The Eyes Know Time: A Novel Paradigm to Reveal the Development of Temporal Memory

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Temporal memory in 7-year-olds, 10-year-olds, and young adults (N = 78) was examined introducing a novel eye-movement paradigm. Participants learned object sequences and were tested under three conditions: temporal order, temporal context, and recognition. Age-related improvements in accuracy were found across conditions; accuracy in the temporal conditions was correlated with conventional time knowledge. Eye movements tracked the veridicality of temporal order memory in adults and 10-year-olds seconds before providing memory judgments, suggesting that these movements reflect implicit access to temporal information. Seven-year-olds overall did not show this eye-movement effect, but those who did were more accurate than those who did not. Results suggest that eye movements capture aspects of temporal memory development that precede overt decision processes—with implications for hippocampal development.

Episodic memory enables us to consciously remember a past event and the spatiotemporal context in which the event occurred (Tulving, 1972). Memory for the temporal information associated with past events, and the ability to temporally organize events of our past, is a critical and defining feature of both episodic memory (e.g., Tulving, 2002; Wheeler, Stuss, & Tulving, 1997) and autobiographical memory (e.g., Nelson & Fivush, 2004; see also Burt, 2008). Furthermore, our memories for a past event would seem incomplete without accompanying information about when the event occurred (Friedman, 2004). It is not always possible to recollect the precise time of a past event; however, our memory for temporal context can provide broad information about what happened before and after an event, creating a sense of continuity in our memories (Tulving, 1972). Although integral to episodic memory, relatively little is known about the development of memory for temporal information. Different studies have focused on different types of temporal information, making it difficult to compare and thus understand how the various aspects of temporal memory are related (see Pathman & St. Jacques, 2013, for review). In addition, the majority of research on this capacity has focused on young children and has not included an adult comparison group to explore the developmental trajectory of temporal memory (e.g., Friedman, 1991, 1992; Friedman, Gardner, & Zubin, 1995; Friedman & Kemp, 1998; Pathman, Larkina, Burch, & Bauer, 2013).

To begin to fill this gap in the literature we examined 7-year-olds’, 10-year-olds’, and adults’ memory for two types of temporal information, temporal order and temporal context, using the same paradigm. Furthermore, we examined whether eye movements during retrieval of temporal information could reflect an implicit signal of veridical memory, previously identified for other components of episodic memory but never for temporal information (see Hannula et al., 2010), and explored whether this signal changes with development. By combining overt behavioral responses with measures of eye movements we furthered our understanding of developments in temporal memory.

Remembering Time: The Role of Temporal Order and Context

Temporal information about past experiences can be retained in several ways (see Pathman & St. Jacques, 2013, for discussion). Temporal memory can
involve relating two or more events based on their **temporal order** (e.g., Y happened after X) or their **temporal context** (e.g., Y happened around the same time as X). In the laboratory, adults’ memory for temporal order is tested by asking participants to place events in order (e.g., pictures encoded during the experiment, Jenkins & Ranganath, 2010; autobiographical events encoded prior to the experiment, Burt, Kemp, Grady, & Conway, 2000); in contrast, adults’ memory for temporal context is tested by asking participants to place events on a timescale (e.g., line representing early to late during the experimental session, Jenkins & Ranganath, 2010; conventional timescale, Huttenlocher, Hedges, & Prohaska, 1992).

The ability to remember the temporal order of events seems particularly important as one could argue that ordering events in the sequence in which they occur might underlie, or be somewhat involved, in identifying the temporal context in which the event occurred. This may perhaps be the reason why temporal order in episodic memory has been studied much more extensively than temporal context in animal models (e.g., Fortin, Agster, & Eichenbaum, 2002; Kesner, Gilbert, & Barua, 2002; Manns, Howard, & Eichenbaum, 2007), human infants, and adults (e.g., see Bauer, 2007; Burt et al., 2000; Jenkins & Ranganath, 2010; Lehn et al., 2009; St Jacques, Rubin, Labar, & Cabeza, 2008; Suzuki et al., 2002; Tubridy & Davachi, 2011). Overall, this research shows that memory for temporal order emerges in infancy and is supported by a network of regions including the medial temporal lobe (MTL; e.g., Jenkins & Ranganath, 2010; St-Laurent, Moscovitch, Tau, & McAndrews, 2011; Tubridy & Davachi, 2011) and prefrontal cortex (PFC; e.g., Amiez & Petrides, 2007; Jenkins & Ranganath, 2010; Kimura et al., 2010; see Newcombe, Lloyd, & Ratliff, 2007).

Of interest, there is a significant degree of overlap of brain regions involved in memory for temporal order and context (Jenkins & Ranganath, 2010), suggesting a functional relation between the two. However, memory for temporal context also recruits distinct neural regions (Jenkins & Ranganath, 2010), and could reflect differences between order and context in the extent to which controlled processes such as reconstruction and distance-based processes are involved. As discussed by Friedman (1993, 2004), adults use reconstruction processes (using other contextual information, such as environmental cues) and distance-based processes (using relative strength of memory traces) as ways to infer when past events occurred. Despite the conceptual connection between temporal order and context, little work has directly compared the two; thus, further work is needed to understand the relation between them. One way to obtain a better understanding of these types of temporal memory is to examine their developmental trajectories and determine whether they are separable.

Although research in which children’s memory accuracy for temporal information is directly compared to an adult control is rare, differences in temporal memory are expected based on what is known about the protracted development of episodic memory (e.g., Ghetti & Angelini, 2008; Shing, Werkle-Bergner, Li, & Lindenberger, 2008), and brain regions supporting this function (hippocampus, a structure within the MTL, and the PFC; e.g., Ghetti, DeMaster, Yonelinas, & Bunge, 2010; Gogtay et al., 2006; Ofen et al., 2007; Paz-Alonso, Ghetti, Donohue, Goodman, & Bunge, 2008; see also Ghetti & Bunge, 2012), including memory for temporal information (see Romine & Reynolds, 2004, for a discussion of relation between sequential memory and frontal lobe development). The next section discusses the basis of our prediction further.

