notice that the change circle (1) is now the second fixation rather than the first and third fixations, as it was in the original run. This procedure allowed us to produce random streams of fixations that might be expected by chance while preserving both the fixation durations and the gaps between fixations. Once the data for every participant had been replaced with permuted data, we then simply recalculated preference scores for each sample bin (see below) and compared them with chance, noting the duration of successive runs of significance or run lengths. This permutation process was then repeated 1,000 times, resulting in a distribution of maximum significant run lengths expected from chance, that is, the null distribution. We then used the 95th percentile derived from this null distribution as our criterion for significance, and any run length exceeding this criterion was considered significant (see Table 3 for run lengths and significance criteria for each condition).

Change preference over time. To examine change preference over the 3-s test interval, we calculated change preference at every sample bin across all participants. This resulted in arrays of change-preference scores, one for each sample bin, spanning the entire test interval (see Fig. 3, solid blue line, for means and 95% confidence intervals). We then compared change preference for each sample bin with chance (.25) using a one-tailed t test. If the majority of participants included in that sample bin were able to detect the color change, then mean change-preference scores should be significantly greater than chance (Fig. 3, dotted blue line). Although these comparisons are informative, a more cautious approach is to assess the duration of successive significant runs (Cheng et al., 2019; Gaspelin et al., 2017; Oakes et al., 2013). To accomplish this, we calculated the number of successive significant samples observed in our change-preference scores (i.e., run lengths) and compared them with the maximum run lengths that might expected by chance (Fig. 3, blue shaded area; see Permutation Approach for details). If the majority of participants detect the color change, they should dwell longer on that circle, producing significantly longer run lengths that would be expected by chance.

Results demonstrated significant change-preference runs for the one-back condition, which were apparent

Table 3. Results of Hypothesis Tests Comparing Change Preference and Location Bias

Hypothesis and condition	5-month-olds			11-month-olds			Adults		
	Maximum run length	Significance criterion	H_0	Maximum run length	Significance criterion	H_0	Maximum run length	Significance criterion	H_0
H_0: change preference = chance									
One-back	**150.0**	10.5	Reject	**92.0**	14.0	Reject	**150.0**	15.0	Reject
Two-back	**28.0**	13.0	Reject	**17.0**	12.0	Reject	**141.0**	17.0	Reject
Change-other	0.0	13.0	Retain	0.0	14.0	Retain	**118.0**	14.0	Reject
H_0: location bias = chance									
One-back	**55.0**	13.0	Reject	**24.0**	15.0	Reject	**150.0**	15.0	Reject
Two-back	0.0	14.0	Retain	0.0	13.0	Retain	0.0	14.0	Retain
Change-other	0.0	13.0	Retain	0.0	12.5	Retain	0.0	14.0	Retain
H_0: change preference = location bias									
One-back	**18.0**	13.5	Reject	15.0	17.0	Retain	**150.0**	16.5	Reject
Two-back	**32.0**	15.0	Reject	**60.0**	15.5	Reject	**150.0**	19.0	Reject
Change-other	3.0	14.0	retain	6.0	16.0	Retain	**134.0**	16.0	Reject

Note: Three hypotheses (H_0) were tested to compare both change preference and location bias with chance (.25) and to compare change preference with location bias directly. Maximum significant run lengths observed during the 3-s test array were calculated, and all run lengths that exceeded the significance criterion are indicated in boldface. The significance criterion for each hypothesis tested was based on the 95th percentile of maximum run lengths observed from 1,000 iterations of permuted gaze data. Values of zero for either maximum run length or significance criterion indicate that no successive runs of significance were observed. Prior to permutation, gaps shorter than 20 ms (10 samples) were filled with the nearest-neighbor values (blinks and saccades excluded), and data were subsequently resampled to 50 Hz.

from the first sample (Fig. 3, blue shaded areas). Significant change-preference runs were also present for the two-back condition at all ages, though the latency of this effect was delayed relative to the one-back condition, reaching significance 380 ms, 360 ms, and 200 ms after test array onset for 5-month-old infants, 11-month-old infants, and adults, respectively. This suggests that younger infants took longer to move their eyes to the change location likely because of greater perseverative looking to the last-fixated item (see Location Bias Over Time below) coupled with relatively inefficient orienting mechanisms. Results for the change-other condition revealed a significant and substantially delayed change-preference run for adults only, reaching significance only after 660 ms. Neither 5- nor 11-month-old infants demonstrated significant change-preference runs for the change-other condition within the 3,000-ms test interval.

