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Using Space to Remember Time

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## **Abstract**

### **Using Space to Remember Time**

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Although we cannot see or touch time, across many cultures, we use spatial representations to think about this abstract concept. Such representations help us reason and think about this abstract domain, which helps us in many realms, including but not limited to forming rich episodic memories, imagining the future, and contextualizing personally relevant events. In early childhood, memory for the temporal order of events tends to be weaker than memory for the location of those events. A potential solution to this challenge is to engage the mental timeline, a linear projection of time onto space. Although adults and older children spontaneously activate the mental timeline when remembering the order of events, the mental timeline is slow to develop, and little is known about the interaction between the development of the mental timeline and temporal memory development. Here we show that the development of a mental timeline is related to temporal memory development at 5-to-6 years of age. In two experiments, we explored how individual differences in the development of the mental timeline relate to temporal memory, and whether priming linear representations of time can improve temporal memory. In Experiment 1 we asked whether individual differences in the strength of 5-to-6-year-old children's mental timelines predict their memory for temporal order. Linearity of

children's mental timelines predicted 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 suggest that children may reference these spatial representations to remember temporal order. Nonetheless, children who do not have consistent mental representations of time may not spontaneously activate the mental timeline when encoding temporal order, may still benefit when encouraged to use this strategy. Experiment 2 tested if priming 5-year-old children to represent temporal order linearly strengthens temporal memory. Contrary to our prediction, there was no effect of priming condition on temporal memory performance. There are several reasons why our priming task did not have the intended effect, such as the lack of visuo-motor engagement in the activity, the short duration of visual exposure to spatial primes, and the delay resulting from the memory task in between the priming activity and the timeline task. Our future work focuses on mitigating these issues by designing an activity to successfully prime the use of a mental timeline in young children. Our results from these two experiments provide preliminary evidence that the development of the mental timeline supports the development of temporal memory and provide insight into various constraints of spatial priming activities in influencing spatial mental representations.

## **Introduction**

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)

Previous work on the mental representation of time suggests that the mental timeline is a cross-culturally pervasive way of representing time (Bonato et al., 2012). This mental model of time is based off a linear reference frame and allows us to represent the flow of time in a spatial layout. For most Western adults, the mental timeline has a left-to-right, horizontal spatial layout (Bonato et al., 2012). Individuals who think about time using this mental timeline layout associate past events with the left side and future events with the right side. In this layout, the flow of time is thought of as a continuous movement towards the right (Bender & Beller, 2014). Cultural factors such as reading and writing direction, linguistic metaphors, and calendars can influence the spatial orientations of the mental timeline (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).

Studies on the development of the mental timeline with children in the US and Canada show evidence that the mental timeline begins to emerge around 5 years of age. The linearity and orientation of the mental timeline becomes more entrenched as children become more proficient

readers and gain experience with cultural artifacts like calendars (Tillman et al., 2018, 2022; Tversky et al., 1991). Tillman and colleagues (2018) explored the emergence and flexibility of the mental timeline with a task in which participants were prompted to spatially arrange different time events. In this study, 4-to-6-year-old children and adults were asked to arrange icons that represent temporal events, such as ‘yesterday’, ‘today’ and ‘tomorrow’, on a piece of paper. The experimenters then coded whether participants made linear or nonlinear arrangements, as well as the spatial orientations of the linear arrangements.

Their results show that when 4-to-6-year-old children are developing mental timelines, their representations of time are initially more malleable and becomes more entrenched with cultural conventions in adulthood (Tillman et al., 2018). For example, for participants in this sample, the culturally dominant representation of time is in a left-to-right, horizontal layout. When asked to spontaneously arrange icons that represent temporal events, however, preschool-aged children in this sample were not as likely as kindergarteners or adults to arrange these icons in a line. Further, the proportion of culturally dominant, left-to-right arrangements were higher in kindergarteners relative to preschoolers, and higher in adults relative to both kindergarteners and preschoolers (Tillman et al., 2018).

The experimenters also explored the malleability of these mental timeline arrangements using a spatial priming paradigm. In this paradigm, the experimenter first created either a vertical or a horizontal arrangement with three different colored blocks. The participants were then asked to place stickers that matched the colors of these blocks on a piece of paper, to match the orientation of the blocks. The presence of both vertical and horizontal spatial primes increased the proportion of linear timeline arrangements in preschool and kindergarten aged children. Further, children in this sample produced a higher proportion of vertical timelines, which is a

timeline that is unconventional in their culture, after being primed with a vertical block arrangement. Adults, on the other hand, did not show malleability to spatial primes in their timeline representations, and made a high proportion of the culturally dominant, left-to-right linear arrangements across all conditions (Tillman et al., 2018). These results suggest that even when preschoolers have the ability to represent time events in terms of the mental timeline, whether they spontaneously represent time events in a linear order is highly variable and their representations of time are malleable relative to that of adults. This study demonstrates that the mental timeline is gradually constructed in early childhood and becomes more robust in adulthood.

