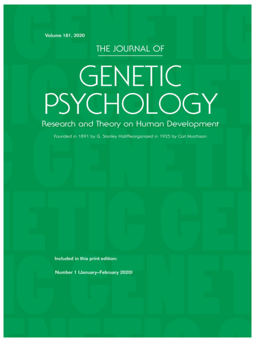

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Longitudinal Development of Memory for Temporal Order in Early to Middle Childhood

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ABSTRACT

Existing studies examining the development of temporal order memory show that although young children perform above chance on some tasks assessing temporal order memory, there are significant age-related differences across childhood. Yet, the trajectory of children's ability to retrieve temporal order remains unclear as existing conclusions are drawn from cross-sectional studies. The present study utilized an accelerated longitudinal design in order to characterize the developmental trajectory of temporal order memory in a sample of 200 healthy 4- to 8-year-old children. Specifically, two tasks commonly used in the literature were tested longitudinally: a primacy judgment task and an ordering task. Results revealed that, even after controlling for differences in IQ, linearly increasing trajectories characterized age-related change in performance for both tasks; however, change appeared greater for the temporal ordering task. Further, performance on the two tasks was positively related, suggesting shared underlying mechanisms. These findings provide a more thorough understanding of temporal order memory in early to middle childhood by characterizing the developmental trajectories of two commonly used tasks and have important implications for our understanding of children's developing memory more broadly.

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Development; early childhood; longitudinal change; temporal order memory

> Organization of knowledge in the episodic (memory) system is temporal. One event precedes, co-occurs, or succeeds another in time. – Tulving (1984, p. 225)

Think back to one of your favorite days. Can you remember what you did that day and the order in which the day's events occurred? Likely, your answer is yes. This memory of a favorite day highlights that remembering sequences within and across events is critical to building an individual past, an ability known as episodic memory. This ability allows one to recall detailed past events, whether it is a significant event (e.g., your favorite day) or more commonplace event (e.g., a trip to the grocery store), through the binding of items to the spatiotemporal context in which they occur (e.g., what happened, who was there, when and where did it occur; Olson & Newcombe, 2014; Tulving, 2002).

Given that memory for temporal information (Friedman, 1993, 2004), is a central feature of episodic (and autobiographical) memory (see Burt, 2008; Konkel & Cohen, 2009; Nelson & Fivush, 2004; Tulving, 2002), it has been widely investigated in non-human animals (e.g., DeVito & Eichenbaum, 2011; Fortin, Agster, & Eichenbaum, 2002; Howland, Harrison, Hannesson, & Phillips, 2008), typical young adults (e.g., Jenkins & Ranganath, 2010; Tubridy & Davachi, 2011),

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older adults (e.g., Allen, Morris, Stark, Fortin, & Stark, 2015; Rotblatt et al., 2015) and neuropsychological patients (e.g., Mangels, 1997; McAndrews & Milner, 1991; Shimamura, Janowsky, & Squire, 1990). There is also a large literature on human infants' ability to remember the temporal order of actions within a sequence (e.g., Bauer, Wenner, Dropik, & Wewerka, 2000; Bauer & Lukowski, 2010). This literature shows that the ability to retain information about temporal order within events emerges in the first two years of life but is rudimentary and likely relies on different cognitive and neural mechanisms than those later in development (for review see Bauer, 2007; Bauer, Hertsgaard, Dropik, & Daly, 1998; Bauer & Leventon, 2013). Yet, in contrast to the number of studies with the above mentioned groups, relatively little is known about the development of temporal order memory in early to middle childhood.

This period of childhood is interesting given both practical and theoretically-relevant transitions that occur during this time. In terms of the former, this period is when children transition into formal schooling, which is accompanied by increased experience with structured routines across the day and talk between children and teachers about time and temporal order (e.g., "We'll go to the library after recess"; see Zhang & Hudson, 2018, for discussion). Further, children in early to middle childhood gain experience and structured instruction in reading. Direction of reading supports the mental timeline (e.g., past to future events are mapped from left to right for English speakers; see Boroditsky, Fuhrman, & McCormick, 2011), and studies have shown that the mental timeline develops in the early school years (Tillman, Tulagan, Fukuda, & Barner, 2018) and is predicted by literacy skills in kindergarten (Autry, Jordan, Girgis, & Falcon, 2020). The mental timeline can support memory for temporal order (Pathman, Coughlin, & Ghetti, 2018), and thus children's increasing experience with reading in early to middle childhood could have implications for the development of temporal order memory. In terms of theory, the period of early to middle childhood is implicated in models of temporal cognition (Hoerl & McCormack, 2018; McCormack & Hoerl, 2017), which posit key transitions within this period (for example between 4- and 5-year-olds and children older than 5 years of age; McCormack & Hoerl, 2017). In addition, there are age-related differences within early to middle childhood in the hippocampus (e.g., Riggins, Blankenship, Mulligan, Rice, & Redcay, 2015; Riggins, Geng, Blankenship, & Redcay, 2016), a brain region thought to support temporal order memory (e.g., DeVito & Eichenbaum, 2011; Tubridy & Davachi, 2011). For these reasons, it is important to investigate the development of temporal order memory in early to middle childhood.