Location bias over time. To determine whether perseverative looking contributed to visual preferences, we additionally created a location-bias score using only the no-change trials. Our approach in creating this score was identical to that in creating the change-preference score, only rather than reflecting preference for a color change that occurred at a particular location, it reflected

preference for the location itself (Fig. 3, green solid line). We then once again calculated significant deviations from chance (Fig. 3, green dotted line) as well as significant run lengths (Fig. 3, green shaded area; see Permutation Approach for details). If participants show perseverative looking to either the last fixated location (one-back) or the second-to-the-last fixated location (two-back), then they should dwell longer at those locations despite the lack of a color change, resulting in run lengths that are longer than would be expected by chance (Fig. 3, green shaded area). Note that power for the two-back location-bias analysis was somewhat lower, as not every trial contained two or more looks (41.1% fewer valid trials). However, this was also the case for our two-back change-preference analysis (37.6% fewer valid trials). In addition, because participants completed more trials in the no-change condition than in any other condition (Table 2), trial counts for the two-back location-bias score (740) were actually higher than the two-back change-preference score (657), making it a strong test of our location bias hypothesis.

Results demonstrated significant location-bias runs to the one-back location for all ages, with 5-month-olds showing greater location bias than 11-month-olds and adults showing significant location bias for the entire duration of the trial (Fig. 3, green shaded area). The
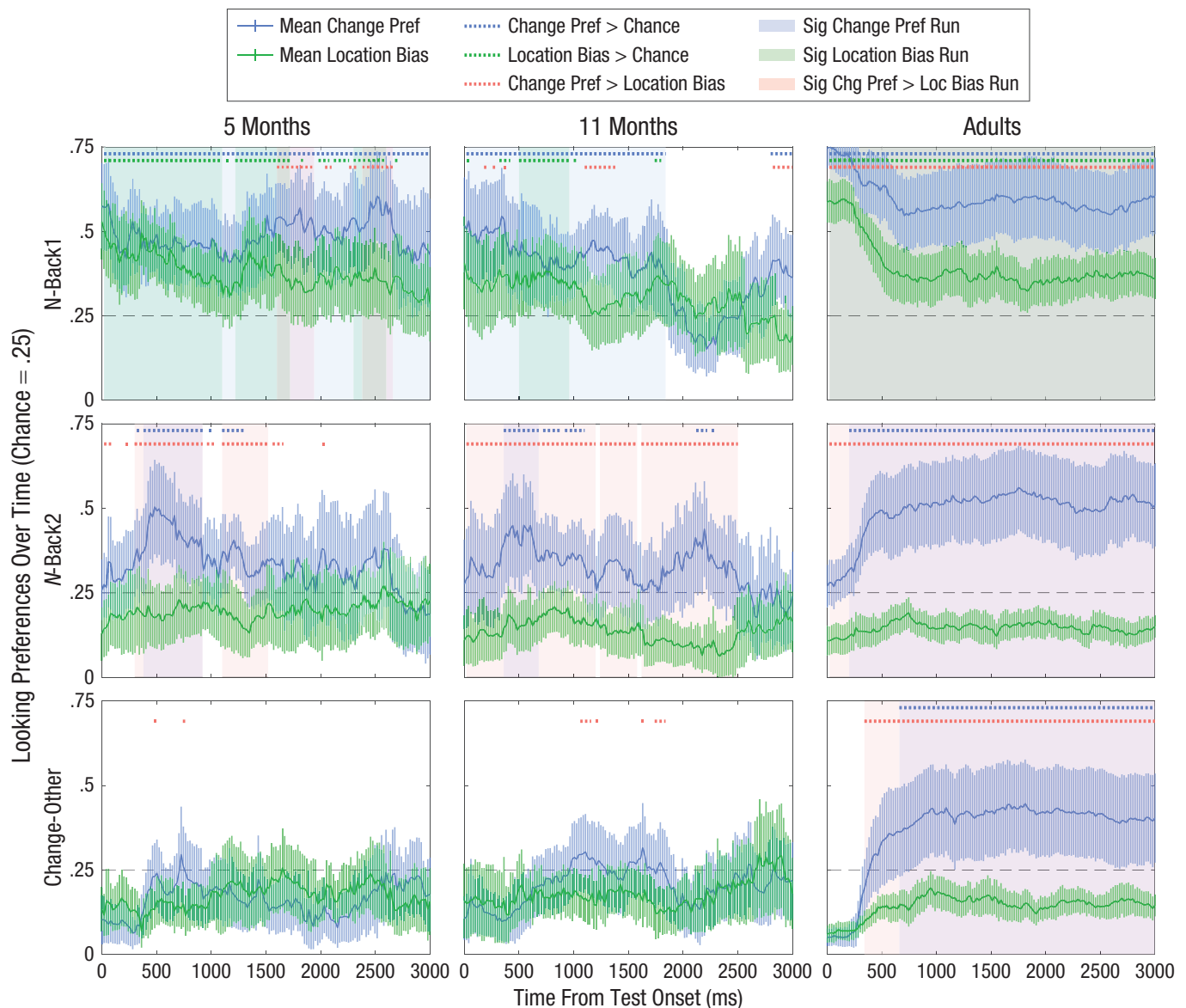
Fig. 3. Mean change preference and location bias over time as a function of array condition and age group. Condition was determined randomly on the basis of fixation order during the sample array, with one-back indicating the last circle fixated, two-back indicating the second-to-last circle fixated, and change-other indicating one of the nonfixated circles. Change-preference scores were the proportion of time spent looking to the location of the color change, and location-bias scores were the proportion of time spent looking to a particular location. Significant preferences are indicated by the dotted lines, and shaded areas represent runs of preference that exceeded the 95th percentile derived from a permutation analysis (iterations = 1,000). Error bars represent 95% confidence intervals.