**Development of Temporal Memory During Childhood**

The majority of, if not all, studies about school-aged children’s memory for temporal information involve life events varying on several dimensions (e.g., age of events, distance between events, and personal significance of events). Although it is generally clear that age-related improvements during middle to late childhood are observed in memory for both temporal order (e.g., judging the order of two events; Friedman, 1991, 1992; Friedman & Kemp, 1998; Friedman et al., 1995; Pathman, Doydum, & Bauer, 2013; Pathman, Larkina, et al., 2013) and temporal context (e.g., placing events in time; Bauer, Burch, Scholin, & Guler, 2007; Friedman, 1991, 1992; Friedman & Kemp, 1998; Friedman & Lyon, 2005; Friedman, Reese, & Dai, 2011; Pathman, Larkina, et al., 2013), whether the trajectories of temporal order versus context differ remains unknown because no studies have examined temporal order and temporal context using the same task. However, a handful of studies have examined memory for temporal order and temporal context in the same group of children (e.g., Friedman, 1991, 1992; Friedman et al., 2011; Pathman, Larkina, et al., 2013). For example, Pathman, Larkina, et al. (2013) had 4-, 6-, and 8-year-olds order two autobiographical events and place autobiographical events on a conventional timescale (e.g., month of year); they found that 4-year-olds were
less accurate than both older groups in ordering these events; 6- and 8-year-olds did not differ. In contrast, age-related improvements were seen between each of the three age groups when they placed past events on a conventional timescale. These results suggest that memory for temporal order may develop more rapidly than memory for temporal context for autobiographical events; however, one cannot exclude the possibility that age-related improvements in memory for temporal context continued in the 6- to 8-year range because this task required knowledge of timescales, which was not necessary in the temporal order task. Indeed Friedman et al. (2011) found that performance on a Conventional Time Knowledge (CTK) test was correlated with accuracy in placing past events in conventional timescales, but not ordering those events in 8- to 12-year-olds, despite the little overall age-related improvement in accuracy for either task in this age range. Pathman and colleagues similarly found no difference in accuracy between 8- and 10-year-olds in a task that involved ordering pairs of autobiographical events. Nevertheless, these children were significantly less accurate than a group of young adults (Pathman, Doydum, et al., 2013).

Overall, improvements in memory for temporal order and temporal context are evident from middle to late childhood. It should be noted, however, that these studies involve autobiographical events. Although autobiographical and episodic memory are related constructs, they also rely on distinct mechanisms (McDermott, Szpunar, & Christ, 2009), which makes it necessary to investigate the development of temporal memory outside the context of autobiographical events. Furthermore, the order of autobiographical events can be established based on script knowledge (e.g., We open birthday gifts after eating cake), or knowledge of routine events (e.g., We go to the restaurant and then we go to the movies; We go to the movies on Saturday night).

Examining temporal memory in middle to late childhood using laboratory-based stimuli would help elucidate mechanisms of temporal organization in memory beyond the contribution of knowledge-based inferences. Moreover, the nature of the temporal relation among events can be precisely controlled. For example, ordered recall of events that have enabling relations between them (i.e., one event must occur before the next for the desired end result) is higher than ordered recall of events that have arbitrary relations between them (see Bauer, 1992). If we aim to understand the processes that regulate temporal memory, then examining arbitrary temporal sequences is most appropriate, and laboratory procedures afford the best way for doing so.

No studies, to our knowledge, have examined memory for temporal order and context of arbitrary relations in school-aged children in the laboratory. This is paradoxical as there is a relatively vast literature on the development of memory for arbitrary sequences in infancy (see Bauer, 2007, for review) and early childhood (Riggins, Miller, Bauer, Georgieff, & Nelson, 2009). Furthermore, arbitrary sequences are typically used to assess temporal memory in adults (e.g., Jenkins & Ranganath, 2010; Tubridy & Davachi, 2011). Thus, there is a conspicuous gap in the literature between infancy and adulthood. In the present investigation, we tested arbitrary event sequences using laboratory stimuli so that we could directly compare age groups, and directly compare temporal order and context.

One could argue that memory for temporal order may show faster development than memory for temporal context based on the observation of robust temporal order memory in infancy (see Bauer, 2007, for review), and the suggestion that with autobiographical events temporal order memory performance stabilizes more quickly than temporal context memory during childhood (see Pathman, Larkina, et al., 2013). On the other hand, temporal context (e.g., X occurred around the same time as Y) could require less precision than temporal order (e.g., X occurred before Y) and thus may show steeper development in childhood. To investigate these types of information, we not only tested overt behavior but we also introduced to the temporal memory literature an assessment of eye movements which have been fruitful in understanding other components of episodic memory.

Eye Movements: Implicit Signal of Veridical Memory

To better understand the development of temporal memory it would be helpful to understand the ability to integrate temporal information in the representation of an episode. Eye movements may provide a window into this representation because they have been found to track associations between episodes and the context in which they had occurred (e.g., Hannula et al., 2010). Eye-movement measures have been used for this purpose with typical adults and amnesic patients (e.g., Althoff & Cohen, 1999; Hannula, Ryan, Tranel, & Cohen, 2007; Ryan, Althoff, Whitlow, & Cohen, 2000). In Hannula
et al. (2007), participants studied faces superimposed on complex scenes, and at test were shown trials in which three previously studied faces were superimposed on previously studied scenes. Adults showed greater viewing of the faces that had been paired with the scenes during the study phase 500–750 ms after onset of the three-face display. Amnesic patients with hippocampal damage did not show this eye-movement effect (Hannula et al., 2007), suggesting that the hippocampus is necessary for this type of context memory and eye-movement-based memory effects. Additional evidence that these eye-movement effects capture hippocampal contribution to memory comes from a fMRI study in which adults were tested in a similar paradigm (Hannula & Ranganath, 2009), and hippocampal activity predicted eye-movement-based memory effects.