Recent work suggests that adults may draw on the mental timeline to remember the temporal order of events. One important realm in which encoding, organizing, and remembering temporal information is critical, is forming episodic memories. Episodic memory allows us to have rich representations about events that include information about “what” happened, “where” it happened, and “when” it happened. It is also thought to be at the center of our abilities to build an autobiographical memory (Fivush, 2011) and other cognitive processes that involve mental time-travel such as envisioning and planning for the future (Mullally & Maguire, 2014). Between infancy and middle childhood, the ability to form and retrieve episodic memories, and the ability to bind the different components of an event, changes dramatically (Ghetti & Lee, 2011; Ngo et al., 2019). However, the developmental trajectories for these different binding processes are asymmetric: the development of the ability to remember “when” lags behind the ability to remember “what” and “where”, and it reaches adult-like levels several years later (Hayne & Imuta, 2011; Lee et al., 2016; Prabhakar & Ghetti, 2020). Pathman and colleagues (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 present work explores the hypothesis that one reason why time-space associations are so common is that representing time in terms of space is beneficial for temporal memory. Although the idea that spatial representations of time are helpful for reasoning about time is common (Lakoff & Johnson, 1980; Casasanto & Boroditsky, 2008; Pathman et al., 2018), little work has explicitly focused on the development of these associations and how they may support temporal memory development. Little is known about how children who are in the process of constructing the mental timeline might make use of these mental representations to remember temporal information, and it is unknown 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.

We explored how the development of the mental timeline relates to temporal memory through two approaches, one based on individual differences, and one based on spatial priming. In Experiment 1, we tested 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. 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). If the development of the mental timeline supports temporal memory, how children make timeline arrangements will specifically relate to their memory for the temporal order but not the location of events. Specifically, if representing time linearly is beneficial for temporal memory, then we would expect children who have more linear mental timelines to have better temporal order memory relative to children who represent time in 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 spatial arrangements. On the other hand, if children's temporal memory and location memory performance are independent of the strength and orientation of their mental timelines, this might suggest that the development of the mental timeline is unrelated to temporal memory.

In Experiment 2, we tested whether priming the use of a linear mental timeline boosts children's temporal memory performance. We explored whether a priming activity could encourage children to activate spatial representations of temporal events, and in turn prompt them to use these representations as a strategy to encode and retrieve temporal order information. In our priming activity, we had children represent the order of events in a story sequence either in a left-to-right linear, or nonlinear spatial arrangements. Then, we asked children to complete the same memory and timeline tasks we used in Experiment 1. If encouraging children to activate the mental timeline improves their temporal memory performance, we would expect children in the linear priming condition to perform better in temporal, but not location, memory questions in the subsequent memory task, relative to children in the nonlinear priming condition.

## **Experiment 1**

### **Method**

#### ***Participants***

The final sample included 96 participants ( $M_{age} = 6.22$  years, range: 5.08 – 7.02, 44 female). Data from an additional 23 children were excluded due to experimenter error ( $n = 7$ ), technical difficulties during the task ( $n = 5$ ), not completing the experiment ( $n = 8$ ), not paying attention to the task ( $n = 2$ ) or taking written notes during encoding ( $n = 1$ ). Ninety-three families filled out the demographic information form. Caregivers described their children's racial-ethnic identities as: White,  $n = 56$ , (59.6%), Multiracial,  $n = 24$  (14.6%), Asian,  $n = 8$  (8.5%), Hispanic or Latino/a,  $n = 3$ , (3.2%), and another racial category not listed,  $n = 2$  (2.1%). Most participants in our sample learned English as their first language ( $n = 92$ ), and 22 children spoke one or more languages at home at least 20% of the time. Children came from primarily middle- and upper-class families.

Children were recruited through the University of Washington's participant pool database via email 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's Institutional Review Board. Each family received a \$5 Tango Gift card that could be redeemed online and a junior scientist certificate of completion as a token of our appreciation.

### **Materials**

#### ***Memory Game***

This task was used to assess memory for the order and location of events. The stimuli consisted of three one-minute videos. Each video had a unique character and nine unique events with unique background images and unique objects that the character interacts with (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 also 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".

All events started with the character coming into the unique scene, 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 moved into the next scene. Each event lasted approximately six 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 animation, 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 order of videos, as well as the order of questions within the location memory and temporal memory question types, were counterbalanced. Children always answered the location memory questions first and the temporal memory questions second, because in the initial design of the task, the choice alternatives presented for the temporal order questions could cue children about the location of the activities. However, this was not the case in the final design of the task.