Current work across different types of studies and using different age groups suggest that temporal order memory undergoes substantial improvements in early childhood (i.e., 4–6 years; Friedman, 1991) that continue into middle childhood (i.e., 7–9 years) and young adulthood (Lee, Wendelken, Bunge, & Ghetti, 2016; Pathman, Doydum, & Bauer, 2013; Pathman & Ghetti, 2014; cf. Pathman et al., 2018). Thus, although infants show evidence of temporal order memory, this type of memory is quite protracted, and may lag behind other features of episodic memory, such as factual and spatial information (Picard, Cousin, Guillery-Girard, Eustache, & Piolino, 2012). Although statements about general age-related improvements can be made based on past studies (Friedman, 1991; Hayne & Imuta, 2011; Pathman, Doydum et al., 2013; Pathman, Larkina, Burch, & Bauer, 2013), making sense of this literature is complicated. For example, existing research during early childhood suggests that 4-year-old children perform above chance in some (Friedman, 1991, Experiments 2 and 3; Friedman, Gardner, & Zubin, 1995), but not all (Friedman, 1991, Experiment 1; Friedman et al., 1995; Friedman & Kemp, 1998; Pathman, Larkina et al., 2013), temporal order memory studies. Importantly, it is not possible to determine the trajectory of change of this ability from past studies for two reasons. First, prior studies use different types of events (e.g., recurring events versus unique events; lab-based versus autobiographical events) and different tasks to assess temporal memory (e.g., primacy/recency judgments versus placing events on either conventional or arbitrary time scales), with variable distances between events. These variations limit the ability to make inferences about the developmental trajectory of temporal order memory, especially because past work shows that using different types of tasks and events results in variable levels of performance accuracy and, subsequently, differing conclusions about differences between age-groups (e.g., Pathman, Samson, Dugas, Cabeza, & Bauer, 2011; see also Chen, Gilmore, Nelson, & McDermott, 2017). Second, and critically, all prior studies examining the development of temporal order memory are, to our knowledge, cross-sectional.

Though cross-sectional studies have enriched our understanding of the development of temporal order memory, they are limited in their ability to make claims about age-related changes and trajectories. Importantly, cross-sectional analyses do not provide a model of developmental growth that considers the correlations of repeated measurements within individuals. In contrast, longitudinal analyses allow researchers to ask questions of how change occurs. For example, developmental trajectories can be characterized by estimating models of different trajectory shapes (i.e., null/no change, linear, quadratic) while accounting for intra-individual variability in development, and subsequently examining which model (e.g., linear versus quadratic) best fits the observed data. Although findings from cross-sectional and longitudinal samples can be similar, cross-sectional samples may not have the sensitivity to detect developmental effects, may underestimate developmental effects, or may differ from results of the longitudinal sample (Nyberg et al., 2010; Pfefferbaum & Sullivan, 2015; Raz et al., 2005; Salthouse, 2019; see relevant discussions specific to memory development in early to middle childhood: Schneider & Weinert, 1995). Further, because developmental effects can be confounded by cohort effects, assuming cross-sectional results fully explain development can be problematic both analytically (Lindenberger, Von Oertzen, Ghisletta, & Hertzog, 2011) and empirically (e.g., Nyberg et al., 2010). For example, in cross-sectional designs, cohort effects and individual development (e.g., participants of different ages differ in factors other than age) are not appropriately accounted for by the overall population parameters (Lindenberger et al., 2011). For example, it is not readily apparent how different schools and classroom teachers (across countries, but importantly across time periods with changing curriculums) emphasize asking children about memories of past events, including "when" information. In addition, little is known regarding variations in different school systems' emphasis on formal instruction about time and conventional time scales, aspects of temporal knowledge that relate to memory for temporal order in both lab-based and autobiographical tasks (e.g., Friedman, Reese, & Dai, 2011; Pathman & Ghetti, 2014). In longitudinal studies changes in time are not confounded by cohort differences, and convergence of cohorts can be tested analytically (see Methods below). Thus, possible cohort effects such as different curriculum (i.e., experience in school) can be avoided with longitudinal designs. Overall, longitudinal work examining the *changes* in temporal order memory, a critical aspect of episodic memory, is necessary in order to characterize trajectories of development during the period of early to middle childhood.

Studies assessing temporal order memory frequently use one of two types of tasks. Although the details of what is being judged for order can vary (e.g., pictures, action sequences, staged events, naturalistic, or autobiographical events), these tasks are used in both children (e.g., Friedman, 1991, Experiment 1; Friedman et al., 1995; Hayne & Imuta, 2011; Pathman, Doydum et al., 2013; Ribordy Lambert, Lavenex, & Banta Lavenex, 2017; Riggins, Miller, Bauer, Georgieff, & Nelson, 2009; Roberts et al., 2015) and adults (e.g., McAlister & Schmitter-Edgecombe, 2016). One type of task is known as a primacy judgment, relative recency judgment, or primacy/recency judgment task (e.g., Friedman, 1991). This type of task involves making judgments about temporal order between only two items or events; individuals are shown stimuli and make either a primacy (i.e., "Which did you see/experience first?") or recency (i.e., "Which did you see/experience more recently?") judgment between two items from that series. Primacy/recency judgment tasks place a relatively lower demand on participants because they are presented with two events and asked to choose which was encountered first/last. Another type of task is known as an ordering or sequencing task (e.g., Pathman, Doydum et al., 2013; see also Bauer et al., 2013). This type of task involves asking or showing individuals stimuli that represent multiple events; individuals then reconstruct the sequence of events (more than two items) in the exact order that they were presented from memory. This type of task places relatively greater demands on participants because the whole sequence (i.e., >2 items) must be recreated from memory.

Although most developmental studies of temporal order memory use a single task, studies that have used multiple tasks to assess temporal order memory highlight the potential utility of comparing children's performance between tasks. Friedman and Kemp (1998) report results from primacy/recency and ordering type tasks, but results were across experiments (Study 1: relative recency judgment; Study 2: placing past events in order on arbitrary timeline) and thus the same participants were not tested on both tasks. However, a study that included tests of both primacy/recency and ordering for picture stimuli (line drawings) in the same participants found no differences between 8- to 10-year-old children and adults for the primacy/recency task, but adults outperformed children on the ordering task (Pathman, Doydum et al., 2013). This finding of differential age-related patterns based on the type of temporal order task used in late childhood/adulthood highlights the importance of using multiple temporal order tasks with varying levels of difficulty in order to gain a better, more nuanced, understanding of temporal order memory development.