Only two studies have examined the eye-movement effects reported previously with adults (e.g., Hannula & Ranganath, 2009; Hannula et al., 2007) in developmental populations, and results are mixed. Richmond and Nelson (2009) found that 9-month-old infants showed disproportionate looking to the matching face (greater than would be expected by chance) within 1 s of onset of the probe, whereas 4-year-olds (Koski, Olson, & Newcombe, 2013) showed disproportionate viewing only across the full length of the probe. Furthermore, when Koski and colleagues examined eye movements in a way that paralleled analyses with adults (correctly selected faces compared to incorrectly selected faces; Hannula & Ranganath, 2009), the eye-movement effects seen in adults were not found in 4-year-olds. The inconsistency in the results in these studies despite both testing relational representations over delays of seconds suggests that the relational components captured by eye movements over longer delays may be a late developing phenomenon.

Furthermore, the absence of a previous investigation of eye movements of temporal memory makes a compelling case for establishing a method that might track this important relational component even in adults. Ryan and Villate (2009) published the only evidence that eye movements might track temporal information, but they did not test whether they may track long-term retention of temporal information: They showed adults three objects presented one at a time on a computer screen. During retrieval, on each trial, participants were first shown one item—that served as the cue—and then were asked to identify the item that had come directly after it in the encoded quadruplet among three items displayed simultaneously. The nature of the two distractors changed as a function of experimental condition. In the temporal order condition, the distractors were from the same sequence as the cue and target. Thus, participants could only establish what item followed the cue by recollecting the specific temporal order with which items within a quadruplet were presented. In the temporal context condition, the distractors were from other sequences previously shown during the encoding task. Thus, participants could establish what item followed the cue by identifying which item was presented in the same sequence as the cue (i.e., which item had appeared around the same time as the cue). Finally, in the recognition condition, the two distractors were completely novel; this condition was included as a control to ensure that participants exhibited acceptable memory for the items and understood the task. By including these three within-subject conditions, we were able to compare temporal order and temporal context using the same task and instructions and test the alternative predictions outlined in an earlier section.

Another goal of this research was to establish whether eye movements could signal veridical memory for the temporal information associated with an episode. We also sought to examine whether this differed across age groups. Using the same approach as previous investigations of memory for item and context associations (Hannula & Ranganath, 2009; Hannula et al., 2007; Koski et al., 2013) we compared proportion of time spent viewing correctly selected items to proportion of time spent viewing incorrectly selected items. Disproportionate viewing of the selected item for correct compared to incorrect trials in this task would suggest that the eyes “know” time (i.e., signaling
veridical memory for temporal order or context). Based on these investigations (e.g., Hannula et al., 2007; Hannula & Ranganath, 2009), we predicted that eye movements would show disproportionate viewing for targets compared to incorrect distracters, and these eye movements would be detectable considerably earlier than overt responses. In addition, given work on protracted development of the functional contribution of the hippocampus to memory for contextual information (e.g., Ghetti et al., 2010), we expected different patterns for children and adults. One possibility is that the eye-movement effect is not present in children, suggesting a late emergence of an eye-movement signature of temporal memory. An alternative possibility is that children show the effects in later time windows, but still prior to decisions (e.g., Koski et al., 2013), which would be consistent with the possibility that processes underlying eye movements are similar in children and adults, but in children operate more slowly. The state of the literature is such that we cannot make strong predictions, as temporal memory has not been investigated with eye movements in children.

We also examined how early eye movements could contribute to overt decisions about temporal memory. To do so, we accounted for CTK, a factor that has been shown to contribute to overt temporal memory judgments for autobiographical events (Friedman et al., 2011). In the present investigation we included a CTK task as a proxy for one type of controlled process necessary for temporal information, involving semantic knowledge, flexible thinking, and mental imagery (see Friedman, 1989).

In summary, we examined memory for temporal order and context in school-aged children and adults using the same paradigm. We provide the first examination of age-related differences in memory judgments and eye movements associated with temporal order and temporal context. In addition, for the first time we are able to use eye-movement data and CTK data to predict memory for temporal order and temporal context in 7-year-olds, 10-year-olds, and young adults.

**Method**

**Participants**

Twenty-six 7-year-old children ($M = 7.53$ years, $SD = .31$), twenty-six 10-year-old children ($M = 10.42$ years, $SD = .29$), and 26 young adults ($M = 20.95$ years, $SD = 1.88$) took part in this study. Half the participants in each age group were female. For adults, 26% identified themselves as Asian, 53% identified themselves as Caucasian, and 15% identified themselves as multiracial. For children, the majority (85%) were Caucasian. All participants took part in one session that took approximately 1.5 hr to complete, including breaks. An Institutional Review Board approved the protocol. Children were recruited from a pool of families who had expressed interest in participating in research. A parent provided written parental consent, and families received $10 for participating after the session. Adults were recruited from a university participant pool, provided written consent, and received course credit for their participation. For screening purposes participants were tested for IQ based on the two-subtest Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). No participants needed to be excluded because of low IQ: WASI two-subtest IQ score means (and standard deviations) were 116.19 (16.48), 116.08 (11.89), and 105.73 (9.33), for 7-year-olds, 10-year-olds, and adults, respectively. An additional one adult and six children were tested but were not included in the final sample because eye-movement data were not obtainable ($n = 2$), they did not complete the task ($n = 3$), or performed at chance in the recognition condition ($n = 2$; see the Procedure subsection).

**Materials and Procedures**

**Stimuli.** We selected 350 items most appropriate for use with children from a bank of standardized color photographs of objects (Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010).

**Eye tracker.** All stimuli were presented on a white background using a Tobii (http://www.tobii.com) T-120 eye tracker (eye tracker integrated into a 17-in. monitor). Calibration procedures were conducted before each run of trials; participants were asked to follow a red circle, which moved to five different locations on the screen. Default Tobii fixation filter settings were used for eye-movement data reduction (velocity threshold: 35 pixels per sample; distance threshold: 35 pixels). Timing of eye-tracker computer setup was tested according to Tobii guidelines (Tobii Technology, 2010) and the synchronization offset was on average 65.22 ms ($SD = 17.12$).