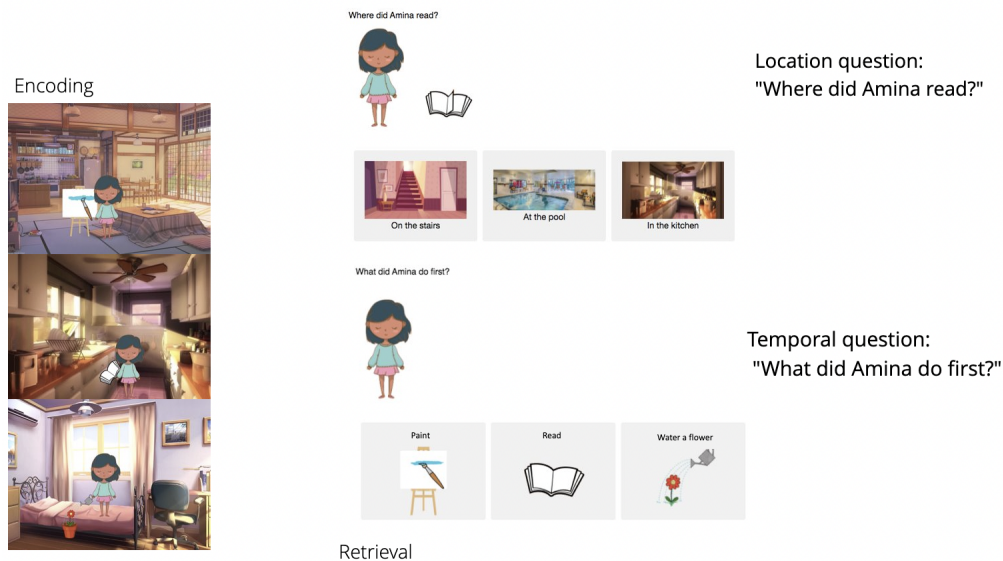


Figure 1. Schematic of the memory game.

### ***Timeline task***

This task was adapted from Tillman and colleagues (2018). The stimuli consisted of a Google Slides presentation with two pages, both of which had a large square with a black, circular icon on it which was referred to as a “sticker”. On one page, there were two additional red and blue circular icons, and on the other page, there were two additional green and yellow circular icons. The experimenter then asked the child to think about different days, such as “yesterday”, “today” and “tomorrow” (see Figure 2). The experimenter then verbally labeled the

black icon in the middle of the card as “today” and children were asked to verbally confirm the label of this icon to ensure they understood what it represents. The experimenter then asked the participant to place the two, colored icons on the card for “yesterday” and “tomorrow”, as they wished on the card. Children also did a second trial of this task with different time labels (“morning”, “noon” and “night”). To place the icons, we gave children remote access to the screen over Zoom so they could click and drag the icons 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 in which they wanted to place their icon and asked their caregivers to help move the icon to where they were pointing.

All children performed two trials of this task, and the icon colors and labels were counterbalanced across participants. If the child did not know the word “noon”, the question options were modified as “breakfast”, “lunch” and “dinner”. Two experimenters independently assessed the linearity for each arrangement, using the guide from Tillman et al., (2018). Each icon arrangement counted as a line if the smallest angle the three icons created was between 140 and 180 degrees, and the icons were placed on opposite sides of the central icon, such that their placement resulted in an ordered sequence along any axis. Arrangements were coded for linearity and for the orientation of the lines (see Figure 2 for example arrangements and how they were scored).

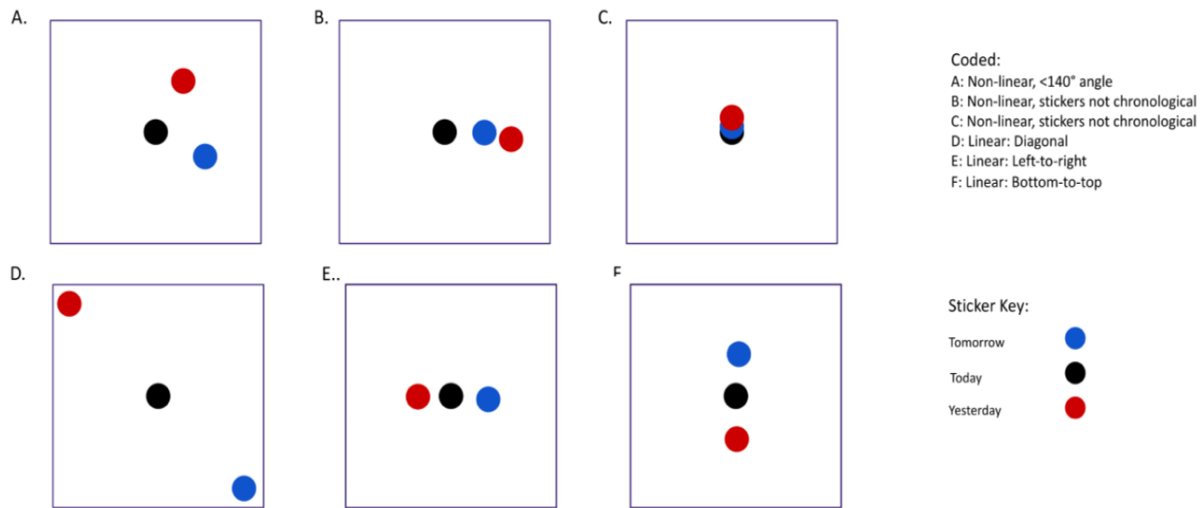


Figure 2. Example timeline arrangements.

**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 laptop or desktop computers 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 twenty minutes.

