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The Development of the Mental Timeline is Related to Temporal Memory

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ABSTRACT

Although we cannot see or touch time, across many cultures, we use spatial representations to think about this abstract concept. Spatial representations of time are thought to support temporal concepts that might otherwise be difficult to represent and reason about, such as the temporal component of episodic memory. One common form of spatially representing time is the mental timeline, which is a linear projection of time onto space. Adults and older children from many cultures spontaneously activate the mental timeline when remembering the order of events. However, the mental timeline develops slowly throughout early childhood as children gain increasing experience with formal schooling and cultural artifacts. Here, we explored how individual differences in the development of American children's mental timelines relate to their memory for temporal order ($N = 96$, $M_{age} = 6.22$ years). We first tested children's memory for the order and location of events through a memory task involving short videos. We then tested children's spontaneous spatial representations of temporal order using an open-ended timeline construction task. The linearity of children's timeline arrangements predicted their memory for temporal order but not memory for locations: children who spontaneously represented time linearly had significantly better temporal memory performance than children who represented time nonlinearly, but there was no difference in location memory performance. These data provide preliminary evidence that the development of the mental timeline may support the development of temporal memory.

Spatial representations of time are all around us. In many languages, we use space to describe time, such as saying things like "the future is ahead of us" or describing a deadline as "fast approaching" (Lakoff & Johnson, 1980). Similarly, we tend to use co-speech gestures while talking or reasoning about time, such as moving our hands in a forward motion when talking about the future, which adds a spatial component to spoken language (Cooperrider & Núñez, 2009). In addition to these external manifestations of spatiotemporal associations, internal representations of time also invoke spatial representations (Bonato & Umiltà, 2014; Srinivasan & Carey, 2010).

Spatial representations of time are likely so common across cultures because they are beneficial for representing and reasoning about time (Casasanto & Boroditsky, 2008; Lakoff & Johnson, 1980). Time is an abstract domain, which means we cannot directly experience it through the senses – we cannot see or touch time. Space, on the other hand, is a concrete domain. To improve our ability to reason about time, it is advantageous to conceptualize

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time as having properties that apply to physical entities: as an entity that flows in one direction, such that the past and the future have different properties; as a unified entity such that each point in time is ordered relative to each other; and as a transient entity, such that each point in time occurs once (Bender & Beller, 2014; Galton, 2011). Applying these properties to time makes temporal concepts more concrete, which in turn supports temporal reasoning.

It has long been noted that young children have difficulty reasoning about time (Piaget, 1969, 1970). Especially early in development, children use spatial information when making judgments about temporal duration and order, which indicates that space and time are closely related in children's minds (Piaget, 1969, 1970). Studies exploring the relations between spatial and temporal reasoning suggest that the two domains are asymmetrically related, such that children and adults use spatial information to make judgments about time more than they use temporal information to make judgments about space (Casasanto et al., 2010). Because spatial information may be primary to temporal information, in some settings, people, and especially young children, use spatial information to infer temporal information even when it is incorrect to do so.

One theory of temporal development argues that the linear, directional understanding of time supports mature temporal cognitive abilities (McCormack & Hoerl, 2017). In their model of the development of temporal concepts, McCormack and Hoerl (2017) suggest that as temporal concepts mature, children demonstrate a shift from representing points in time through a sequence of events to an understanding of time that is independent of specific events. Before they have abstract representations of time, children may represent time in terms of familiar sequences of events or concepts, such as expecting a bedtime routine in which they bathe before they put their pajamas on (McCormack & Hoerl, 2017) or thinking of "tomorrow" as something that happens after they go to bed (Tillman et al., 2017). As children form more abstract conceptualizations of time, they become able to think about points in time independent of particular events (e.g., "tomorrow" will come whether they go to bed or not). Specifically, children may be able to understand that points in time are systematically related, and as we move through time, our perspective of time also moves, rendering terms like "yesterday" and "tomorrow" relative rather than fixed: although "yesterday" is in the past and no longer alterable, it was once "tomorrow" and therefore alterable (McCormack, 2014). An event-independent understanding of time allows children to develop more sophisticated temporal reasoning abilities, such as the ability to mentally "move" possible events in time to plan for the future.

McCormack and Hoerl (2017) argue that the mastery of a conventional clock and calendar system further supports children's ability to think about abstract time. When children's representations of time consist of familiar sequences of events, it may be difficult to recognize how points in time are related to each other, independent of which events may take place at those points. Learning to use calendars may facilitate children's reasoning about abstract time by making properties such as linearity and directionality more transparent and concrete by helping detach temporal concepts from particular events (e.g., "last year" was when I had my last birthday) (Campbell, 2006; Friedman, 1990; McCormack & Hoerl, 2017). For instance, calendars feature repeated cycles of temporal units, such as days and weeks, which highlight how terms like "yesterday" are relative to the present, and they visualize the temporal distance between concepts like "yesterday" and "last week." Because calendars provide a visual demonstration of temporal concepts, they can facilitate the ability to reason about the abstract properties of time by explicitly linking temporal and spatial representations (Campbell, 2006; Friedman, 1990; McCormack & Hoerl, 2017)

Linear representations of time are present not just in external cultural artifacts, such as calendars, but also in internal, mental representations of time. Specifically, the mental timeline is a culturally widespread representation of time that represents the flow of time as linear and unidirectional (Bender & Beller, 2014; Bonato et al., 2012). For most Western adults, the mental timeline has a left-to-right, horizontal spatial layout. Individuals who think about time using this layout associate earlier and past events with the left side and later and future events with the right side. The orientation of the mental timeline is influenced by several cultural factors including reading and writing direction, linguistic metaphors, and calendars (Bergen & Chan Lau, 2012; Boroditsky et al., 2011; Pitt & Casasanto, 2020; Starr & Srinivasan, 2021). For instance, English-speaking adults organize temporal sequences in a left-to-right order, while Hebrew speakers, whose reading and writing direction is from right-to-left, arrange them in a right-to-left order (Fuhrman & Boroditsky, 2010; Tversky et al., 1991).