**Procedure.** Participants sat in front of the eye tracker. In the encoding phase, participants were instructed to remember the order of items presented in quadruplets. From the 350-item stimulus set, we randomly selected 75 groups of four items to be presented in encoding trials (Figure 1a). Each
object within a quadruplet was presented in the center of the screen for 1.5 s. Following the sequence of objects, participants were shown one of the objects from the sequence (probe item) and asked whether it was the first, second, third, or fourth object in the sequence (see Jenkins & Ranganath, 2010, for similar encoding procedures). The probe item remained on screen until participants made a response via button press. We randomly selected which items from the sequence would be used as probes. The 75 encoding trials were randomly split into three runs of 25 trials each, separated by a 1- to 2-min break. Following encoding, participants were given a 10-min break.

In the retrieval phase, participants were told that they would see one of the objects from the encoding phase (retrieval cue; same object as probe item from encoding phase) and were to choose the object that came immediately after that object in the sequence (target item) from an array of three objects (Figure 1b). Of the 75 probe items from the encoding phase, 60 had been presented either in the first, second, or third position in the quadruplet and could be used to probe memory for the item that came next. An additional 15 probe items from the encoding phase had been presented in the fourth position and thus could not be used here (as no object came immediately after it within a sequence); these trials had been included to ensure that participants attended to the whole sequence of four items during encoding, but were excluded from the retrieval phase. For each retrieval trial array, one object was the target (object that followed the retrieval cue) and the other two objects were distracters. The spatial placement (top, left, right) of the target item in the retrieval array was randomly selected with the constraint that the target item would be in each of the three positions an equal amount of times across trials. The test was self-paced.

The distracters varied across trials as a function of experimental condition. In the temporal order condition, the distracters were items from the same sequence as the retrieval cue and target item. In the temporal context condition, the distracters were items from other sequences (i.e., each distracter was not from the same sequence as the target item or the other distracter). In the recognition condition, the distracters were novel items; this condition served as a control condition. There were 60 retrieval trials in total divided equally across conditions. All trials were randomized and then split into three runs of 20 trials each, separated by a 1- to 2-min break. The randomization procedures described throughout this section were performed to create a total of two randomized stimulus sets of encoding and retrieval task versions. Before the encoding and the retrieval phase, participants were given practice trials to ensure that they understood the directions and the task.

Following the temporal memory task, participants were tested in two additional tasks. Children and adults were tested using the two-subtest version of the WASI (Wechsler, 1999). Last, children and adults participated in the “image representation of the months” portion of the CTK test (Friedman et al., 2011). This test examines the capacity to flexibly represent timescales, like months of the year, and was modeled after Friedman (1989). A sample question from this test is: “If you’re going backwards [through the months of the year] and you start in May, which would you come to first, September or January?” The other portions of the CTK were not administered because they were not as appropriate for use with both children.
Accuracy on the Temporal Memory Task

Encoding phase. One-sample t tests were conducted to compare encoding task accuracy to chance (25%) for each age group. All groups were above chance: 7-year-olds (M = 70.11%, SD = 11.75), t(25) = 19.58, p < .0001; 10-year-olds (M = 87.18%, SD = 8.74), t(25) = 36.28, p < .0001; adults (M = 94.56%, SD = 6.38), t(25) = 55.56, p < .0001. Analysis of variance (ANOVA) showed a main effect of age in accuracy during the encoding task, F(2, 75) = 48.07, p < .0001, ηp² = .56. Pairwise comparisons revealed that adults were more accurate than 10-year-olds, and 10-year-olds were more accurate than 7-year-olds (pairwise comparisons to follow-up ANOVAs for these and remaining analyses were conducted with Bonferroni correction for multiple comparisons).

To ensure that there were no accuracy differences during encoding for trials that were assigned to the three conditions in the retrieval condition, a 3 (age: 7-year-olds, 10-year-olds, adults) × 3 (condition: temporal order, temporal context, recognition) repeated measures ANOVA was conducted. There was no main effect of condition, F(2, 150) = 1.89, p = .16, or Condition × Age interaction, F(4, 150) = .21, p = .93. There was a main effect of age, F(2, 75) = 44.35, p < .0001, ηp² = .54, as expected. As there were age-related differences in the encoding phase, only correct trials from the encoding phase were included in analyses in the retrieval phase.

Retrieval phase. An Age × Condition ANOVA revealed a main effect of condition, F(2, 150) = 215.53, p < .0001, ηp² = .74; a main effect of age, F(2, 75) = 23.86, p < .0001, ηp² = .39; and no interaction, F(4, 150) = 1.94, p = .11. As shown in Figure 2, adults were more accurate than 10-year-olds, and 10-year-olds were more accurate than 7-year-olds. Furthermore, accuracy in the recognition condition was higher than accuracy in the temporal order condition, which in turn was higher than accuracy in the temporal context condition. Finally, we conducted one-sample t tests to compare retrieval task accuracy to chance (33%) for each age group. All age groups were above chance for all test conditions ts(25) > 3.39, ps < .005, with the exception that 7-year-olds did not perform above chance in the temporal context condition, t(25) = .25, p = .80.

To ascertain that low performance in the youngest age group was not due to group differences in decreased vigilance during the task, we compared accuracy at the beginning of the retrieval phase (Run 1) to that at the end (Run 3) in an Age × Condition × Run ANOVA. We found no main effect of run, F(1, 75) = .28, p = .60, ηp² = .004; no Age × Run interaction, F(2, 75) = .02, p = .98, ηp² = .00; and no Age × Condition × Run interaction, F(4, 148) = 1.60, p = .21, ηp² = .02. Thus, decreases in vigilance or fatigue cannot account for age-related differences in performance.

Temporal Memory Response Times

All participants took several seconds to respond to each trial (see Table 1). An Age × Accuracy
(correct, incorrect) × Condition (temporal order, temporal context) ANOVA revealed a main effect of accuracy, $F(1, 74) = 10.04$, $p < .005$, $\eta_p^2 = .12$, and age, $F(2, 74) = 7.57$, $p < .005$, $\eta_p^2 = .17$. Response times were faster for correct than incorrect trials across age groups. Pairwise comparisons revealed that adults respond more quickly than children; 7- and 10-year-olds did not differ. There was no main effect of condition, $F(1, 74) = .07$, $p = .79$, or interactions, $F$s $< 1.5$, $ps > .23$. Thus, response times did not differ between the temporal order and context conditions.