**Data Analysis**

This study design was pre-registered, which can be accessed at [https://aspredicted.org/7CZ\\_TB5](https://aspredicted.org/7CZ_TB5). We decided that we would stop data collection when we reached thirty participants who made two lines (linear arrangements on both trials), and thirty participants who made zero lines (nonlinear arrangements on both trials) for the timeline task

based on the power analysis we conducted. All data cleaning and analyses were performed in R using the lmerTest and tidyverse packages (Kuznetsova et al., 2017; Wickham et al., 2019)

## Results

### Memory Game

In the first series of analyses, we assessed whether there is 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:  $\text{accuracy} \sim \text{memory question type} + (\text{memory question type} | \text{subject\_id})$ ). We found that there was a main effect of question type, such that children had higher accuracy for location memory questions relative to temporal memory questions (see Figure 3).  $\beta = -2.64, p < .001$ , (Location:  $M = .92, SD = .11$ ; Temporal:  $M = .57, SD = .21$ ).

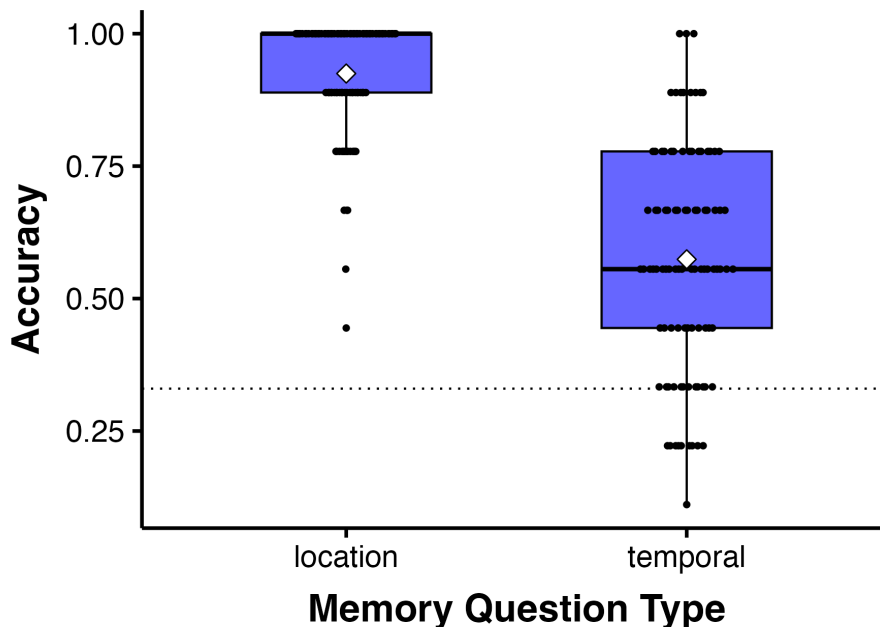


Figure 3. Memory accuracy by question type. The diamonds represent the mean accuracy for each question type, and the black dots represent individual participants.

### *Timeline Task*

We explored the emergence of a linear mental timeline, as well as which orientations were most common. First, we looked at the proportion of trials in which participants placed the stickers in a linear configuration. Figure 4 depicts the proportion of sticker arrangements into each line type. Overall, 29 (30%) children made zero lines, 20 (21%) children made one line and 47 (49%) children made two lines. This distribution is different from chance, and participants are predominantly making two linear arrangements across the two trials ( $\chi^2(2) = 11.8, p = .003$ ).

In the next series of analyses, we looked at the orientations of the linear arrangements (See Figure 4). We found that children who made only one line during this task made a mix of linear arrangements and did not show a predominant preference for a certain orientation when they did make lines ( $\chi^2(4) = 5.0, p = .29$ ). However, children who made two lines showed a higher preference for left-to-right linear arrangements compared to other linear arrangements ( $\chi^2(4) = 24.6, p < .001$ ). This pattern of results suggests that as children start showing a higher preference for linear arrangements to represent time events, their arrangements are also becoming increasingly in line with the culturally dominant mental timeline orientation.

We also explored how internally consistent children are in their timeline arrangements. Among the children who made two lines in both trials, 26 out of 47 (55%) children arranged both lines in the same orientation, with only half of these children placing the lines in a left-to-right order. These results show that children display a lot of variability in their mental timeline development, both in terms of internally consistent representations and the development of the culturally dominant, left-to-right arrangement. Even when children are consistently representing time linearly, about half of them are make a mixture of linear arrangements instead of

consistently representing time in the same orientation. Our results suggest that the development of the culturally dominant, left-to-right mental timeline follows a relatively protracted trajectory. Although we found that children who are more consistently making lines are showing an increased preference for the left-to-right oriented lines, only 13 out of 96 (14%) children in our sample made two left-to-right oriented lines across both timeline construction trials.