For children in the US, Canada, and Israel, the mental timeline emerges around 5 years of age. Children's mental representations of time become increasingly linear and aligned with cultural conventions as they gain experience with reading and cultural artifacts like calendars (Autry et al., 2020; Tillman et al., 2018, 2022; Tversky et al., 1991). The development of the mental timeline has frequently been assessed using a paradigm developed by Tversky et al. (1991). In this paradigm, participants place stickers on a piece of paper to represent temporal events (e.g., morning, noon, and night). In each trial, the experimenter places the reference sticker in the middle of the page (e.g., noon), and participants place the other two stickers on the page (e.g., morning, night). Tversky et al. (1991) tested English, Hebrew, and Arabic-speaking participants and found that written language conventions had a significant influence on how participants arranged the stickers. English-speaking participants arranged temporal events predominantly from left-to-right, whereas Arabic and Hebrew-speaking participants arranged them predominantly from right-to-left, consistent with the reading and writing directions of these languages.

Tillman et al. (2018) adapted this paradigm to explore the emergence and flexibility of the mental timeline in 4-to-6-year-old children and adults. Participants arranged stickers that represent temporal events on a piece of paper. The experimenters then coded whether participants made linear or nonlinear arrangements, as well as the spatial orientation of the linear arrangements. Their results suggest spatial representations of time become increasingly aligned with cultural norms between the ages of 4 and 6 (Tillman et al., 2018). Preschool children (aged 4.0–5.0 years) were much less likely to arrange the stickers in a line compared to kindergarten children (aged 5.0–6.9 years) and adults. When preschoolers did create lines, the proportion of left-to-right arrangements was higher in kindergartners relative to preschoolers, and higher in adults relative to both kindergartners and preschoolers. This pattern of results suggests that the mental timeline is gradually constructed in early childhood and likely becomes more robust as children are increasingly exposed to written text and other cultural artifacts that spatialize time.

One specific way in which the mental timeline may benefit temporal cognition is by supporting memory for the temporal order of events. With respect to the different components of episodic memory, remembering *when* things happened tends to be more difficult than remembering *what* or *where* (Picard et al., 2012). This difference is present throughout childhood (Hayne & Imuta, 2011; Lee et al., 2016; Prabhakar & Ghetti, 2020) and persists into adulthood (Pathman et al., 2018). Episodic memory is thought to be at the center of our abilities to build an autobiographical memory (Fivush, 2011) and other cognitive processes, such as envisioning the future, that require mental time travel (Mullally & Maguire, 2014). Unlike objects, agents, and locations, time cannot be directly perceived by the senses. The abstract nature of time may be the reason why the temporal component of episodic memory is the most difficult for both children and adults. By representing the flow of time in terms of progression through space, the mental timeline may make representations of temporal order more concrete and contribute to more robust episodic memories.

In support of this view, recent research suggests that older children and adults draw on the mental timeline for encoding and retrieving information about temporal order. Pathman et al. (2018) found that American adults display a strong memory advantage for remembering temporal order when items are presented in a left-to-right spatial pattern compared to right-to-left or nonlinear patterns. This finding suggests that temporal memory is facilitated when the spatial locations and temporal order of the items within a sequence are congruent with the mental timeline and negatively affected when the locations and order are incongruent. The same benefit for encoding and retrieving temporal order for stimuli that were presented from left-to-right relative to the other orientations was also found in children aged 7-to-9-years (Pathman et al., 2018), which suggests that once children have developed a mental timeline, they activate it when encoding and retrieving the temporal order of events. The presence of a benefit for remembering temporal order when events are presented congruent with the mental timeline suggests that the mental timeline bolsters memory for temporal information.

We propose that one reason why time-space associations are so common is that representing time in terms of space is beneficial for temporal memory. Specifically, the present work explores the hypothesis that the development of the mental timeline benefits temporal memory development. Although the idea that spatial representations of time are helpful for reasoning about time is common (Casasanto & Boroditsky, 2008; Lakoff & Johnson, 1980; Pathman et al., 2018), to our knowledge, no work has explicitly focused on how the development of these associations supports temporal memory development. It is unknown how children who are in the process of constructing the mental timeline might make use of these mental representations to remember temporal information and whether the process of developing a mental timeline itself can support the ability to use this spatial framework to encode and retrieve temporal order information.

In the present study, we explored how the development of the mental timeline relates to temporal memory by testing for an association between individual differences in the development of 5- to 6-year-old children's memory for temporal order and the development of their mental timelines. The selected age range is a time at which most, but not all, children start to represent time linearly and is also a period in which children show rapid development in their episodic memory abilities (Ngo et al., 2019; Tillman et al., 2018). This variability makes children at this age ideal candidates for exploring how the development of the mental timeline interacts with temporal memory. In our memory task, we introduced children to short, animated video clips and tested their memory for the order and location of the events featured in the videos. We tested the development of children's mental timelines using a timeline task adapted from Tillman et al. (2018) in which children were asked to arrange icons to represent the order of events. If representing time linearly is beneficial for temporal memory, then we would expect children who make linear arrangements in the timeline task to have better temporal order memory relative to children who represent time with nonlinear spatial arrangements. Because the conventionally oriented mental timeline in our sample is from left-to-right, we would also expect children who spontaneously represent temporal events from left-to-right to have better temporal order memory relative to children who represent time in other linear arrangements. On the other hand, if children's temporal memory performance is independent of the strength and orientation of their mental timelines, this might suggest that children do not engage the mental timeline to support temporal memory until later in development.