finding that 5-month-old infants have high location-bias scores may help to explain the observation of relatively high change-preference scores for very young infants in the context of a one-shot task (e.g., Ross-Sheehy & Eschman, 2019, and change-preference results presented above). Interestingly, location biases were completely absent from two-back and change-other trials, suggesting that the influence of location bias is limited to only the most recently visited array location.

Change preference versus location bias. Although the previous analyses were sufficient to test our hypotheses, we additionally compared change-preference scores directly with location-bias scores at every sample using paired-samples *t* tests (Fig. 3, red dotted line). We then used the previously permuted maximum run-length distributions for both change detection and location bias to determine the minimum significant run length expected by chance (Fig. 3, red area). This approach does not rely

on assumptions regarding chance and directly tests the relative contribution of change preference and location bias on moment-to-moment visual preferences.

Results reveal that adults' change-preference scores were significantly higher than location-bias scores for all conditions, suggesting that change detection is a stronger orienting signal than location bias. However, the pattern of results was a bit more nuanced for the infants. Specifically, 5-month-olds demonstrated significantly higher change-preferences scores for the one-back condition, whereas 11-month-olds did not. Although 11-month-olds' change preference was significantly higher than location bias for several of the samples (Fig. 3, red dotted line), the continuous runs of significance did not quite reach the criterion for significance (maximum observed run = 15, significance criterion = 17; Table 3). Both 5- and 11-month-old change-preference and location-bias scores were indistinguishable in the change-other condition. Taken together, these analyses of preference over time provide strong evidence of color memory for at least two overtly fixated items (in infants and adults) and nonfixated items (in adults only) that cannot be explained by simple location biases.

Discussion

In the current study, we used a modified *n*-back change-detection task to determine whether visual STM persists across multiple object fixations, whether memory is stronger for previously fixated array locations, and whether infants and adults form memories for nonfixated array locations. Overall, results suggest that adults and 5- and 11-month-old infants can encode and remember at least two sequentially fixated array items, with weaker evidence of memory for nonfixated array items. Across all measures, the strength of the memory trace varied with sequential position, with the strongest evidence of memory for the last item fixated and diminishing memory with increasing *n*-back. Although the permutation analysis also revealed strong location-bias effects for the one-back condition, it did not appear to be driving change detection for the two-back condition, suggesting memory for at least two items.

All participants had significantly longer run counts for overtly fixated array items (one-back and two-back conditions) relative to nonfixated array items (change-other condition) and compared with trials in which no color changed (no-change condition). Run counts also varied by age, with 5-month-olds demonstrating significantly longer run counts than 11-month-olds. This suggests that developmental limits in capacity are not driven by sluggish orienting. To the contrary, it appears that 5-month-old infants oversampled the individual array items, which

may simultaneously decrease encoding time and increase interference. Although this could contribute to developmental differences in STM, we did not observe a significant decrement in change preference in our 5-month-olds; all participants demonstrated memory for two items. This is important and suggests that our *n*-back approach was successful in eliminating performance confounds that may have arisen from nonmemory systems. Results from our change-preference analysis further demonstrate that the sequential order of fixations during the sample array can influence change detection, with infants and adults demonstrating significantly higher change-preference scores in the one-back than two-back conditions and in the two-back than change-other conditions. One explanation for this pattern is that participants are biased to particular array locations, either because of a prepotent tendency to revisit previously visited locations (Gliga et al., 2018) or because of attentional inertia/perseverative looking (Hood & Atkinson, 1993; Oakes et al., 2004; Richards & Hunter, 1997), a possibility that was evaluated with a permutation analysis.