**Temporal Memory Eye Movements**

A major goal of this investigation was to examine eye movements for the temporal order and temporal context conditions. Eye movements were not examined for the recognition condition for two reasons. First, although useful as a control, this condition was not a manipulation of interest. In addition, as two of the three items in the retrieval array for the recognition condition were novel, we could expect eye movements to show a different pattern for the recognition condition compared to the other conditions in which all of items had been studied (e.g., Fagan, 1970; Fantz, 1964; Manns, Stark, & Squire, 2000). Only distracters in the two temporal memory conditions had all been studied; thus, direct comparison of eye movements for only these two conditions was appropriate.

To parallel previous investigations that have assessed eye movements during retrieval of a context in adults (e.g., Hannula & Ranganath, 2009), we examined a time window in the early phase of the trial. Proportion of viewing to the selected object for each time bin was calculated by summing the duration of fixations made to the selected object and dividing that by the sum of durations made to all AOIs (target + distracter 1 + distracter 2). The selected object was the target for correct trials, and was a distracter for incorrect trials. Like Hannula and Ranganath (2009), we examined whether participants spent more time viewing selected items in correct trials compared to selected items in incorrect trials. Disproportionate viewing for correct trials compared to incorrect trials would suggest that eye movements reflect veridical memory. We first report time-course measures to determine how soon after stimulus onset any disproportionate viewing emerged early in the trial. We then report proportion of looks using each participant’s full length of the retrieval trial array (i.e., based on when the participant made a button press response).

**Time course of looking.** We examined a time-course analysis in the “early” phase of the retrieval array trial length. We examined looking up to 4,000 ms after stimulus onset in 1,000-ms bins. This maximum time point was selected such that it was later than those reported in previous eye-movement investigations of memory for context in adults (e.g., Hannula & Ranganath, 2009; Hannula et al., 2007), but earlier than when participants made their button press responses. We conducted an Age × Accuracy × Condition × Time bin (0–1,000, 1,000–2,000, 2,000–3,000, and 3,000–4,000 ms) ANOVA. This analysis revealed a main effect of accuracy, $F(1, 72) = 4.86$, $p < .05$, $\eta_p^2 = .06$; a main effect of time bin, $F(3, 216) = 48.95$, $p < .0001$, $\eta_p^2 = .41$; a Condition × Time Bin interaction approaching significance, $F(3, 216) = 2.67$, $p = .05$, $\eta_p^2 = .04$; and an Accuracy × Time Bin interaction, $F(1, 216) = 5.37$, $p < .001$, $\eta_p^2 = .07$. These effects were subsumed by a four-way interaction: Age × Condition × Accuracy × Time Bin interaction, $F(6, 216) = 2.37$, $p < .05$, $\eta_p^2 = .07$. To follow up, we conducted an Age × Accuracy × Time Bin ANOVA for each condition separately. For the temporal order condition, there was a main effect of accuracy, $F(1, 73) = 5.07$, $p < .05$, $\eta_p^2 = .07$, and a main effect of time bin, $F(3, 219) = 35.29$, $p < .0001$, $\eta_p^2 = .33$ (see Figure 3a). Importantly, there were also Accuracy × Time Bin, $F(3, 219) = 6.15$, $p < .0001$, $\eta_p^2 = .08$, and Age × Accuracy × Time Bin, $F(6, 219) = 2.19$, $p < .05$, $\eta_p^2 = .06$, interactions. When we conducted the ANOVA for each age group separately, all age groups showed an Accuracy × Time Bin interaction ($F$s $> 2.74$, $ps < .05$). Thus, we conducted separate paired $t$ tests comparing accurate and inaccurate trials for each time bin. This revealed a differential pattern for each age group (see Figure 4). Specifically, for 7-year-olds (Figure 4a), none of the time bins showed greater proportion of viewing to selected item for correct compared to incorrect trials. The only effect was that in the first time bin (0–1,000 ms), there was disproportionate looking to selected item for the incorrect (distracter) trials compared to correct trials, $t(25) = -3.39$, $p < .005$, $d = 0.66$. Both 10-year-olds (Figure 4b) and young adults (Figure 4c) showed increased viewing for correct trials compared to incorrect trials in one of the time bins; however, adults showed this effect sooner after stimulus onset compared to 10-year-olds. For 10-year-olds, there was greater viewing of selected item for correct compared to incorrect trials in the 3,000- to 4,000-ms time bin, $t(25) = 4.33$, $p < .0001$, $d = 0.86$, and for adults this effect was apparent in
the 2,000- to 3,000-ms time bin, \( t(24) = 2.70, p < .05, d = .55 \). To obtain even greater precision, we repeated this analysis for 10-year-olds and adults using 500-ms time bins (see Table 2 for results): Adults showed disproportionate viewing to correct trials earlier than 10-year-olds.

For the temporal context condition, there was only a main effect of time bin, \( F(3, 219) = 19.32, p < .0001, \eta^2_p = .21 \). As expected, overall percent duration of looks to the selected item, regardless of its accuracy, increased across this portion of the trial length (see Figure 3b).

In summary, eye movements showed a memory effect in the temporal order condition, but not in the temporal context condition. Furthermore, an interesting age-related pattern emerged such that the eye-movement effect for temporal order was apparent in the older, but not younger, group of children; furthermore, the older group of children shows the effect at a later time point than adults.

Proportion of viewing over the full length of the retrieval trial array. To avoid concerns that the selection of the time bins may have biased age-related effects, we examined eye movements over the full retrieval array trial length (which varied per trial per participant based on response time).