Method

Participants

The final sample included 96 participants ($M = 6.22$ years, range: 5.08–7.02, 43 female). Data from an additional 23 children were excluded due to not completing the experiment ($n = 11$), experimenter error ($n = 5$), technical difficulties during the task ($n = 2$), not paying attention to the task ($n = 2$), parental interference while completing the task ($n = 1$) or taking written notes during encoding ($n = 1$). All data came from participants residing in the United States. Ninety-four families filled out the demographic information form. Caregivers described their children's racial-ethnic identities as: White, $n = 56$, more than one race, $n = 25$, Asian, $n = 8$, Hispanic or Latino/a, $n = 3$, and another racial category not listed, $n = 2$. Most participants in our sample learned English as their first language ($n = 91$), and 22 children spoke one or more languages at home at least 20% of the time. Eighty families reported their income, and most ($n = 56$) families reported income above the area median income ($110,800 per year in 2021). We obtained education information from 170 parents, and most parents ($n = 164$) reported education levels equivalent to a college degree or higher.

Children were recruited through the University of Washington participant pool database via e-mail invitations. Verbal and written consent was obtained from the children's guardians prior to participation, as well as verbal assent from the children. All informed consent and data collection procedures were approved by the University of Washington Institutional Review Board. Each family received a $5 Tango gift card and a junior scientist certificate of completion as a token of our appreciation.

Materials and procedure

Participants were tested in their own homes on their own devices during a Zoom meeting with a caregiver and an experimenter present. Each participant was sent a Zoom user guide prior to the study date. Participants were asked to use a laptop or desktop computer to ensure that the stimuli were displayed similarly across participants. The memory game utilized Qualtrics, and the timeline task utilized Google Slides. All participants completed the memory game first, followed by the timeline task. The entire testing session took approximately 20 minutes. Detailed information about questions, answer choices, and counterbalancing conditions for all tasks is available at https://osf.io/qnk5r.

Memory Game

This task was used to assess memory for the temporal order and location of events. The stimuli consisted of three 1-minute videos. Each video had a unique character who engaged in nine unique events, each involving unique background locations and objects (see Figure 1).

Encoding

The experimenter started by informing the participant that they would watch a video and meet a character, who would show them what they like to do on a fun day. The experimenter informed the participants that they would be asked questions about the video and prompted the participants to try to remember what these characters did, before presenting the first video: "For this game, we're going to watch a few videos and meet some friends. They will show us what they like to do on a fun day! I will then ask you some questions about what we watched, so try to remember what they did."

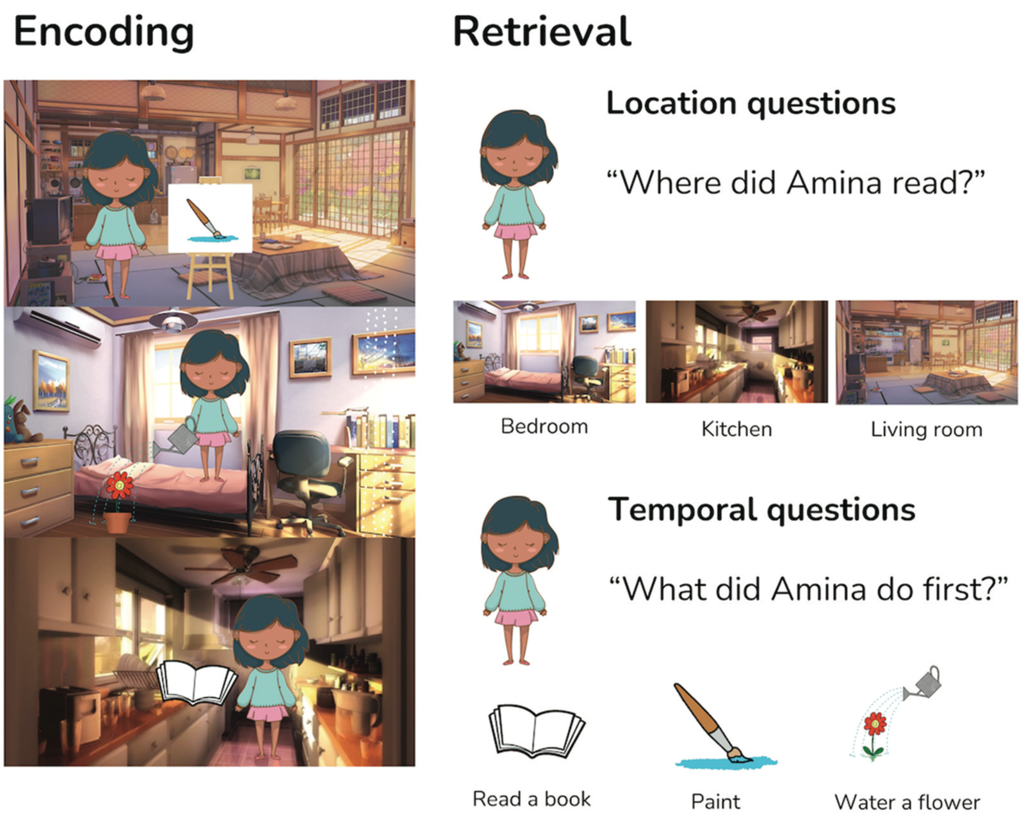

Figure 1. Schematic of the memory game. Examples of encoding scenes (left) and retrieval questions (right).