To our knowledge, no study has yet examined *changes* in temporal order memory using multiple tasks in the same children during the period of early to middle childhood. The present study utilized an accelerated longitudinal (i.e., cohort-sequential) design in order to characterize trajectories of developmental change in 4- to 8-year-old children's temporal order memory using two temporal order tasks thought to differ in demands. As prior longitudinal research assessing another aspect of episodic memory development (source memory; Riggins, 2014) observed non-linear increases in the trajectory of children's performance over a two-year period, we examined the possibility that the developmental trajectory of temporal order memory would show no change, linear change, or non-linear change. Specifically, age-related changes in temporal order memory were assessed via a primacy judgment task and an ordering task. Previous research suggests the former may be less demanding and thus show less developmental change, whereas the latter may be more demanding and show greater age-related change (Pathman, Doydum et al., 2013). Finally, we also explored the extent to which the developmental improvements on both types of temporal order memory tasks related to assess the extent to which these tasks similarly measure this critical ability during early to middle childhood.

Method

Participants

The current study was part of a larger research project examining the development of memory. Prior to data collection, all methods were approved by the Institutional Review Board at The University of Maryland. This report examines age-related changes in temporal order memory over time using the accelerated longitudinal sample.

A total of 200 4- to 8-year-old children (100 reported females; 100 reported males) were recruited for the current study. The current report includes data from 198 participants (two participants were excluded because they were not administered the IQ test). An accelerated longitudinal (i.e., cohort-sequential) design with three waves of data collection was employed with cohorts overlapping at age 6 to simulate a longer longitudinal trajectory and assessment of developmental changes (Duncan, Duncan, & Hops, 1996). Children who were recruited at 4 or 6 years of age were invited back at two subsequent time points, while children who were recruited at 5, 7, or 8 years of age were not invited back for subsequent testing. Specifically, 112 participants provided data at a single wave, 7 participants provided data at 2 waves, and 79 participants provided

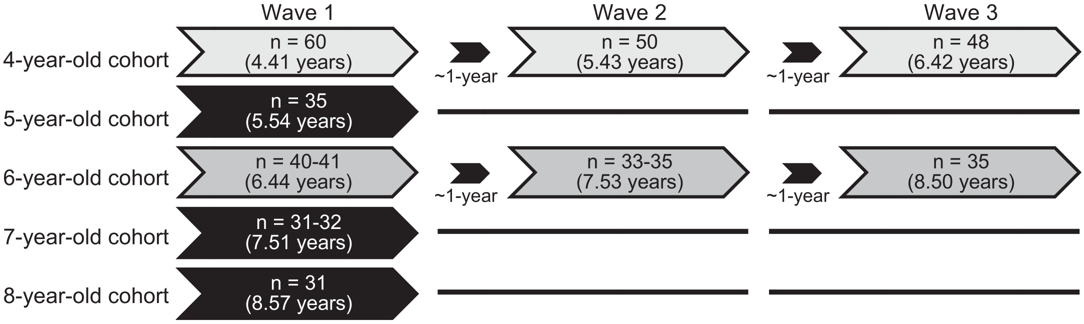

Figure 1. Schematic representation of the cohort-sequential study design including the number of participants and average age of participants in each cohort at the three waves. Four- and six-year-old participants at the initial wave were invited back for two subsequent visits. Five-, seven-, and eight-year-olds at the initial wave were not invited back for subsequent waves.

data at all 3 waves. However, two children completed only one of the two tasks at Wave 1 and Wave 2 (i.e., four children in total). Wave 1 included data from 197 children (99 males, *M* = 6.16 years, *SD* = 1.52 years, range = 4.00–8.95 years). Wave 2 included data from 83 children (45 males, *M* = 6.26 years, *SD* = 1.07 years, range = 5.02–8.03 years) collected, on average, 1.04 years later (*SD* = 0.09 years, range = .96–1.40 years,). Wave 3 included data from 83 children (47 males, *M* = 7.30 years, *SD* = 1.07 years, range = 6.00–9.53 years) collected, on average, 0.98 years later (*SD* = 0.11 years, range = .58–1.50 years). For a depiction of the study design, including the number of participants and average age of participants at each wave by cohort, see Figure 1.

The final sample of participants was approximately 56% Caucasian, 13% African American, 5% Asian, and 19% Multiracial from middle- to high-income households (median = >$105,000, range = < $15,000 - >$105,000). An additional 7% of parents did not disclose their child's race and 5% did not disclose income. Children were screened to ensure they were not born premature, had normal or corrected-to-normal vision, and had no diagnosis for any neurological conditions, developmental delays, or disabilities. Informed consent was obtained from parents, and written assent was obtained for children older than 7 years.