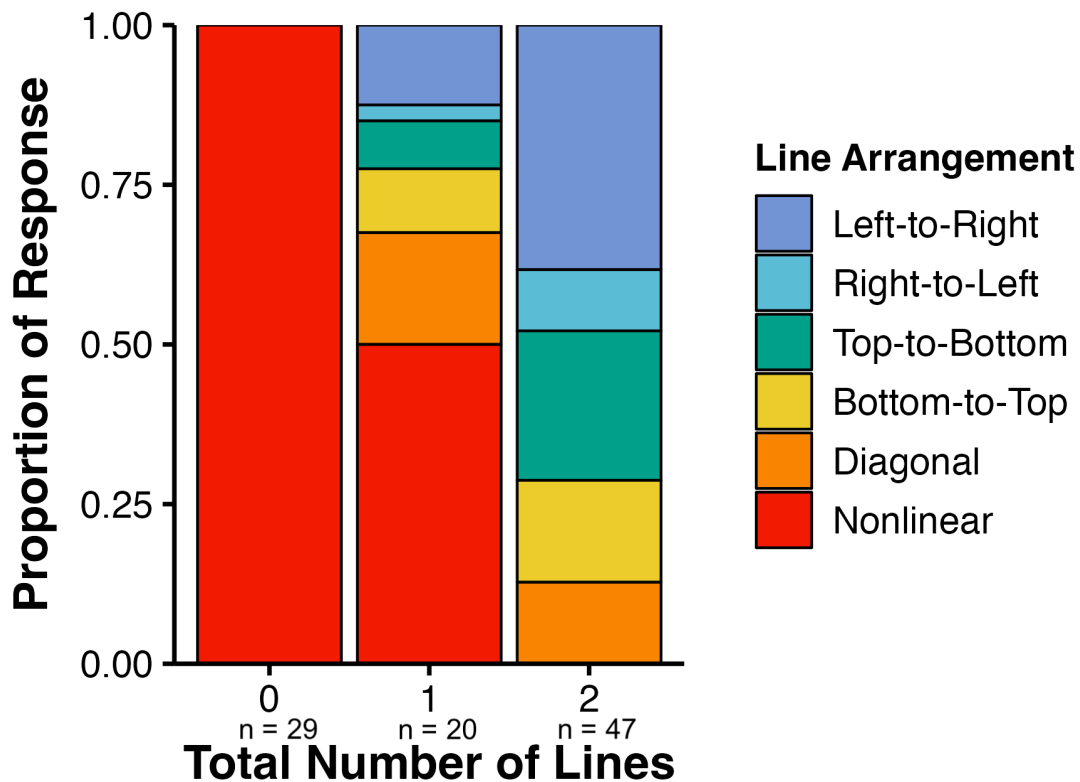


Figure 4. Distribution of timeline arrangements.

### *The Mental Timeline's Interaction with on 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 lines participants made in the timeline task related to their memory accuracy (model syntax: accuracy ~ memory question type \* # of lines + (memory question type | subject\_id)). Our results show a

main effect of question type, and no significant effect of the number of lines made during the timeline task on memory performance. Overall, children were more accurate in the location memory questions relative to temporal questions ( $\beta = -3.00, p < .001$ ) but number of lines did not predict overall memory performance ( $\beta = -0.08, p = .69$ ).

The interaction between the number of lines made and memory question type was not significant in this model ( $\beta = 0.30, p = .12$ ). Because this was our main question of interest, we ran a post-hoc independent samples t-test to explore differences in memory performance in children who made zero lines and two lines during the timeline task. Relative to children who made zero lines, children who made two lines had significantly better temporal memory accuracy ( $t(56.7) = -2.21, p = .03$ , 0 lines:  $M = .50, SD = .21$ ; 2 lines:  $M = .61, SD = .19$ ), but not better location memory accuracy ( $t(61.5) = 0.36, p = .72$ , 0 lines:  $M = .93, SD = .12$ ; 2 lines:  $M = .92, SD = .12$ ). Children who made one line across the two timeline trials were not significantly different than children who made zero lines or two lines in either question type (all  $t$ s  $< 1.5$ , all  $p$ s  $> .15$ ). This pattern of results shows that children who spontaneously represent time linearly are also more accurate in remembering temporal order information.