All events started with the character entering the location, accompanied by footstep sounds. After the character entered the scene, an object appeared with a "pop" sound. The objects were animated and moved in a slight up-and-down motion on the screen to emphasize that the character was interacting with these objects. The character then moved off-screen accompanied by footstep sounds and reentered the screen in a new location. Each event lasted approximately 6 seconds, and each video contained nine events. The events were selected to be location-neutral so that children could not deduce the activity based on location during retrieval.

Retrieval

After watching each video, the experimenter asked the participant three location memory questions (e.g., "Where did Amina read?") and three temporal memory questions (e.g., "What did Amina do first?"). All questions employed a three-alternative forced-choice paradigm. The answer choices featured events that occurred between one and five events from each other. The first and last events were never included as possible answer choices. The order of videos, the order of questions within the location memory and temporal memory question types, and the positions of the answer alternatives were counterbalanced across participants. Children always answered the location memory questions first and the temporal memory questions second.

Timeline task

This task was adapted from Tillman et al. (2018) to be suitable for completing on a computer screen. On each trial, children saw a large white square with a black circle in the middle and two additional colored circles to be placed within the white square. The experimenter referred to these circles as "stickers." On one trial, the experimenter asked the child to think about different days: "yesterday," "today," and "tomorrow" (see Figure 2). The experimenter verbally labeled the black sticker in the middle of the card as "today," and children were asked to verbally confirm the label of this sticker to ensure they understood what it represented. The experimenter then asked the participant to place the other two stickers on the screen to represent "yesterday" and "tomorrow." To place the stickers, we gave children remote access to the screen over

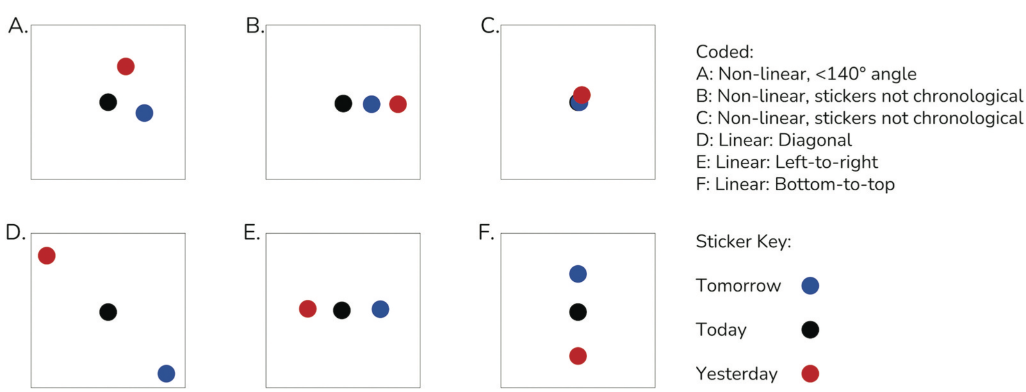

Figure 2. Example timeline arrangements.

Zoom so they could click and drag the stickers to the desired location on the screen. If the child had issues navigating the mouse, we asked the child to point to a location on the screen where they wanted to place the sticker and asked their caregiver to move the sticker to where they were pointing. All children performed two trials. One trial used a deictic time scale with the labels "yesterday," "today," and tomorrow," and one trial used a sequential time scale with the labels "morning," "noon," and "night." The order of the trials, the order in which children were asked to place the sticker corresponding to the earlier versus later event, and the color of the stickers were counterbalanced across participants. Two children did not know the word "noon," and for these children, the labels for the sequential trial stickers were changed to "breakfast," "lunch" and "dinner."

Line coding

Two experimenters independently assessed the linearity for each arrangement, using the guide from Tillman et al. (2018). Each sticker arrangement counted as a line if the smallest angle created between the three stickers was between 140 and 180 degrees and the stickers were placed on opposite sides of the central sticker, such that their placement resulted in a correctly ordered sequence along any axis. Arrangements were coded for linearity, and linear arrangements were additionally coded for their orientation (see Figure 2 for example arrangements and how they were scored). Because there were two trials, a participant could make 0, 1, or 2 lines in the task.

Data analysis

The preregistration for this study can be accessed at https://osf.io/9y45k. We planned to stop data collection when we reached 30 participants who made two lines (linear arrangements on both trials) and 30 participants who made zero lines (nonlinear arrangements on both trials) in the timeline task. A sample size of 60 provides 80% power to detect an effect size of $d = 0.65$ at an alpha level of 0.05 for the prediction that temporal memory performance would be greater in children who make two lines compared to children who make zero lines. Our final sample size was larger than planned due to the unexpectedly large number of children who made one line. Data cleaning and analyses were performed in R using the tidyverse and lmerTest packages (Kuznetsova et al., 2017; Wickham et al., 2019)

Results

Memory game

We assessed whether there was a difference in memory performance between the temporal memory and location memory questions. We analyzed memory accuracy for these different question types across all participants using a logistic mixed effects model (model syntax: accuracy ~ memory question type + (memory question type | subject_id)). There was a significant main effect of question type ($\beta = -2.64$, $p < .001$). Children had higher accuracy for location memory questions relative to temporal memory questions (location: $M = 0.92$, $SE = 0.01$; temporal: $M = 0.57$, $SE = 0.02$, Figure 3).