Overall, our permutation analysis provided strong evidence of memory for object color that could not be explained by simple location biases. Although we did observe one-back location biases for both infants and adults, change preference was also strong and was significantly higher than location biases for 5-month-olds and adults. Moreover, results from the two-back condition revealed clear evidence of memory for item color and no evidence of location bias, indicating color memory for at least two previously fixated items. Results from the change-other condition revealed strong evidence of memory for adults; however, neither 5- nor 11-month-old infants produced significant runs of change preference when the color change occurred at an array location that was not fixated in the sample array.

Taken together, the results presented here address the unanswered questions posed in the introduction. First, our findings demonstrate clear evidence of persistent visual STM for sequentially fixated items, something that to our knowledge has not previously been demonstrated in infants. Second, these results demonstrate that nonfixated array items are at least partially encoded into visual STM, though in infants, this effect was apparent only in run counts. This supports the possibility that run counts may reveal a general sense of familiarity or novelty, whereas change-preference scores may require more specific recollection memory. Third, sluggish orienting could not explain developmental effects, as 5-month-old infants looked at more circles during the sample array and demonstrated significantly longer run counts across all conditions than 11-month-old infants. Indeed, we found surprisingly

few developmental effects, with 5- and 11-month-old infants both demonstrating evidence of memory for two items, provided they had both been previously fixated. Fourth, our adult findings demonstrate similar overt fixation effects, despite sufficient capacity to encode all items. This is likely due to the lack of behavioral response (passive task) and suggests that our relatively long sample intervals were short enough to isolate short-term memory systems. In addition to these important contributions, results from our permutation analysis revealed that observation of change preferences could not be attributed to perseverative looking.

Unique contributions

The use of a gaze-contingent paradigm allowed us to address specific questions about visual STM that were previously intractable. This approach revealed STM capacity of at least two objects that is apparent by 5 months, younger than previously observed (though see Ross-Sheehy & Eschman, 2019). This may be partially due to the yoking of color changes to gaze behavior, as it ensured that all participants were able to detect a color change for a significant portion of trials. This kept task engagement high, resulting in higher trial counts, lower attrition, and increased power. Further, testing infants and adults in the exact same task revealed striking parallels between infant and adult performance. For example, both infants and adults showed changes in visual scanning as a function of memory strength, and both showed evidence of recency effects, with the strongest change detection for the most recently overtly fixated items. This is somewhat surprising given that adult capacity should be sufficiently high to enable encoding of the entire array, regardless of fixation status. This may be due in part to the passive nature of the task, which more closely resembles visual STM during naturalistic viewing. Finally, this paradigm shows promise as a tool for accurately estimating individual capacity in infants, paving the way for long-term outcome studies, improving our understanding of neural development and working memory more generally.

Limitations

There are some limitations that should be taken into consideration. For example, the generalizability of these findings is potentially limited to infants and college-age students from a predominantly White, non-Hispanic/Latinx university population. In addition, it is currently unclear whether infants and adults can retain memory for more than two sequentially fixated array items. Although all participants periodically looked to more than two items, the relatively short duration of the

sample array (1,500 ms) precluded a more thorough analysis of this question. In addition, the free-viewing nature of the task made it impossible to control encoding time across participants and trials. Thus, participants sometimes fixated only one or two circles for long durations and sometimes fixated several circles for shorter durations. Although our approach to condition assignment resulted in relatively balanced groups, it was nonetheless dependent on fixation sequences observed during the sample array and thus could not be perfectly balanced. We have conducted pilot studies of other tasks in which we attempted to control these issues by controlling the duration of encoding for each fixated circle (e.g., present circle array, then remove circles one at a time on the basis of a predefined looking criterion). However, these manipulations were somewhat unnatural, resulting in atypical scanning behavior and poor memory. Cognitive researchers will also recognize an all-too-familiar conundrum regarding task control: Is it better to equalize encoding time across individuals and let depth of processing vary or to let encoding time vary across individuals to ensure equal depth of processing? Future work will continue to tackle these challenges.