This analysis replicated the above effects and confirmed condition and age group pattern differences. The Age \( \times \) Accuracy (correct, incorrect) \( \times \) Condition (temporal order, temporal context) ANOVA revealed a main effect of accuracy, \( F(1, 74) = 11.37, p < .005, \eta^2_p = .13 \); Age \( \times \) Accuracy interaction, \( F(2, 74) = 4.91, p < .05, \eta^2_p = .12 \); and Condition \( \times \) Accuracy interaction, \( F(1, 74) = 6.22, p < .05, \eta^2_p = .08 \). To follow-up these interaction effects, we conducted Age \( \times \) Accuracy ANOVAs for each condition separately. For the temporal order condition, there was a main effect of accuracy, \( F(1, 74) = 21.24, p < .0001, \eta^2_p = .22 \), and an Age \( \times \) Accuracy interaction, \( F(2, 74) = 4.68, p < .05, \eta^2_p = .11 \). Seven-year-olds showed no difference in viewing for correct (\( M = .48, SD = .08 \)) compared to incorrect (\( M = .47, SD = .06 \)) trials, \( t(25) = .34, p = .74 \). Ten-year-olds showed disproportionate viewing for correct (\( M = .52, SD = .06 \)) compared to incorrect (\( M = .43, SD = .05 \)) trials, \( t(25) = 6.37, p < .0001, d = 1.27 \). Similarly, adults showed disproportionate viewing for correct (\( M = .48, SD = .08 \)) compared to incorrect (\( M = .44, SD = .08 \)) trials,
In summary, only for the temporal order condition did eye movements capture veridical temporal information across the full length of the retrieval trial array. Indeed, when we calculated the difference score between accurate and inaccurate trials looks across the full trial length in the temporal order condition (what we will call “eye-movement effect for order”), and correlated that with retrieval accuracy (controlling for age), we found that this index of eye movements was positively correlated with performance in the temporal order, $r(74) = .34$, $p < .005$, and temporal context, $r(74) = .26$, $p < .05$, conditions, but not the recognition condition, $r(74) = .10$, $p = .39$.

The absence of an eye-movement effect in 7-year-olds suggests an age-related difference in the way event information is bound to its temporal order. Next, it is important to establish whether a subset of 7-year-olds show the eye-movement effect for order and, if so, whether performance of those children who show the effect is better than those children who do not show the effect. A group of 7-year-olds ($n = 12$) did show the effect (i.e., difference score in looking between accurate and inaccurate trials was positive). When we divided 7-year-olds into two groups based on whether they showed this eye-movement effect or not, we found that those 7-year-olds who showed the eye-movement effect ($n = 12$) were more accurate than those who did not show the effect ($n = 14$) in both temporal conditions of the retrieval task. Specifically, for the temporal order condition, the 7-year-olds who showed this eye-movement effect for order ($M = 49.27$, $SD = 9.48$) were more accurate than the 7-year-olds who did not show this effect ($M = 39.05$, $SD = 11.58$), $t(24) = 2.44$, $p < .05$. Similarly, for the temporal context condition, the 7-year-olds who showed this eye-movement effect for order ($M = 42.04$, $SD = 16.45$) were more accurate than the 7-year-olds who did not show this effect ($M = 26.63$, $SD = 10.65$), $t(24) = 2.88$, $p < .01$. These two groups of 7-year-olds did not differ in performance in the recognition condition, $t(24) = .05$, $p = .96$. (Note that this particular analysis was not conducted on older children and adults because the majority of both groups showed the eye-movement effect for order.) This exploratory analysis further supports the notion that the eye-movement effect we found in the temporal order condition is reflecting veridical memory for time.

**CTK Test**

We verified that there were age-related differences in performance on the CTK consistent with Friedman et al. (2011) and found a main effect of age, $F(2, 75) = 41.10$, $p < .0001$, $\eta_p^2 = .52$. Pairwise
comparisons revealed that adults ($M = 7.92$, $SD = .27$) were more accurate than 10-year-olds ($M = 7.00$, $SD = 1.50$), and 10-year-olds were more accurate than 7-year-olds ($M = 4.69$, $SD = 1.72$). Partial correlation analyses (controlling for age) revealed a positive correlation between accuracy on the CTK task and retrieval in the temporal order condition, $r(75) = .28$, $p < .05$, and temporal context condition, $r(75) = .29$, $p < .05$, but not the recognition condition, $r(75) = .14$, $p = .24$. Performance on the CTK was not correlated with eye-movement effects ($ps > .05$).

Finally, we sought to determine whether age, eye movements, and CTK contribute unique variance to overt temporal memory accuracy. First, we conducted a multiple regression analysis with age, eye-movement effect for order, and CTK accuracy, predicting behavioral accuracy in the temporal order condition. The regression model was significant, $F(3, 76) = 15.24$, $p < .001$, $R^2 = .39$, adj. $R^2 = .36$, and each predictor contributed unique variance to temporal order condition accuracy (age: $\beta = .33$, $p < .01$; eye-movement effect for order: $\beta = .26$, $p < .01$; CTK: $\beta = .25$, $p < .05$). Second, we conducted a similar analysis predicting behavioral accuracy in the temporal context condition. Again the regression model was significant, $F(3, 76) = 14.03$, $p < .001$, $R^2 = .37$, adj. $R^2 = .34$, and each predictor contributed unique variance to temporal context condition accuracy (age: $\beta = .34$, $p < .01$; eye-movement effect for order: $\beta = .18$, $p = .06$; CTK: $\beta = .27$, $p < .05$). Overall, our results show that age, eye movements, and CTK each make independent contributions to overt temporal memory judgments. Eye movements predicted overt temporal memory judgments even when age and CTK accuracy were accounted for.