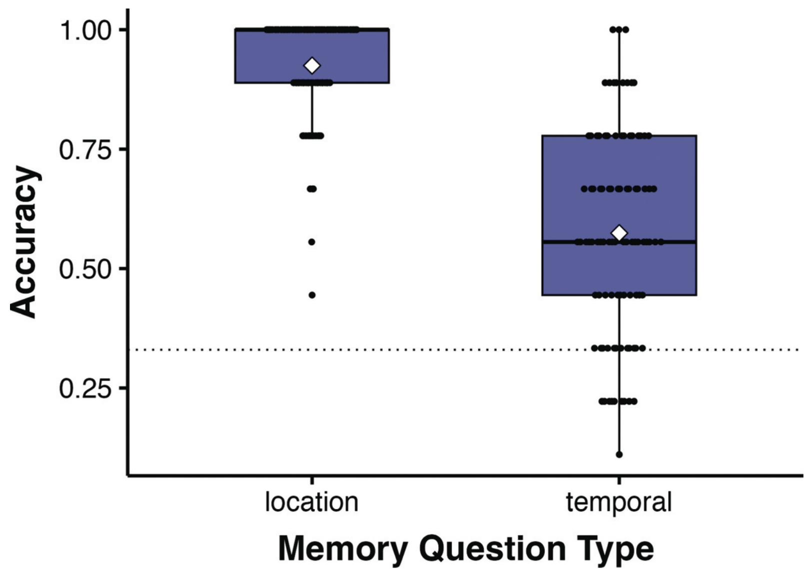

Figure 3. Memory accuracy by question type. The white diamonds represent the mean accuracy for each question type, and the black dots represent individual participants. The colored boxes represent the lower quartile (bottom) and upper quartile (top) values. The dotted line represents the chance-level performance.

Next, we assessed whether age was related to children's memory performance. Age was positively correlated with overall memory accuracy, $r(94) = .45$, $p < 0.001$, and with each memory type (location: $r(94) = .29$, $p = 0.004$; temporal: $r(94) = .43$, $p < 0.001$). Comparison of these correlation coefficients suggests that one memory type is not more strongly correlated with age than the other ($z = 1.29$, $p = 0.20$). These results demonstrate that both temporal and location memory are improving between the ages of 5 and 6 years.

Timeline task

First, we explored whether children's use of linear arrangements and culturally conventional left-to-right arrangements increased with age using Spearman's rank-order correlations. The number of linear arrangements children made, and the number of left-to-right lines children made were not correlated with their age (total number of lines: $r(94) = -0.01$, $p = 0.93$; number of left-to -right lines: $r(94) = -0.06$, $p = 0.56$). We also explored whether children made different numbers of lines on the sequential versus deictic timescale trials. Similar to previous studies that have used this task, we did not find that one trial type led to more linear arrangements than the other (39 lines produced for each trial type; $\chi^2(1) = 0$, $p = 1$) (Starr & Srinivasan, 2021; Tillman et al., 2018). Because there was no influence of age on whether children made lines or left-to-right lines, and the number of lines did not vary as a function of trial type, all subsequent analyses were collapsed across age and trial type.

Next, we examined the frequency of the different orientations of sticker arrangements (Figure 4). Overall, 30% of children made zero lines, 21% of children made one line, and 49% of children made two lines. This distribution is significantly different from chance ($\chi^2(2) = 11.81$, $p = .003$), and a plurality of children made a line on both trials. Children who

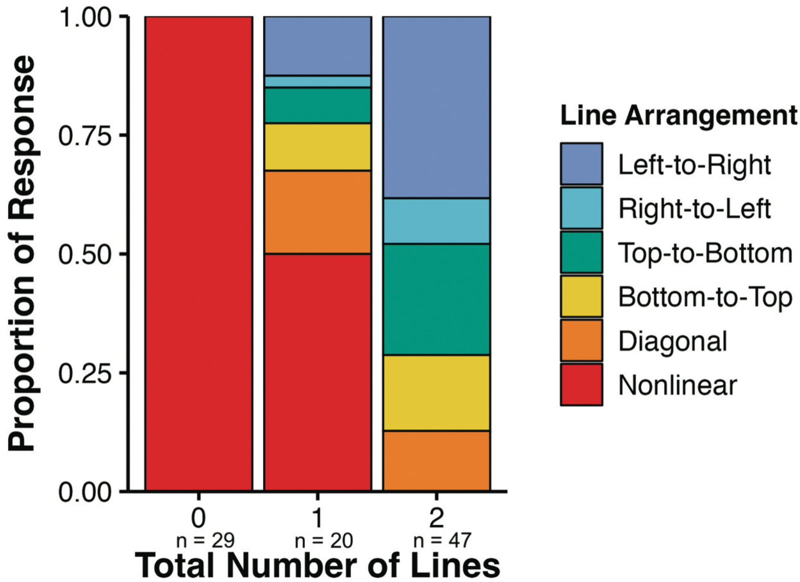

Figure 4. Distribution of timeline arrangements made by children depending on the number of lines they created across the two trials.

made two lines were more likely to make left-to-right linear arrangements compared to other linear arrangements ($\chi^2(4) = 24.62$, $p < .001$). However, children who made only one line made a mix of linear arrangements and did not show a preference for a specific orientation ($\chi^2(4) = 5.00$, $p = .29$). This pattern of results suggests that as children start showing a higher preference for arranging temporal events linearly, their arrangements are also becoming increasingly aligned with the culturally dominant mental timeline orientation.

We also explored children's internal consistency in their timeline arrangements. Among the children who made two lines, 55% of children arranged both lines in the same orientation, and 50% of these children placed both lines in a left-to-right order. In other words, only 14% of children in our sample made a left-to-right line on both trials. This pattern of results shows that children display great variability in their mental timeline development, both for developing internally consistent representations and acquiring a preference for the culturally dominant left-to-right arrangement. Even though left-to-right was the most common linear arrangement in our sample, very few children created this arrangement consistently in both trials.