Conclusions

Presented here are findings from a new passive change-detection task designed to assess visual STM for sequentially fixated items in infants and adults. Results across several measures revealed clear evidence of memory for at least two sequentially fixated items at every age, with additional evidence of memory for nonfixated items in adults. Across all groups, the strength of memory representations also varied with serial position, demonstrating clear recency effects. Results from the permutation analysis revealed that change preferences could not be attributed to perseverative looking, although location biases for the most recently fixated item were strong. In addition to providing a more natural assessment of visual STM over time, passive change-detection tasks could be used to inform individual capacity estimates in infants, an important predictor of cognitive developmental outcomes.

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References

Adam, K. C. S., Vogel, E. K., & Awh, E. (2017). Clear evidence for item limits in visual working memory. *Cognitive Psychology*, *97*, 79–97. https://doi.org/10.1016/j.cogpsych.2017.07.001

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *Psychology of learning and motivation* (Vol. 8, pp. 47–89). Elsevier.

Baddeley, A. D., & Hitch, G. J. (1994). Developments in the concept of working memory. *Neuropsychology*, *8*(4), 485–493.

Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 28–61). Cambridge University Press. https://doi.org/10.1017/CBO9781139174909.005

Bays, P. M., Catalao, R. F. G., & Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *Journal of Vision*, *9*(10), Article 7. https://doi.org/10.1167/9.10.7

Beckner, A. G., Cantrell, L. M., DeBolt, M. C., Martinez, M., Luck, S. J., & Oakes, L. M. (2020). Visual short-term memory for overtly attended objects during infancy. *Infancy*, *25*(3), 347–370. https://doi.org/10.1111/infa.12332

Buss, A. T., Ross-Sheehy, S., & Reynolds, G. D. (2018). Visual working memory in early development: A developmental cognitive neuroscience perspective. *Journal of Neurophysiology*, *120*(4), 1472–1483. https://doi.org/10.1152/jn.00087.2018

Cheng, C., Kaldy, Z., & Blaser, E. (2019). Focused attention predicts visual working memory performance in 13-month-old infants: A pupillometric study. *Developmental Cognitive Neuroscience*, *36*, Article 100616. https://doi.org/10.1016/j.dcn.2019.100616

Cowan, N. (2016). Working memory maturation: Can we get at the essence of cognitive growth? *Perspectives on Psychological Science*, *11*(2), 239–264. https://doi.org/10.1177/1745691615621279

Cowan, N., Elliott, E. M., Saults, S. J., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. A. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*(1), 42–100. https://doi.org/10.1016/j.cogpsych.2004.12.001

Feigenson, L., & Carey, S. (2005). On the limits of infants' quantification of small object arrays. *Cognition*, *97*(3), 295–313. https://doi.org/10.1016/j.cognition.2004.09.010

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2017). Suppression of overt attentional capture by salient-but-irrelevant color singletons. *Attention, Perception, and Psychophysics*, *79*(1), 45–62. https://doi.org/10.3758/s13414-016-1209-1

Gliga, T., Smith, T. J., Likely, N., Charman, T., & Johnson, M. H. (2018). Early visual foraging in relationship to familial risk for autism and hyperactivity/inattention. *Journal of Attention Disorders*, *22*(9), 839–847. https://doi.org/10.1177/1087054715616490

Hood, B. M., & Atkinson, J. (1993). Disengaging visual attention in the infant and adult. *Infant Behavior and Development*, *16*(4), 405–422. https://doi.org/10.1016/0163-6383(93)80001-O

Kaldy, Z., Guillory, S. B., & Blaser, E. (2016). Delayed match retrieval: A novel anticipation-based visual working memory paradigm. *Developmental Science*, *19*(6), 892–900. https://doi.org/10.1111/desc.12335

Káldy, Z., & Leslie, A. M. (2005). A memory span of one? Object identification in 6.5-month-old infants. *Cognition*, *97*(2), 153–177. https://doi.org/10.1016/j.cognition.2004.09.009

Kibbe, M. M. (2015). Varieties of visual working memory representation in infancy and beyond. *Current Directions in Psychological Science*, *24*(6), 433–439. https://doi.org/10.1177/0963721415605831

Kuchenbecker, J., & Broschmann, D. (2013). *Plates for color vision testing* (1st ed.). Thieme.

Kwon, M. K., Luck, S. J., & Oakes, L. M. (2014). Visual short-term memory for complex objects in 6- and 8-month-old infants. *Child Development*, *85*(2), 564–577.