Materials and procedures

Primacy judgment task

One task used to assess temporal order memory was a primacy judgment task (Figure 2). It consisted of a modified version of a task used in two previous investigations of temporal order memory using primacy judgments in early to middle childhood (Alden, 1994; Mathews & Fozard, 1970). Children were presented with four different lists of pictures. Because of the age-range of participants and accelerated longitudinal design of the study, we used both two shorter 8-item lists and two longer, more demanding, 12-item lists. Including both 8-item and 12-item lists allowed us to examine increased task demands within the task and possible differences in age-related changes in performance. Each child was also given a 4-item practice list to ensure task understanding. Item lists were composed of simple line-drawings of common objects (e.g., button, paper bag). Each item was presented individually with a verbal label (e.g., "button," "paper bag") at a rate of approximately 1 picture every 2 seconds and placed face up in a pile on the table to eliminate spatial cues (Figure 2A). Children were instructed to remember the order of the pictures (Figure 2B). After each list was presented, the Experimenter either immediately presented the child with two 2-alternative forced-choice questions or an age-appropriate distractor task before asking the forced-choice questions to explore the extent to which working memory/ rehearsal may have been playing a role in performance. For the distractor task, the child either

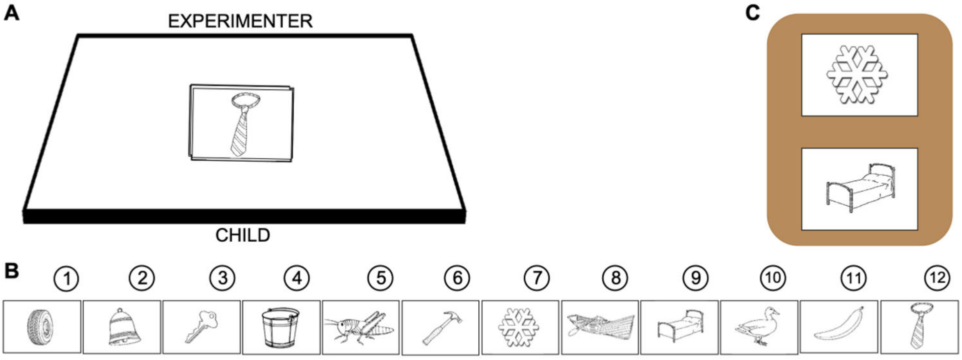

Figure 2. Example from the primacy judgment task showing (A) the experimental set up for list presentation, (B) the 12-item list presented to children flat on a table at a rate of 1 card per second, and (C) a sampled test pair of items for the order judgment.

played tic-tac-toe or was given instructions to draw a house if they did not know how to play tic-tac-toe. The delay for either distractor task was approximately 1 minute.

Children judged which of the two pictures was presented earlier in the sequence (a primacy judgment). Each pair of items used for primacy judgments was presented an equal distance apart within the lists (with one picture in between). One pair of items was drawn from the first half of the list and the second pair from the second half of the list. Thus, for both 8-items lists, items 2 and 4 were paired and items 5 and 7 were paired for primacy judgments. For 12-item lists, one tested judgments for items 3 and 5, and items 7 and 9, the other tested judgments for items 4 and 6, and items 8 and 10. This list design was used in order to ensure 1) the first and last items presented were not used for judgments, and 2) there was no overlap between pairs of items. Presentation location of the correct item (Figure 2C) varied across lists (i.e., the correct picture was on the top for some trials and on the bottom for others) and these presentation locations were varied between subjects throughout data collection. List presentation order and lists assigned immediate judgments or a distractor task before judgments were counterbalanced across participants. Children's primacy judgment task performance was measured as the proportion of correct primacy judgments across lists.

Ordering task

The second task used to assess temporal order memory was an ordering task (Figure 3; Bauer et al., 2013; Pathman, Doydum et al., 2013). Children were shown one 4-item practice picture sequence (Yard) to ensure understanding, and then two of three possible 9-item picture sequences (Pet Shop, Park, Fair). These events were thematically related but relations between items were arbitrary (i.e., they did not contain enabling relations). Laminated index cards were used for each picture. The order of the two 9-item sequence presentations was counter-balanced and pairs of lists were randomly assigned across participants. The Experimenter introduced all of the sequences with a verbal label (e.g., "I'm going to show you how I work in the yard"). The Experimenter then demonstrated the sequence by showing the child each picture in the sequence (e.g., "mow the lawn") accompanied with a verbal label and placing the pictures on the table in an upside down "V" shape (from child's left to right; Figure 3A). No causal or temporal language cues (e.g., "next" or "then") were given in the verbal labels. When the sequence was finished, the event label was provided again, (e.g., "That's how I work in the yard"). Upon completion, the Experimenter shuffled the pictures and the child attempted to reconstruct the sequence (Figure 3B).

Participants were randomly assigned to a distractor task between the presentation of one of the 9-item picture sequences and its reconstruction to explore the extent to which working

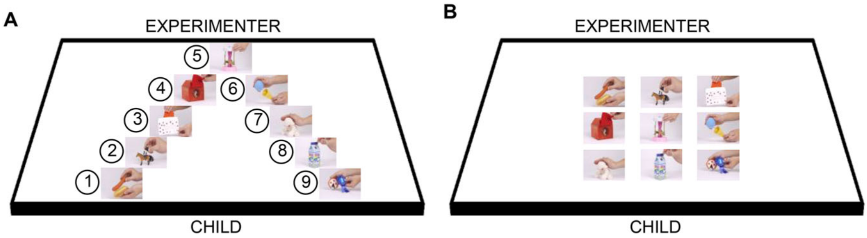

Figure 3. Example of sequence from the ordering task (Fair). Note: numbers were not shown on the cards children saw. (A) Encoding portion presented pictures to children in a set order one at a time. (B) At retrieval, cards were shuffled, and children were required to recreate the encoded sequence. Children received one point for each pair of cards placed sequentially (e.g., 4 followed by 5), in their reconstructed sequence (adjacent pairs). Children would not receive a point for pairs reconstructed non-sequentially (e.g., 4 followed 6) as these items were not adjacent in the initial sequence.

memory/rehearsal may have been playing a role in performance. For the distractor task, the child either played tic-tac-toe or was given instructions to draw a house if they did not know how to play tic-tac-toe. The delay for either distractor task was approximately 1 minute. Once the child reconstructed the sequence to the best of their ability, the Experimenter recorded the child's reconstructed sequence order. Children's reconstructions were scored on the number of adjacent pairs (two items in the exact correct order, one after another, such as 6 and 7), with 8 possible adjacent pairs for each sequence (16 total adjacent pairs possible). Children's ordering task performance was measured as the proportion of adjacent pairs recalled across sequences.