**Development of Temporal Memory**

**Temporal Distance Across Events: Examining Lures in the Temporal Context Condition**

The results thus far suggest that temporal order within a sequence is a fundamental dimension for temporal organization. However, one could ask whether participants respond differently to the distance across events. In the temporal context condition, the distractors were objects from other sequences. Each distractor was selected randomly from other sequences, and so we could determine the temporal distance of each distracter from the target; one would expect that distracters that were closer to the target sequence would be selected more often than distracters that were further from the target sequence. To test this hypothesis, we averaged the distracter distances for selected distracters and nonselected distracters for each incorrect trial for each participant. An ANOVA was conducted to compare the distances for selected distracters and nonselected distracters, and whether this effect differed across age groups. The ANOVA revealed that across age groups, the distracter distances for selected distracters ($M = 21.83$, $SD = 5.26$) were smaller than distracter distances for nonselected distracters ($M = 23.68$, $SD = 4.96$), $F(1, 75) = 5.46$, $p < .05$, $\eta^2_p = .07$. There was no effect of age group, $F(2, 75) = .42$, $p = .66$, or interaction, $F(2, 75) = .28$, $p = .76$. Thus, when participants erred in the temporal context condition, they were more likely to choose the distracter that was temporally closest to the target object during encoding.

**Discussion**

The purpose of the present investigation was to examine the development of memory for temporal order and context. To our knowledge, this is the first examination of these two types of temporal memory within the same task, and the first investigation of this type with two groups of children and a group of adults. Furthermore, this is the first study that documents eye-movement effects related to long-term temporal memory binding, extending previous research showing eye-movement effects for other types of item–context associations (e.g., Hannula & Ranganath, 2009; Hannula et al., 2007; Richmond & Nelson, 2009; see also Koski et al., 2013). The age-related differences in accuracy and eye movements provide further evidence for the protracted development of temporal memory. Furthermore, the individual differences analyses shed new light on the processes involved in temporal memory and its development. These findings are discussed in turn.

**Developmental Differences in Overt Temporal Memory**

The first goal of the present research was to compare developmental differences in memory for temporal order and temporal context. Upon verifying strong performance in the recognition condition, suggesting that all participants remembered individual items and understood the task, both memory for temporal order and context showed strong differences from 7-year-olds to 10-year-olds to adults, and across age groups temporal order proved less challenging than temporal context.
Although temporal order requires finer grain discrimination than temporal context, temporal order test arrays included the most information that could be used to reconstruct the correct answer. First, unlike the temporal context condition in which two of the items in the retrieval array were from different sequences, in the temporal order condition, all the items were from the same sequence. Thus, it is possible that participants were able to reconstruct temporal order because the encoding context was more successfully reinstated. In other words, the temporal order condition provided participants with the most contextual cues to support retrieval (see Murnane, Phelps, & Malmberg, 1999). Second, it is possible that performance was higher in the temporal order condition because it allowed for more use of “temporal tags” compared to the temporal context condition. In other words, participants may have encoded the absolute ordinal position of each item in the quadruplet. Although time-tagging accounts of temporal memory have not gained much traction in the field especially in comparison with reconstruction accounts (see Friedman, 2004), it is possible that participants encoded the ordinal position of each item during our encoding task and that these temporal tags were then used at retrieval to reconstruct order information. In the temporal order condition, by definition, each item in the retrieval array could be uniquely tagged (i.e., each item had a unique ordinal position, 1–4). In the temporal context condition, however, the distracters were randomly selected from different sequences, and so unique ordinal position of items within the retrieval array was less likely.

One could be concerned that temporal context was less likely to be successfully encoded. However, across age groups, we found participants were more likely to select distracters that had been presented in quadruplets that were closer in time to the target quadruplet than further in time. Thus, participants responded in a way that is consistent with them having encoded events that happened around the same time as the target quadruplet, a signature of temporal context; memory for the continuous temporal stream of events was available to both children and adults. Overall, this study documents for the first time developmental differences in two aspects of temporal memory and shows protracted age-related improvements that are akin to those observed in other aspects of episodic memory (e.g., spatial context, item–background associations; Bauer et al., 2012; Ghetti et al., 2010; Lloyd, Doydum, & Newcombe, 2009). Despite their similar developmental trajectory, temporal order and context appeared to function on the basis of different mechanisms as suggested by their different eye-movement effects in addition to overall level of performance.

Eyes Know Time: Tracking Veridical Temporal Order Prior to Overt Choice

The second goal of the present research was to identify specific eye-movement signatures of temporal memory. For the first time, we found eye-movement effects associated with veridical memory for time. In the temporal order condition, but not the temporal context condition, adults showed eye-movement effects as early as 1,500–2,000 ms after stimulus onset. Ten-year-olds also showed veridical memory reflected in their eye movements, in the 3,000- to 3,500-ms window, a time point later than adults. The presence of these early eye-movement effects in the temporal order, but not temporal context condition, could be due to the same factors that contributed to differences between these two conditions in overt decisions. On the one hand, the inclusion of all members of the same quadruplet as distracters in the temporal order condition may have cued the memory more strongly compared to the temporal context condition and evidently guided eye movements more effectively. On the other hand, eye movements may respond uniquely to order as a central organizational principle of temporal memory. This possibility is consistent with the individual differences in eye-movement effect in the temporal order condition being significantly associated with both temporal order and temporal context accuracy. Future research should garner further evidence to test this possibility. For example, one could manipulate the temporal context condition such that each target and distracter within a retrieval array trial consisted of items with unique temporal tags (discussed earlier; unique ordinal position for each item from encoding phase). If temporal order is a significant organizational principle, then we would expect little difference in accuracy between the temporal order condition and this type of temporal context condition.

The eye-movement effects for temporal order are promising in that they parallel those reported in the adult literature for face–scene pairs (e.g., Hannula & Ranganath, 2009; Hannula et al., 2007); these effects have been linked to hippocampal function with both patients with hippocampal lesions and neuroimaging evidence in typical adults (e.g., Hannula & Ranganath, 2009; Hannula et al., 2007; see also Bachevalier & Nemanic, 2008; Jutras &
Buffalo, 2010; for further discussion of eye movements and hippocampus in animal models). The fact that 7-year-olds as a group did not show the eye-movement effects, but 10-year-olds did, despite no group difference in overt response times, suggests that there is still continued development of the hippocampus in this age range. But even at 10 years of age, the eye-movement effects were not adult-like; the onsets of the eye-movement effect were about 1–2 s later in 10-year-olds compared to adults. Future neuroimaging studies are needed to confirm that these eye-movement effects for temporal order are rooted in the hippocampus, but this work provides indirect support for the continued development of the hippocampus in middle to late childhood documented with structural and functional neuroimaging (see Ghetti & Bunge, 2012). Future evidence against a connection between hippocampus and these eye-movement effects would not detract from the importance of the current findings; eye movements occurred several seconds before overt decisions were made and thus may track the emergence of conscious recollection of temporal information.