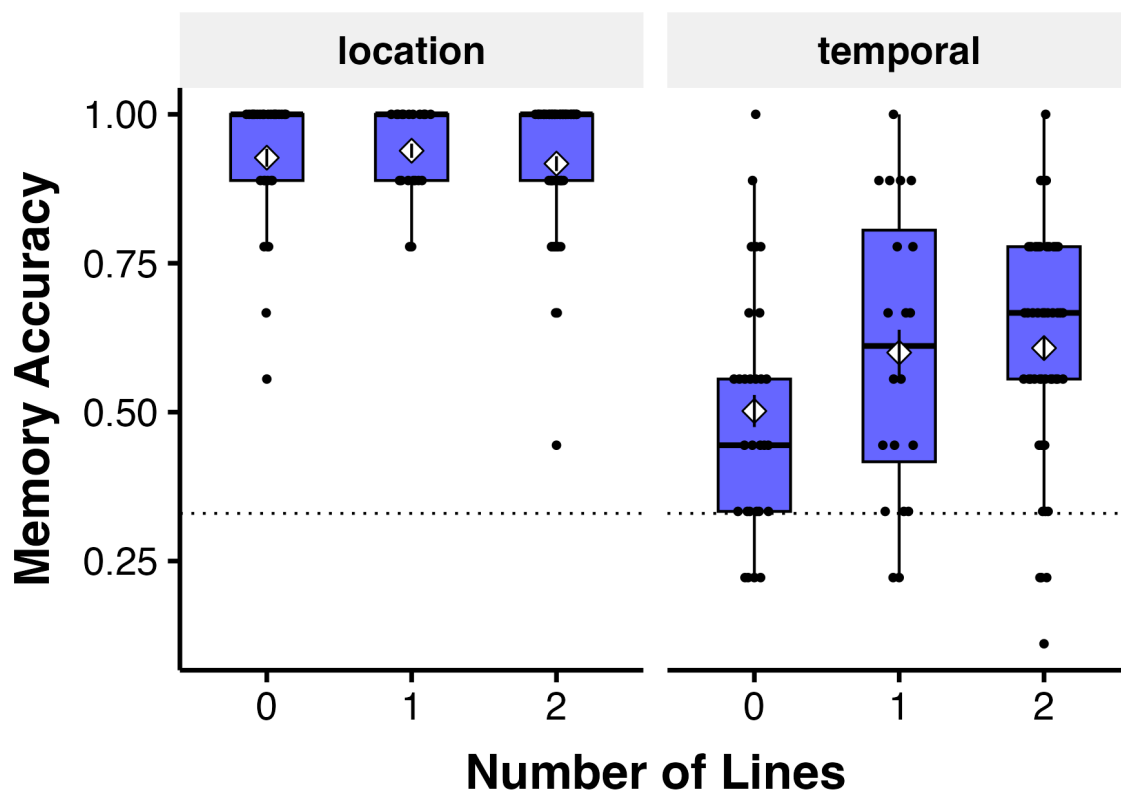


Figure 5: Location and temporal memory accuracy by number of lines.

Finally, we tested whether the number of left-to-right oriented lines was specifically 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 of the number of left-to-right linear arrangements with temporal memory performance ( $\beta = 0.74, p = .09$ ).

### Discussion

In Experiment 1, we found that 5- to 6-year-old children are less accurate for recalling the temporal order of events, relative to recalling the location of those events. This is in line with the idea that for young children, remembering ‘when’ an event occurred is more difficult than

remembering ‘where’ that event occurred (Hayne & Imuta, 2011). In the timeline task, we found that most children in our sample are representing time linearly, however, few children are consistently representing time in the culturally dominant mental timeline orientation. Our results show that there is an increase in the propensity to make the culturally dominant, left-to-right oriented lines as children make more lines. These results suggest that around 5-to-6-years of age, children are highly variable in whether they spontaneously represent time linearly, whether they are internally consistent in their mental timeline representations, and whether these representations are in line with the culturally dominant orientation.

We also found that the linearity of children’s mental timelines predicted their memory for temporal order, but not their memory for the location of events. Compared to children who made zero lines, children who made two lines had better memory for the temporal order questions. Critically, both groups of children performed equivalently on the location memory questions, which suggests that the difference in temporal memory performance is unlikely to be the product of group differences in task attention or engagement.

These results suggest that children make use of their mental timelines while encoding and retrieving temporal information to mentally represent the order of events. Notably, the orientation of children’s timeline arrangements was not related to their memory performance. Regardless of the orientation of these lines, children who represented time events linearly benefitted in their temporal memory accuracy. The development of a linear mental timeline could be encouraging children to spontaneously activate and reference spatial frameworks to encode and retrieve temporal order information. Because remembering the temporal order of events is more difficult than remembering the location of those events, learning to ground representations of temporal order in terms of space may improve the development of temporal

memory. In Experiment 2, we tested whether priming children to represent time linearly would benefit their temporal memory.

## **Experiment 2**

In Experiment 2, our goal was to take a causal approach to the main question of whether the development of the mental timeline influences temporal memory development. We tested whether encouraging children to represent temporal order in terms of the mental timeline can facilitate temporal memory accuracy. First, we introduced children to a priming activity, in which they viewed a spatial schema as they listened to a story. These schemas were arranged in either a left-to-right linear or nonlinear spatial arrangement and had icons that represented events from the story. In Experiment 2A, children passively viewed the spatial schema while they listened to the story. In Experiment 2B, children were also instructed to point to locations on the schema as they listened to the story. After the priming activity, children completed the memory game and the timeline task from Experiment 1.

Previous work shows that although young children are not likely to spontaneously make use of mnemonic strategies, they may benefit from them when prompted to use them (Schneider & Sodian, 1997). Further, prior work investigating the development of the mental timeline has shown that 4-to-6-year-old children are more likely to represent time linearly when exposed to spatial primes (Tillman et al., 2018). We predict that encouraging children to activate the mental timeline to represent the temporal order of events will improve their temporal memory accuracy in a subsequent task. This is because young children, for whom the mental timeline is still in development, may not spontaneously engage the mental timeline to represent the order of events (Tillman et al., 2018).

In this experiment, we focused on 5-year-old children. Because nearly half of the children in Experiment 1 were spontaneously creating lines in the timeline task, we opted to focus on an age group in which the majority of children are unlikely to already possess a linear timeline. Because children's accuracy for the location questions was near ceiling in Experiment 1, in Experiment 2, children answered the temporal questions before the location questions in order to confirm that the differences in memory accuracy among the question types were due to the type of memory being probed, and not the length of delay between encoding and retrieval.