IQ

Age-appropriate subtests from standardized intelligence assessments were administered at Wave 1. The Wechsler Preschool and Primary Scale of Intelligence (WPPSI) was administered to 4- and 5-year-olds and the Wechsler Intelligence Scale for Children (WISC) was administered to 6-, 7-, and 8-year-olds. Two children were not administered the IQ test. The current report includes scaled scores from the block design subtest, which reflects visual-spatial intelligence to control for global differences in intelligence that may relate to temporal order memory.

Statistical analyses

To characterize the development of temporal order memory during early to middle childhood, we utilized linear mixed-effect models. Statistical analyses were performed in R 3.5.2 (https://www.r-project.org) using the package nlme (Pinheiro et al., 2019). The R package ggplot2 (Wickham, 2016) was used for visualization.

Mixed-effect modeling is well-suited to the present study as it allows for planned missingness and does not require subjects to provide data at all measurement occasions (Ghisletta & Lindenberger, 2004). These models can estimate the intercept and slope that characterizes the sample as a group (fixed effects), and additionally, subject level intercepts and slopes that may differ from the group (random effects; Ghisletta, Renaud, Jacot, & Courvoisier, 2015).

In the present study, linear mixed-effect models were used to estimate the fixed effects of measured variables (e.g., age) on two separate tasks to assess temporal order memory (i.e., primacy judgment and ordering tasks) while including within-person variation as random effects. Formal model testing procedures using likelihood ratio tests and fit indices were used to identify the best fitting growth function. Models with lower Bayesian Information Criterion (BIC) values were considered to better fit to the data. This method has been used in longitudinal studies examining other aspects of development (e.g., Hong, Rhee, & Piescher, 2018; Mangin, Horwood, & Woodward, 2017; Park, Weismer, & Kaushanskaya, 2018). Model comparisons were conducted to test whether the inclusion linear and or quadratic age terms increased model fit over the previous lower-order models (e.g., a

Table 1. Bayesian Information Criterion (BIC) values for the unconditional means models and age models by temporal order memory task accounting for sex and IQ.

Task	Random intercept	Age	Age^2	Random slope
Ordering task	-16.16	**-111.30**	-106.27	-99.52
8-item primacy judgment list	-9.26	**-25.93**	-21.80	-15.32
12-item primacy judgment list	16.14	**12.38**	17.91	24.18
Overall primacy judgment task	-217.02	**-236.18**	-230.60	-224.38

Bold highlights $p < .05$ to indicate the best model using likelihood ratio tests comparing models for each of the following steps: 1) null (random intercept) and growth (age) models, 2) best age model with random slope.

linear model compared to the null model). First, a null model was estimated with no effect of age, followed by a linear age model, and finally a quadratic age model. To assess whether individual trajectories significantly varied, we tested whether the inclusion of a random subject slope improved model fit. All models included a random subject intercept and were adjusted for participant sex and IQ. Additionally, we examined the relation between performance on the two tasks using a mixed-effect model with ordering task performance predicted by primacy judgment task performance, controlling for the effects of age, sex, and IQ. Age was centered in order to estimate intercepts at the average age of the entire sample (6.45 years).

Finally, to ensure that cohort differences did not impact the estimation of developmental trajectories, we tested trajectory convergence using the method outlined by Miyazaki and Raudenbush (2000). Results of these comparisons support the assumption that the cohorts followed the same developmental trajectory, therefore only models omitting cohort effects are reported. Estimation of the reported model parameters used restricted maximum likelihood (REML), while model comparisons used maximum likelihood (ML).

Results

Preliminary results

Preliminary analyses examining the impact of the distractor task at each wave revealed that neither performance on the primacy judgment task nor ordering task was impacted by this manipulation. Therefore, performance was collapsed across distractor conditions for both the primacy judgment and ordering tasks. However preliminary analyses examining the effect of list length for the primacy judgment task at each wave suggested that performance on 8-item and 12-item lists differed. Therefore, developmental trajectories for performance on the primacy judgment task were examined both separately for 8-item and 12-item lists and collapsed across 8-item and 12-item lists.

Main analyses

See Table 1 for likelihood ratio tests for best fitting models for primacy judgment task and ordering task performance, Table 2 for a summary of final model parameters for the primacy judgment task, and Table 3 for a summary of final model parameters for the ordering task.

Primacy judgment task

Significant developmental improvements in participants' performance on the primacy judgment task were observed during this period.

8-item list performance. The best fitting model for performance on the 8-item lists included a linear effect of age with a random subject intercept and fixed slope (Table 1). Performance on 8-item list primacy judgment task performance increased linearly with age (Table 2). As is

Table 2. Model parameters for fixed effects in the best fitting age models for 8-item, 12-item, and overall performance on the primacy judgment task accounting for sex and IQ.

Task	β	*b*	*SE*	*t*	*p*
8-item primacy judgment list					
Intercept	–	0.701	0.053	13.24	**< 0.001**
Age	0.25	0.042	0.009	4.82	**< 0.001**
Sex	-0.08	-0.036	0.025	-1.43	0.15
IQ	-0.001	-0.000	0.004	-0.02	0.98
12-item primacy judgment list					
Intercept	–	0.537	0.052	10.29	**< 0.001**
Age	0.16	0.028	0.009	3.11	**0.002**
Sex	0.06	0.027	0.025	1.11	0.27
IQ	0.05	0.004	0.004	0.96	0.34
Overall primacy judgment task					
Intercept	–	0.619	0.040	15.33	**< 0.001**
Age	0.27	0.033	0.007	5.13	**< 0.001**
Sex	-0.02	-0.006	0.019	-0.31	0.76
IQ	0.04	0.002	0.003	0.71	0.48

Notes: β reflect standardized coefficients. *b* values in proportion correct for each task, respectively. Bold indicates $p < .05$.