Although adults in the present investigation showed disproportionate viewing to correctly selected items compared to incorrectly selected items in the temporal order condition, paralleling previous findings in other context memory domains, we observed later onset of the effects compared to previous research (e.g., 500–750 ms, Hannula et al., 2007; 500–1,000 ms, Hannula & Ranganath, 2009). A methodological difference inherent to the type of context memory being tested could account for timing differences between the present work and previous investigations. In previous studies the cue was presented and remained on the screen during presentation of the three-item display as the cue was a background scene. In this study, we elected to present the cue item prior to the presentation of the retrieval array to help reinstate time; the cue was not part of the retrieval array screen. This time reinstatement likely requires more processing resources and could account for slower onset of eye-movement effects. Consistent with this idea the onset time of the effect has been shown to shift later up to a second when the processing demands of the task are increased (see Hannula et al., 2007, Experiment 3; Hannula, Baym, Warren, & Cohen, 2012).

In summary, we contend that eye-movement effects reported here reflect a valid signal of early memory processing of temporal order. Future research could examine the factors that contribute to variations in onset of these effects by including experimental conditions that may facilitate processing of temporal information. These manipulations may also elucidate age-related differences in the eye-movement effects, which may in part depend on the demands of temporal processing.

**Toward Integrating Covert and Overt Temporal Memory**

One reason eye movements are so valuable is that they might reveal how early processing may support later decisions. The eye-movement effect occurred several seconds before participants responded, suggesting that the processing reflected in the eye movements occurred prior to and possibly supported participants’ decisions. Consistent with a two-stage model of episodic memory (Moscovitch, 2008), eye movements may reflect the initial activation of the memory episode; subsequently, control processes may monitor and verify this earlier, presumably hippocampal, output.

Seven-year-olds did not show the eye-movement effect, and so it is possible this could help to explain their lower behavioral accuracy. Indeed, when we divided the 7-year-old group into those who showed the eye-movement effect for order and those who did not, 7-year-olds who showed the effect showed higher accuracy than those who did not. The difference between these two groups did not generalize to the recognition memory condition; the eye-movement effect was specific to temporal memory. Furthermore, differences in the onset of the eye-movement effects (10-year-olds later than adults) suggest that this early activation could in part be responsible for the longer reaction times for 10-year-olds compared to adults, although late decision processes would likely also require more time in children. Overall, development of the hippocampally mediated episode reactivation and prefrontally mediated monitoring and control processing likely contributed to the developmental patterns we observed in memory for temporal order and temporal context. The exact nature of this brain behavior association should be examined in future research.

Finally, we sought to account for additional factors that contributed to the development of temporal memory. We used a test that examines the capacity to flexibly represent timescales, modeled after Friedman (1989) and used in Friedman et al. (2011). Like Friedman et al. we found age-related improvements in performance on this task. Interestingly, performance on this task was correlated with
performance in the two temporal memory conditions, but not the item memory (recognition) condition. Thus, flexibly manipulating the order of semantic knowledge (months of the year) was related to retrieving temporal information in an unrelated episodic memory task, which did not necessitate any knowledge of conventional time. These findings point to the importance of flexible retrieval processes in temporal memory. Research suggests that flexible retrieval of associations between items is dependent on a network involving MTL and PFC (see Zeithamova & Preston, 2010). Of most importance, eye movements predicted overt memory judgments even when accounting for the role of CTK, providing evidence for the first time that an early component process and later component process make independent contributions to memory for temporal order and context. It would be interesting in future work to determine which brain regions show overlapping activations in tasks that require flexible retrieval of semantic temporal information (e.g., CTK task) and flexible retrieval of episodic temporal information (e.g., our temporal memory task).

Furthermore, in relation to flexibility in temporal memory retrieval, future work could examine whether the direction of temporal order or context affects accuracy. In the current investigation, the target item was one that followed the cue. It would be interesting to establish whether the same behavioral accuracy rates and eye-movement effects are seen when the target item was one that preceded the cue. In addition, future work could examine whether the effect of distance in the temporal context condition changes as a function of whether distracters preceded or followed the target sequence. To the extent that events are encoded in a continuous temporal flow (see discussion in MacDonald, Lepage, Eden, & Eichenbaum, 2011), one should expect that direction should not be critical. On the other hand, some research may suggest different predictions: Hannigan and Reinitz (2001) showed that individuals are more likely to create false memories for unstudied pictures depicting the cause of studied effects compared to unstudied pictures depicting effects of studied causes. Although these photographs shared a causal connection in addition to a temporal connection, these results suggest that the temporal direction might matter when examining the magnitude of memory distortions. In the present investigation, whether direction qualified the effect of distance could not be properly addressed because of insufficient number of trials. Future studies in which the effects of direction and distance in the encoding stream are systematically tested are needed.

Together this work highlights how multiple processes are involved in temporal memory, and multiple factors need to come together for adult-like temporal memory. Our work shows that processes reflected in eye movements and flexible retrieval processes are involved in remembering the order of past events. Recent studies in other context memory domains have found relations with executive functioning. For example, Shing et al. (2008) explored strategic processing in associative memory tasks and their relation to the development of episodic memory. Picard, Cousin, Guillery-Girard, Eustache, and Piolino (2012) found that executive functioning was particularly involved in memory for temporal–spatial context. Additional work on the factors that contribute to development of temporal memory, and its relation to episodic memory development more generally, are needed.

In summary, we examined the development of temporal order and temporal context within the same paradigm. We provided the first documentation of eye-movement patterns associated with retrieval of veridical temporal order, examined the relations between memory for temporal order and context, and examined how individual differences in other measures related to temporal memory. Our findings shed new light into temporal memory development and help identify avenues of future research that can help us to understand the parameters and limits of eye movements reflecting veridical memory for context across the life span.

References