The mental Timeline's interaction with memory

In the final series of analyses, we explored how children's timeline arrangements relate to their memory performance (Figure 5). First, we assessed whether the number of linear arrangements participants made in the timeline task (0, 1, or 2) related to their memory accuracy using a logistic mixed effects model (model syntax: accuracy ~ memory question type * number of lines + (memory question type | subject_id)). This model revealed a main effect of question type ($\beta = -3.00$,

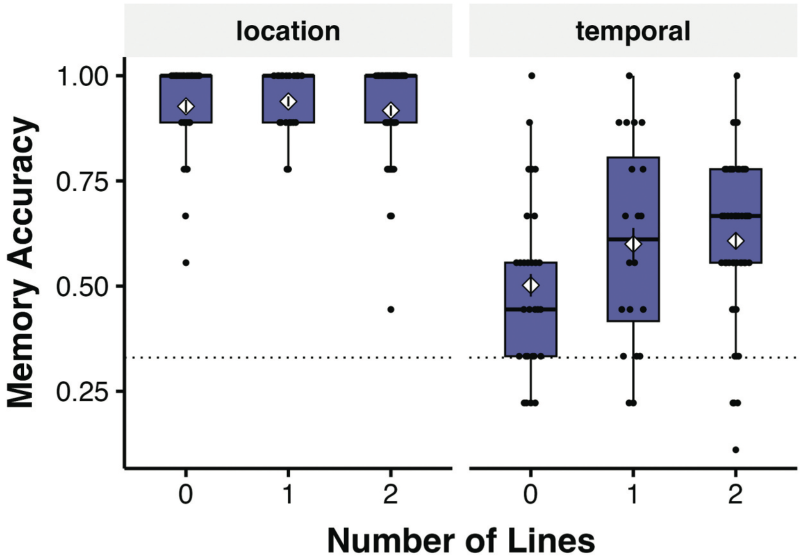

Figure 5. Location and temporal memory accuracy by number of lines. The diamonds represent the mean accuracy for each group, and the black dots represent individual participants. The colored boxes represent the lower quartile (bottom) and upper quartile (top) values. The dotted line represents chance-level performance.

$p < .001$), but no significant effect of the number of lines made during the timeline task ($\beta = -0.08$, $p = .69$) or interaction between the number of lines and memory question type ($\beta = 0.30$, $p = .12$). Given the significant correlation between age and memory performance, we ran an exploratory model with age as an additional fixed effect (model syntax: accuracy ~ memory question type * number of lines + age + (memory question type | subject_id). This model revealed a main effect of question type ($\beta = -$ 2.76, $p < .001$), and a main effect of age ($\beta = 0.77$, $p < .001$). Similar to the first model, there was no significant effect of the number of lines made during the timeline task on memory performance ($\beta = -0.12$, $p = .49$). The interaction between the number of lines and memory question type also remained non-significant ($\beta = 0.32$, $p = .06$).

Both of the mixed effects models included children who made zero, one, or two lines. However, our primary question of interest concerned the difference between children who made zero lines and children who made two lines. Because the interaction term in the main model approached significance, we ran separate mixed-effects models predicting temporal and location memory performance in only children who made zero or two lines, controlling for age (model syntax: accuracy ~ number of lines + age + (1 | subject_id)). For predicting temporal memory accuracy, both the number of lines made ($\beta = 0.21$, $p = .02$) and age ($\beta = 0.63$, $p < .001$) were significant predictors. For predicting location memory, only age was a significant predictor ($\beta = 0.94$, $p = .01$). This pattern of results suggests that children who consistently represented time linearly were more accurate in remembering temporal order information than children who did not yet represent time linearly. This suggests that the difference in temporal memory performance was not due to older children being more likely to make more linear arrangements. Instead, children with more linear representations of time may be referencing the mental timeline to support temporal memory.

Finally, we tested whether the number of left-to-right oriented lines was related to temporal memory performance. For this analysis, we only included children who made at least one line in the timeline task (model syntax: accuracy ~ memory question type * total left-to-right lines + (memory question type | subject_id)). There was no interaction between the number of left-to-right linear arrangements and temporal memory performance ($\beta = 0.33$, $p = .14$). To follow up with our previous results, we ran additional binomial mixed-effect models separately for location and temporal memory performance (model syntax: accuracy ~ number of LR lines + age + (1 | subject_id)). For children who made at least one line, the number of left-to-right lines did not predict location or temporal memory performance (location: $\beta = -0.37$, $p = .12$; temporal: $\beta = -0.04$, $p = .77$; note that only 47 children made two lines and 13 children made two left-to-right lines, so these analyses have limited statistical power). These results suggest that the temporal memory benefit for children who made two lines may stem from representing time linearly but is not dependent on producing lines with the culturally conventional orientation.

Discussion

The main hypothesis motivating this experiment is that the development of a mental timeline is beneficial for temporal memory. We explored the link between the mental timeline and temporal memory development by assessing how individual differences in the development of the mental timeline relate to temporal memory. Through our analyses, we captured the variability in the development of American children's mental timelines with respect to internal consistency and the emergence of culturally dominant representations. Our results suggest that the development of the mental timeline may contribute to temporal memory development.