Luck, S. J., & Vogel, E. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281. https://doi.org/10.1038/36846

Oakes, L. M., Baumgartner, H. A., Barrett, F. S., Messenger, I. M., & Luck, S. J. (2013). Developmental changes in visual short-term memory in infancy: Evidence from eye-tracking. *Frontiers in Psychology*, *4*, Article 697. https://doi.org/10.3389/fpsyg.2013.00697

Oakes, L. M., Baumgartner, H. A., Kanjlia, S., & Luck, S. J. (2017). An eye tracking investigation of color–location binding in infants' visual short-term memory. *Infancy*, *22*(5), 584–607. https://doi.org/10.1111/infa.12184

Oakes, L. M., Hurley, K. B., Ross-Sheehy, S., & Luck, S. J. (2011). Developmental changes in infants' visual short-term memory for location. *Cognition*, *118*(3), 293–305. https://doi.org/10.1016/j.cognition.2010.11.007

Oakes, L. M., Messenger, I. M., Ross-Sheehy, S., & Luck, S. J. (2009). New evidence for rapid development of colour–location binding in infants' visual short-term memory. *Visual Cognition*, *17*(1–2), 67–82. https://doi.org/10.1080/13506280802151480

Oakes, L. M., Ross-Sheehy, S., & Kannass, K. N. (2004). Attentional engagement in infancy: The interactive influence of attentional inertia and attentional state. *Infancy*, *5*(2), 239–252. https://doi.org/10.1207/s15327078in0502_8

Oakes, L. M., Ross-Sheehy, S., & Luck, S. J. (2006). Rapid development of feature binding in visual short-term memory. *Psychological Science*, *17*(9), 781–787. https://doi.org/10.1111/j.1467-9280.2006.01782.x

Posner, M. I., & Keele, S. W. (1967). Decay of visual information from a single letter. *Science*, *158*(3797), 137–139. https://doi.org/10.1126/science.158.3797.137

Richards, J. E., & Hunter, S. K. (1997). Peripheral stimulus localization by infants with eye and head movements during visual attention. *Vision Research*, *37*(21), 3021–3035. https://doi.org/10.1016/S0042-6989(97)00082-5

Rose, S. A., Feldman, J. F., & Jankowski, J. J. (2001). Visual short-term memory in the first year of life: Capacity and recency effects. *Developmental Psychology*, *37*(4), 539–549. https://doi.org/10.1037/0012-1649.37.4.539

Ross-Sheehy, S., & Eschman, B. (2019). Assessing visual STM in infants and adults: Eye movements and pupil dynamics reflect memory maintenance. *Visual Cognition*, *27*(1), 78–92. https://doi.org/10.1080/13506285.2019.1600089

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, *74*(6), 1807–1822.

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2011). Exogenous attention influences visual short-term memory in infants. *Developmental Science*, *14*(3), 490–501. https://doi.org/10.1111/j.1467-7687.2010.00992.x

Ross-Sheehy, S., Reynolds, E., & Eschman, B. (2021). Unsupervised online assessment of visual working memory in 4- to 10-year-old children: Array size influences capacity estimates and task performance. *Frontiers in Psychology*, *12*, Article 2410. https://doi.org/10.3389%2Ffpsyg.2021.692228

Simmering, V. R. (2011). The development of visual working memory capacity during early childhood. *Journal of Experimental Child Psychology*, *111*(4), 695–707. https://doi.org/10.1016/j.jecp.2011.10.007

Simmering, V. R. (2016). I. Working memory capacity in context: Modeling dynamic processes of behavior, memory, and development. *Monographs of the Society for Research in Child Development*, *81*(3), 7–24. https://doi.org/10.1111/mono.12249

Simmering, V. R., & Perone, S. (2013). Working memory capacity as a dynamic process. *Frontiers in Psychology*, *3*, Article 567. https://doi.org/10.3389/fpsyg.2012.00567

SR Research. (2019). *EyeLink Data Viewer* (Version 4.1.1) [Computer software]. https://www.sr-research.com/data-viewer/

Stampe, D. M. (1993). Heuristic filtering and reliable calibration methods for video-based pupil-tracking systems. *Behavior Research Methods, Instruments, & Computers*, *25*(2), 137–142. https://doi.org/10.3758/BF03204486

Wolff, M. J., Jochim, J., Akyürek, E. G., & Stokes, M. G. (2017). Dynamic hidden states underlying working-memory-guided behavior. *Nature Neuroscience*, *20*(6), 864–871. https://doi.org/10.1038/nn.4546