Table 3. Model parameters for fixed effects in the best fitting age model for the ordering task accounting for sex and IQ

Task	β	*b*	*SE*	*t*	*p*
Ordering task					
Intercept	–	0.423	0.051	8.36	**< 0.001**
Age	0.50	0.084	0.008	10.74	**< 0.001**
Sex	-0.09	-0.042	0.024	-1.74	*0.08*
IQ	0.07	0.005	0.004	1.26	0.21

Notes: β reflect standardized coefficients. *b* values in proportion correct for the task. Bold indicates $p < .05$, italic indicates $p < .10$.

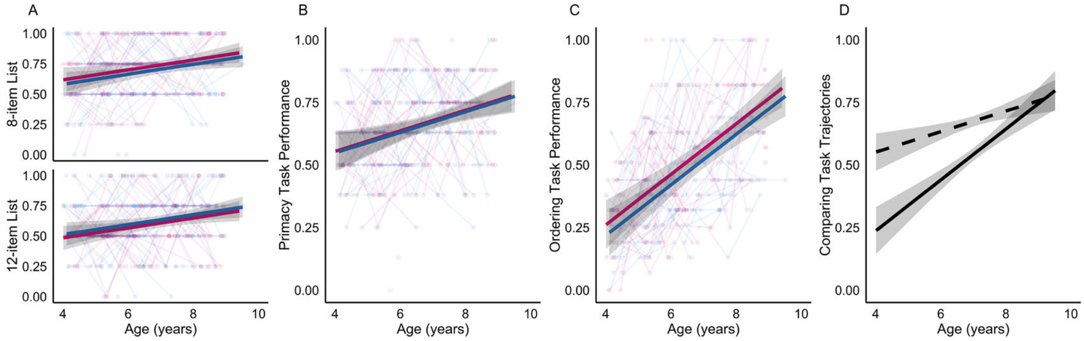

Figure 4. Developmental trajectories for (A) 8-item (top) and 12-item (bottom) primacy judgment task performance, (B) overall primacy judgment task performance, and (C) ordering task performance. (D) Visual comparison of developmental trajectories for both primacy judgment task (dashed line) and ordering task (solid line) performance. Performance measured in proportion correct for each task. For plots A, B, and C female subjects are presented in pink, male subjects in blue. Error bands represent 95% confidence intervals. Participants measured more than once are represented by dots connected by individual lines, and participants measured once are represented by dots.

illustrated in Figure 4A (top), children appeared to perform better on 8-item list judgments compared to the 12-item list.

12-item list performance. The best fitting model for performance on the 12-item lists included a linear effect of age with a random subject intercept and fixed slope (Table 1). Performance on 12-item list primacy judgment task performance increased linearly with age (Table 2). As is illustrated in Figure 4A (bottom), the youngest children appeared to perform worse on 12-item list judgments compared to the 8-item list.

Overall performance. The best fitting model for performance collapsed across 8-item and 12-item lists included a linear effect of age with a random subject intercept and fixed slope (Table 1). Performance collapsed across 8-item and 12-item lists increased linearly with age (Figure 4B). Neither sex, nor IQ, significantly related to changes in performance on the primacy judgment task as a measure of temporal order memory (Table 2).

Ordering task

Significant developmental improvements in participants' performance on the ordering task were observed during this period, as indicated by a positive linear effect of age (Figure 4C). The best fitting model included a linear effect of age with a random subject intercept and fixed slope (Table 1). Neither sex nor IQ was significantly related to changes in performance on the ordering task as a measure of temporal order memory (Table 3).

Relations between tasks

Because we found that performance on both the primacy judgment task and ordering task increased linearly with age (see Tables 2 and 3), we examined the extent to which the two tasks similarly assess temporal order memory. Overall primacy judgment task performance related to ordering task performance (t (162) = 2.54, $\beta = 0.12$, $b = 0.16$, $p = .012$). However, in comparing age-related change for each task, age-related increases in performance appeared greater for the ordering task, compared to the primacy judgement task with apparent differences in task performance earlier, versus later, during this period (Figure 4D).

Discussion

In this accelerated longitudinal study, we examined developmental changes in temporal order memory in 4- to 8-year-old children using two tasks: a primacy judgment task where participants judged which of two items from a set of items was seen first, and an ordering task where participants recalled the sequence for a given set of items. We found that a linear developmental trajectory best accounted for changes in children's performance on each task. In addition, children's performance on one task was related to their performance on the other task. Below we expand on the findings and discuss the implications of this work, how the findings relate to previous cross-sectional work examining temporal order memory development, and raise potential mechanisms that highlight early childhood as a particularly important period to examine.

In the present study, improvements in performance on both temporal order tasks showed linear increases. This finding is important because this linear trajectory differs from previous longitudinal research that showed non-linear increases in children's source memory, another key aspect of episodic memory (Riggins, 2014), in early to middle childhood. The different developmental trajectories support a distinction of these key aspects of episodic memory ability in early childhood. However, future longitudinal research should examine their relation to each other within the same sample in order to directly compare these differing patterns. Although the linear developmental trajectory may not have been predicted based on the non-linear trajectory found in Riggins (2014), it is in line with age-related improvements that are inferred based on cross-sectional studies of temporal memory in early childhood (e.g., Friedman, 1991; Pathman, Doydum et al., 2013). Future studies are needed to expand on the developmental trajectories characterized here to determine whether a steeper trajectory in early to middle childhood plateaus somewhere in late childhood and adolescence. Although this type of pattern across childhood and into adulthood can be inferred based on comparing different studies, using different tasks and age groups (as noted earlier), only future longitudinal work can confirm the trajectory. (For further discussion of why cross-sectional studies provide *indirect* evidence of memory development see Schneider, 2014; see also Reese, 2014.)