Memory development

In our memory task, we found that memory for locations of events was significantly better than memory for the temporal order of events in American children 5- to 6-years-old. Temporal information may be more difficult to remember because it is abstract, whereas location information is concrete. This difference in memory performance is consistent with previous work showing that the ability to remember temporal information develops more slowly than the ability to remember location information (Hayne & Imuta, 2011; Lee et al., 2016; Picard et al., 2012; Prabhakar & Ghetti, 2020; Scales & Pathman, 2021). These prior studies used a variety of different methods for testing memory, including the use of physical objects and simplified computer stimuli, as well as both verbal and visual recall formats. Our findings add to this literature by demonstrating that the difference in relative difficulty for remembering temporal versus location information is consistent across many different paradigms.

One reason for children's difficulty in remembering temporal memory relative to location information could be their inefficient encoding of temporal order. For example, in a study conducted by Picard et al. (2012), experimenters assessed encoding and retrieval success by asking free recall, cued recall, and recognition questions about the same events.

Picard et al. (2012) found that though young children's memory for locations improved when retrieval cues were present, their memory for temporal order did not. This pattern of results suggests that temporal information is encoded less efficiently than location information. Another reason for the slow development of temporal memory relative to location memory may be related to the development of relational binding abilities. Relational binding is the ability to bind the arbitrary features of an event into a cohesive episodic memory. Notably, the ability to bind items to locations seems to develop faster than the ability to bind items to time (Lee et al., 2016, 2020). These differences may in part be related to developmental changes in the hippocampus and surrounding cortical regions, which contribute to the improvement of memory precision and flexibility into adolescence (DeMaster et al., 2013; Ghetti & Fandakova, 2020). Specifically, developmental changes in different sub-regions of the hippocampus predict changes in different binding operations (Lee et al., 2020). Overall, the differences in the ability to encode and bind different relations within an episode may contribute to the slow development of temporal memory relative to location memory.

Development of the mental timeline

We found that children in our sample exhibited striking variability in the linearity, orientation, and consistency of their spontaneous representations of temporal order. Previous studies using the timeline task have focused on age-related differences at the group level regarding the proportions of linear arrangements rather than individual consistency of children's arrangements (Starr & Srinivasan, 2021; Tillman et al., 2018; Tversky et al., 1991). In line with these group-level analyses, the proportion of linear and left-to-right arrangements in our sample was similar to those found in a previous kindergarten-aged sample of children in North America (Tillman et al., 2018). We found that most children in our sample were starting to spontaneously represent time linearly, as indicated by the construction of a line on at least one trial. Children who made only one linear arrangement did not show a preference toward any specific line orientation. However, children who made lines on both trials exhibited a preference for left-to-right oriented lines. These results are consistent with prior work in demonstrating that as children start to represent temporal events in linear arrangements more consistently, they also develop an increased preference for the culturally conventional arrangement (Starr & Srinivasan, 2021; Tillman et al., 2018).

In addition to these group-level analyses, we explored how consistent children are in their performance across trials. Our results indicate that American 5- to 6-year-old children display varied progressions toward building adult-like mental linear representations of time rather than showing a clear switch from non-linear to consistent linear representations. Even though 59% of all arrangements were lines, only 49% of children made lines on both trials and 30% did not make a line on either trial. Although left-to-right was the most common line orientation (36% of all lines), only 14% of children made left-to-right lines in both trials. In addition, a relatively high proportion of children in our sample (21%) made a mix of linear and nonlinear arrangements across the two trials, which suggests that at this age, many children are starting to experiment with constructing linear representations of time but are not yet doing so consistently. We also saw variability among children who made lines on both of the two timeline trials: about half (45%) made lines with two different orientations rather than making the same orientation on both trials. These results suggest that the development of the mental timeline may be more protracted than previously thought. Specifically, there may be quite a lag between when children start to create linear timelines and when they are consistently creating timelines that conform to the culturally conventional orientation (in this case, left-to-right). It is likely that children are exploring multiple types of linear arrangements, or some linear and some nonlinear arrangements while developing their mental representations of time. Future studies could further focus on individual-level data to better understand this variability.

One notable methodological difference between our version of the timeline task and previous versions is the spatial orientation of the testing medium. Previous versions of this task were conducted in person, with stickers placed on physical pieces of paper on a table in front of a child. However, in adapting this task for remote testing, we used icons on a screen. This change altered the spatial orientation of the task materials from the sagittal axis (a piece of paper on a table) to the vertical axis (a computer screen). Despite the differences in testing formats, the patterns from our sample were very similar to patterns from previous North American samples (Tillman et al., 2018), which suggests that children's timeline representations are robust to changes in testing format.

The timeline task requires that children understand the meaning of the words we are asking them to represent with stickers. Although previous work suggests that participants in our age group know the time words used in the timeline task (Tillman et al., 2017), and the words have been previously used in prior studies using this task with children in the same age range (Starr & Srinivasan, 2021; Tillman et al., 2018; Tversky et al., 1991), we did not separately measure children's knowledge of these words. Future studies could directly explore the relationship between the acquisition of time words and the development of the mental timeline.

Interaction of the mental timeline with temporal memory

Our main question of interest was how the development of the strength and orientation of the mental timeline interacts with the development of temporal memory. In line with our prediction, we found that the individual differences in the strength of children's mental timelines predicted their temporal memory performance, at least when comparing children who were most and least likely to create linear arrangements. Relative to children who made zero lines, children who made two lines in the timeline task were significantly more accurate on temporal memory questions. Importantly, though children who made two lines performed better on temporal memory questions, all children performed equally well on the location memory questions. This pattern of results rules out the possibility that children who made zero lines may have been less engaged in the experiment overall. Instead, this result suggests that the difference in performance on the temporal memory questions may be driven by the linear mental representation of time.