## **Experiment 2**

### ***Participants***

#### Experiment 2A

The final sample included 65 participants ( $M_{age} = 5.45$  years, range: 5.03 - 5.99, 33 female). Thirty-one children were tested in the linear prime condition and 34 were tested in the nonlinear prime condition. Data from an additional 18 children were excluded due to not completing the experiment ( $n = 12$ ), experimenter error ( $n = 2$ ), not paying attention to the task ( $n = 2$ ) or having a developmental or learning disability ( $n = 2$ ).

Fifty-one families filled out the demographic information form. Caregivers described their children's racial-ethnic identities as: White,  $n = 35$ , (68.6%), Multiracial,  $n = 12$  (23.5%), Asian,  $n = 3$  (15.7%), and Hispanic or Latino/a,  $n = 1$ , (2%). The majority of participants learned English as their first language ( $n = 50$ ), and children were exposed to more than one language at home. Children came from primarily middle- and upper-class families.

Children were recruited through the University of Washington's participant pool database via email invitations. Each participant was sent consent information and a Zoom user guide prior

to the study date. Participants were asked to use laptop or desktop computers to ensure that the stimuli were displayed similarly across participants. Verbal and written consent was obtained from 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's Institutional Review Board. Each family received a \$10 Tango Gift card that could be redeemed online. We also sent each child a certificate of completion as a token of our appreciation.

## Experiment 2B

The final sample included 15 participants ( $M_{age} = 5.49$  years, range: 5.01-5.9, 5 female). Data from one additional child was excluded due not paying attention to the task ( $n = 1$ ). Sixteen families filled out the demographic information form. Caregivers described their children's racial-ethnic identities as: White,  $n = 13$ , (81.2%), Multiracial,  $n = 1$  (6.2%), and another racial category not listed,  $n = 2$  (12.5%). The majority of participants learned English as their first language ( $n = 15$ ), and 7 children were exposed to more than one language at home. Children came from primarily middle- and upper-class families. The recruitment methods were identical to Experiment 2A.

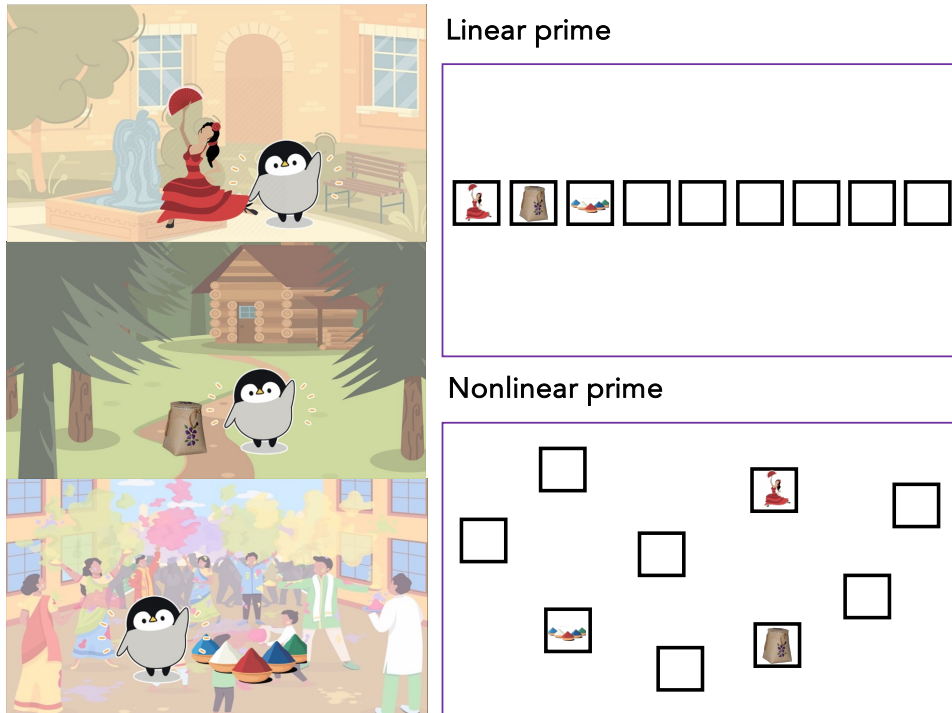
## Materials

### *Spatial Priming Activity*

This game was used to prime children to represent the order of events in a linear or nonlinear arrangement. The stimuli consisted of nine images of different backgrounds with a penguin image, who is the main character of the story (see Figure 6).

The experimenter started by informing the participant that they would meet a character, Frosty the Penguin, who would show his trip around the world. The participant was told that they would help Frosty fill out a virtual sticker sheet so he could remember his journey. These sticker sheets either had a linear or nonlinear arrangement of nine boxes. In the linear condition, the icons that represented Frosty's destinations appeared in a left-to-right linear order, such that the first event appeared on the leftmost box and each new event appeared to the right of the last box. In the nonlinear condition, the boxes were arranged in a nonlinear order with no apparent cue of where the icon for the next event would appear, and the images appeared in a pseudo-random order.