In addition to adding to the literature on the development of temporal memory, the findings of this study have broader implications. First, understanding the differences between young children's ability to retrieve sequences of events compared to the ability to judge the order of two events, and the rate at which temporal order memory changes during childhood may impact eyewitness testimony, as well as the admissibility of children's accounts (Friedman & Lyon, 2005; see also Wandrey, Lyon, Quas, & Friedman, 2012). Studies like ours that explore the different limits of children's abilities are useful for those interviewing children or assessing their memory in legal settings. For example, the primacy judgment task illustrated that, on average, children appeared to perform better on the 8-item primacy judgment list compared to the 12-item primacy judgment list. Another relevant finding to legal settings is the descriptive comparison of the primacy task with the ordering task. Collapsing performance across 8-item and 12-item lists captured variability in primacy judgment performance across this entire age-range, with overall primacy judgments increasing in accuracy during early to middle childhood. Linear age-related increases in performance were also observed for the ordering task during early to middle childhood, with improvements appearing greater in ordering performance compared to primacy judgments across the age range investigated. This task likely placed greater demands on children by requiring them to not only judge which item in a sequence came first, but also required children to recreate 9-item sequences. Overall, this suggests that younger children may be able to judge the temporal order of two events but struggle to reconstruct the order of events, for which the retrieval of sequences is required.

Second, this work has theoretical implications, as it relates to our understanding of episodic memory and its development because temporal order memory is a key feature of episodic memory. The findings from cross-sectional studies, reinforced by the findings from the present longitudinal study, suggest that the protracted development of children's ability to temporally order events contribute to improvements in episodic memory abilities observed during early childhood. Previous cross-sectional work has inferred that memory for temporal information lags behind other aspects of episodic memory such as factual and spatial information (Picard et al., 2012). The protracted development of temporal order memory likely relates to children's performance on other tasks assessing episodic memory, and additional work on the relation between the development of temporal order memory and other features of episodic memory and its development are needed.

Despite apparent differences in trajectory slopes, performance on the two tasks was positively related, suggesting a shared underlying mechanism supporting the ability to retrieve temporal information on these tasks. Possible neural mechanisms supporting the improvements observed during early childhood in episodic memory, and temporal order memory more specifically, may include both the hippocampus and frontal cortex (DeVito & Eichenbaum, 2011; Naya, Chen, Yang, & Suzuki, 2017). In relation to the hippocampus, two neurocomputational processes, pattern separation and pattern completion, have been nominated as potential mechanisms underlying temporal order memory (see Davachi & DuBrow, 2015). The small body of research that has started to examine the correlates of these neurocomputational processes support a role of pattern separation in supporting temporal order memory (Azab, Stark, & Stark, 2014; Tolentino, Pirogovsky, Luu, Toner, & Gilbert, 2012). This process is proposed to minimize the overlap of contextually similar details during encoding (e.g., temporal information), which may facilitate the retrieval of close or similar events. A role for the hippocampus in supporting temporal order memory is also suggested by findings that show this region is preferentially engaged during the successful retrieval of temporal order information in adults (Ekstrom & Bookheimer, 2007). A role of the frontal cortex in supporting temporal order memory is illustrated by impairments in this ability related to frontal lobe dysfunction in aging adults (e.g., Cabeza, Anderson, Houle, Mangels, &

Nyberg, 2000) and patients (e.g., Shimamura et al., 1990). Importantly, development of both the frontal lobes of the cortex and hippocampus is protracted (e.g., Casey, Giedd, & Thomas, 2000; Casey, Tottenham, Liston, & Durston, 2005) and developmental differences in both structure and function of these regions during early to middle childhood relate to performance on tasks assessing episodic memory ability (e.g., Geng, Redcay, & Riggins, 2019; Riggins et al., 2018; see Romine & Reynolds, 2004 for review) and pattern separation ability (Canada, Ngo, Newcombe, Geng, & Riggins, 2019).

Although direct relations between brain development and temporal order memory have not yet been examined during childhood, some work has suggested a relation exists using measures thought to capture differential hippocampal processing in children. Specifically, in a sample of 7-year-olds, 10-year-olds, and adult participants, age-related improvements in performance on a temporal order task were observed (Pathman & Ghetti, 2014). Additionally, eye-movements in adults and the older group of children, but not the younger group of children, tracked correct memory decisions before participants made overt temporal order judgments. This type of eye-movement effect is suggested to reflect hippocampal activity (e.g., Hannula & Ranganath, 2009). Further, although as a group the younger children did not show an eye-movement effect, temporal order memory was better in the subset of younger children who showed an eye-movement effect compared to younger children who did not (Pathman & Ghetti, 2014). This suggests the protracted development of temporal order memory may relate to underlying differences in the hippocampus, a region that is well established as critical to episodic memory (e.g., Milner, Corkin, & Teuber, 1968; Vargha-Khadem et al., 1997). Overall, there is likely a relation between development improvements in temporal order memory and developmental maturation of the brain. Additional research utilizing both behavioral and neuroimaging measures may clarify the individual differences observed in the development of children's temporal order memory.