We assessed next whether the temporal memory advantage was driven by linear arrangements of any orientation or specifically by culturally conventional, left-to-right oriented linear arrangements. Among children who represented time linearly across both timeline task trials, we did not find an improvement in temporal memory performance as the number of left-to-right lines increased. However, because only 13 children produced left-to-right linear arrangements on both trials, we may not be sufficiently powered to detect this effect. Overall, our results imply that the benefit to temporal memory in this age group may come from generally thinking about time linearly, rather than specifically orienting the mental timeline from left-to-right. Although we did not find an effect of line orientation on temporal memory performance, previous work has demonstrated that older children and adults benefit specifically from spatial representations of time that are congruent with the mental timeline orientations that are conventional in their culture, rather than any linear orientation (Pathman et al., 2018). Because children in our sample do not yet have robust mental timelines that are internally consistent, it is likely that they do not benefit from a mental timeline in the same fashion that adults and older children do. Before children have a robust mental timeline, any linear organization of temporal order may be beneficial for temporal memory by encouraging children to spontaneously activate and reference spatial frameworks to encode and retrieve temporal order information. Then later, once children are consistently representing time linearly, there may be an increased benefit from a specific orientation that is congruent with their representations. In the present study, we focused on American children aged 5-to-6-years, an age at which most children are constructing at least one line in the timeline construction task. However, this restricted age range limits our ability to capture a broader picture of how the mental timeline may interact with the temporal memory in early childhood. Future work using other paradigms could expand this age range to observe a wider developmental trajectory.

In early childhood, children are highly variable in whether or not they spontaneously use mnemonic strategies such as verbal rehearsal during a memory task, but the spontaneous use of these strategies increases with age (Flavell et al., 1966; Keeney et al., 1967). In addition, children who spontaneously use such strategies outperform those who do not. An increase in the spontaneous use of mnemonic strategies could be one factor that contributes to the rapid development of temporal memory abilities between early childhood and adulthood. Specifically, drawing on the mental timeline to recall temporal order is one strategy that could contribute to better encoding and retrieval of temporal order information. For example, in the study by Pathman et al. (2018), both older children and adults were less accurate when recalling the temporal order of items relative to their spatial location. However, this difference only appeared when the spatial locations of the items were incongruent with the mental timeline (e.g., they were presented right-to-left or nonlinearly). To directly test this hypothesis, future studies could explicitly encourage children to represent temporal order using the mental timeline.

The use of a mental timeline as a memory strategy may be particularly helpful for recalling the order of events that occurred close together in time. Theories of temporal memory suggest that the ability to recall temporal information depends on processes of active construction (Friedman, 1993, 2004). For example, in his review of different accounts of how temporal information is encoded in memory, Friedman (1993) suggested that one way to reconstruct the location in time for an event is through the use of semantic knowledge about time, such as knowing that summer vacation happens before New Year's celebrations, and the use of contextual cues that aid inferential processes during recall. For example, we may use our memory of the weather during an event to place that event in a particular season or remember what grade we were in when an event occurred to place that event in a specific year. The use of this type of contextual information may be more difficult for events that happened close together in time (e.g., during the same season or year in school) and may be particularly difficult for children to use when their semantic knowledge is still in development (Friedman, 1993; Scales & Pathman, 2021). As a result, children are more accurate in judging the temporal order of events that are widely separated in time compared to events that occurred closer together (Friedman, 2004). The mental timeline may therefore be a particularly helpful mnemonic for encoding and remembering events that occur close together in time.

Individuals may also use additional strategies or skills to support temporal memory. Although we found a relation between the development of the mental timeline and temporal memory performance, some children in our sample demonstrated good temporal memory accuracy despite not producing any linear timelines and some children who produced two linear arrangements demonstrated poor temporal memory accuracy. In the current study, we did not account for individual differences in children's verbal or non-verbal IQ or executive functions. However, prior studies have found that these abilities contribute to episodic memory (e.g., Lee et al., 2016; Raj & Bell, 2010; Rajan et al., 2014). In particular, working memory may support the ability to flexibly move forward and backward through event representations, which in turn may support episodic memory for temporal order (Friedman, 1990; Scales & Pathman, 2021). It is also possible that spatialization of serial order in working memory could influence the ability to recall the temporal order of events. Previous work with adults demonstrate that in Western cultures, a left-to-right, linear organization of temporal events is activated during working memory span tasks (e.g., Abrahamse et al., 2016; Guida et al., 2016; van Dijck & Fias, 2011). Additionally, developmental work on this phenomenon suggests that the left-to-right linear organization of the timeline and spatialization in working memory may emerge around the same age in American and Belgian children (Tillman et al., 2018; van Dijck et al., 2020). Our work expands on this interaction between spatialization of order in working memory by exploring the developmental trajectory of how spatial representations may support episodic memory for temporal order. A direction for future research will be to explore both the development of spontaneous spatialization of serial order in working memory and the development of a linear mental timeline in relation to temporal memory.

Conclusions

The overall goal of this research was to improve our understanding of temporal memory development, especially in relation to the development of the mental timeline. Our experiments constitute an important first step by providing insight into how the mental timeline interfaces with temporal memory using an individual differences approach. We found that among American children aged 5–6 years, there exists remarkable variability in the degree to which children are representing time linearly. However, children who represented time more linearly exhibited stronger memory for temporal order in comparison to children who were not yet representing time linearly. These results provide preliminary evidence that for children in the U.S., the development of the mental timeline may support the development of temporal memory, such that as children begin to represent time linearly, they can use this framework to encode and recall temporal order information more efficiently.

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