Beyond the development of the neural mechanisms supporting temporal order memory, it is useful to consider the cognitive processes implicated in temporal memory and how they relate to the present work. Two types of processes have been implicated in temporal memory: reconstruction and distance-based processes (Friedman, 1993, 2004). Reconstruction involves using contextual details associated with the events (and, if relevant, knowledge about time patterns) to infer when past events occurred. For example, in the present work, one could infer that the "tire" was before "snowflake" because you recall being reminded of your car's flat tire soon after starting the task. Distance-based processes involve using differences in the strength of the memory trace (e.g., how vivid the event feels) to infer when it occurred. For example, one could infer that "tire" was before "snowflake" because the memory for "tire" is not as strong as that for "snowflake." It is also possible that participants encoded temporal tags during the task (e.g., attaching an ordinal position to each item) and that was used to judge temporal order between items. Although time-tagging processes are not as emphasized compared to reconstruction, for example (Friedman, 2004), it is possible that children's memory representations of the events included temporal tags, as in other lab-based tasks of temporal order memory (Pathman & Ghetti, 2015). Age-related differences in the use of all three types of processes could underlie the linear developmental trajectories found in the present work. Future work is necessary to disentangle the use of these different processes in childhood. However, progress has been made in examining reconstruction in cross-sectional studies using different types of tasks. One study in early to middle childhood showed that abilities necessary for reconstruction may not be apparent until 6 years of age (Friedman & Lyon, 2005), but by late childhood, children and young adults may be utilizing reconstruction processes similarly (see Jack, Friedman, Reese, & Zajac, 2016; Pathman, Doydum et al., 2013).

Given that performance on the ordering task included more events within a sequence than the two-item judgment in the primacy task, it is possible younger children's ability to infer temporal order using the above processes was over-burdened when attempting to correctly retrieve all items in order from memory. Finally, it is possible that in addition to these domain-specific time-related processes (e.g., temporal reconstruction, distance-based processes), other controlled, top-down processes (e.g., working memory, attention) may be differentially burdened during primacy judgment versus ordering tasks. Overall, future work is needed to determine and disentangle the mechanisms and processes supporting temporal order memory during childhood.

Although this study provides an important and novel contribution to the literature by examining changes that occur in temporal order memory during early to middle childhood longitudinally, future research is needed to build upon these findings. To achieve its goals, the present study involved lab-based events. Events used in studies of temporal order memory are often lab-based stimuli (e.g., pictures of objects; Jenkins & Ranganath, 2010; Pathman & Ghetti, 2014), but they can also be autobiographical events (e.g., events encountered outside the lab; Burt, Kemp, Grady, & Conway, 2000). Although using autobiographical events in memory assessments allow for high ecological validity, individuals can substantially vary in the events and details they recall, and experimenters often cannot verify accuracy. While both approaches have strengths and weaknesses, a notable strength of controlled, laboratory-based tasks is the ability experimentally manipulate particular aspects of the task (e.g., number of events to be ordered; number of intervening events; delay between encoding and test) and keep them constant across groups. For these reasons, as the first longitudinal study of temporal order memory in childhood (to our knowledge), utilizing lab-based tasks and lab-based stimuli (pictures of objects) was the necessary first step. A future longitudinal study could examine how the developmental trajectory may differ using autobiographical events instead of lab-based stimuli. Moreover, the two different tasks used in the present study were selected because they are often used in the literature. However, although both tasks measure temporal order memory, they differ on multiple surface features. Namely, they differ in the number of items in a list, the number of intervening items at test, and the demands placed on participants (forced choice or sequence recreation). Future studies, either cross-sectional or longitudinal, could control the various parameters of these tasks to examine their effects on performance and whether certain surface features affect particular age groups more or less.

Additionally, it is important to note that memory for temporal information can be considered in multiple ways. The present study focused on memory for temporal order, however we can also show evidence of remembering temporal information associated with past events by placing events on an arbitrary or conventional time scale (e.g., the event happened in the *March*) or by judging the distances of past events from each other or from the present (see Friedman, 1993, 2004). Studies have examined these aspects of temporal context (e.g., conventional time scale; Bauer, Burch, Scholin, & Guler, 2007; Friedman, 1991, 1992; Friedman & Kemp, 1998; Friedman & Lyon, 2005; Friedman et al., 2011; Pathman, Larkina et al., 2013). Future studies could include tasks that measure the different aspects of temporal memory (order, distance, locations; see Friedman, 2004) in the same study. Finally, although temporal order memory is an important aspect of human temporal cognition, it is not the only aspect. Consequently, it is possible that changes in other aspects of temporal cognition contribute to children's increasing temporal order memory ability. Future longitudinal studies could also collect additional measures related to aspects of temporal cognition that show differences in early childhood such as children's knowledge of time (Friedman et al., 2011; Pathman & Ghetti, 2014), use of time related-language (Shatz, Tare, Nguyen, & Young, 2010; Tillman, Marghetis, Barner, & Srinivasan, 2017; Zhang & Hudson, 2018), and ability to reason about time (McCormack & Hanley, 2011).

Overall, the current study offers an important insight into changes in temporal order memory that occur during early to middle childhood. Results from the present study provide converging evidence from cross-sectional research showing developmental improvements in temporal order memory during this developmental period while additionally characterizing trajectories of change in this ability during early to middle childhood. Further, this work has practical implications, such as in forensic settings, discussed above, but also may have implications for remembering everyday activities as well as success in school on tasks that require it (e.g., reading, Autry et al., 2020). Additionally, this work has theoretical implications, as it informs our understanding of episodic memory more broadly, including its development. Remembering the temporal order both within and across events is critical to building an individual past and one's autobiography. Thus, the present work is a first step in using a longitudinal design to examine this critical capacity in early to middle childhood, but future longitudinal research is still needed to understand the developing mechanisms underlying temporal order memory during childhood and the relation between this ability and additional aspects of temporal cognition.

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