The experimenter narrated the story as Frosty visited nine different locations around the world and engaged in a unique activity at each location. After each event, the experimenter asked a question to keep the children engaged, such as "Next, Frosty visited Spain, where he learned to dance the Flamenco just like the dancer next to him. Do you like to dance too?". Every three events, the experimenter showed the participant Frosty's sticker sheet and narrated a recap of events ("Let's remember what Frosty did! First, he went to Spain and danced the Flamenco. Next, he went to Alaska and made a basket out of bark. Next, he went to India and played with colorful powders!") as an icon that represents the location appeared in the appropriate box. At the end of the story, the experimenter recapped all nine locations. Children were not asked any questions on the task other than the engagement questions that were built into the story script.



*Figure 6.* Schematic of the spatial priming activity.

In Experiment 2B, we asked children to point to locations on the screen in which the next icon that represents an event would appear. We ran this task version only in the linear prime condition, in order to compare the modification with results from Experiment 2A to assess whether the pointing manipulation made this task more salient than the version in which children were not asked to point. Children pointed during both the initial storytelling portion and the recap portion of the activity. We also added a red highlight to the box in which the icons appeared as the child was pointing, to draw attention to the location.

### ***Memory Game***

Children played the memory game following the spatial priming activity. The materials and questions of the memory game were identical to the memory game described for Experiment 1.

## ***Timeline Task***

Children completed the timeline task introduced in Experiment 1 with three modifications. The first modification was the labels in one of the trials. Because several children in Experiment 1 were unfamiliar with the word "noon", in Experiment 2 we substituted "breakfast", "lunch", and "dinner" for "morning", "noon", and "night". Another modification was to the icons themselves, which were changed to more child-friendly images rather than colored dots (see Figure 7). Finally, because many children had difficulty placing the icons themselves, we asked children to point to the location on the screen in which they would like to move the icon to and asked the caregivers to help move the icon to where they were pointing.

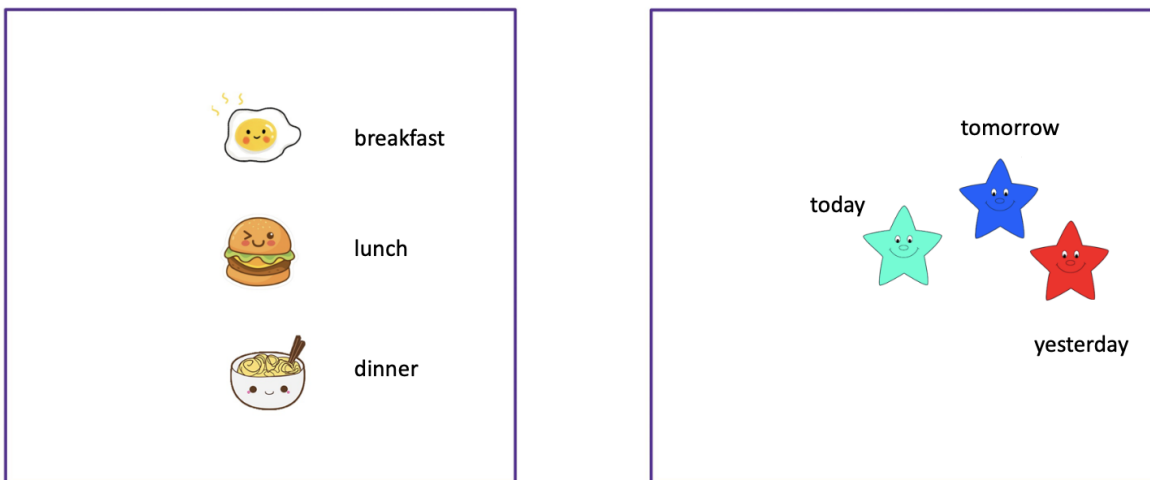


Figure 7. *Example timeline arrangements.*

## ***Procedure***

Participants were tested in their own homes on their own devices during a Zoom meeting with a caregiver and an experimenter present. The spatial priming activity utilized Microsoft PowerPoint, the memory game utilized Qualtrics, and the timeline task utilized Google Slides.

All participants completed the spatial priming activity first, followed by the memory game and finally, the timeline task. The entire testing session took approximately thirty minutes.

### ***Data analysis***

This study design was pre-registered, which can be accessed at [https://aspredicted.org/WV5\\_9BT](https://aspredicted.org/WV5_9BT). We decided to collect data from 60 5-year-old children in the linear condition and 60 in the nonlinear condition. We determined this sample size using a 2-sample t-test power analysis based on the difference in temporal memory accuracy between children who made zero lines and two lines during the timeline task in Experiment 1, which had an effect size of .53. However, for Experiment 2A, data collection was stopped early at 85 participants when anecdotal observations suggested that children were not engaged with our priming activity and preliminary analyses suggested no effects of priming group on memory accuracy. Experiment 2B was exploratory and was not pre-registered. Data collection was stopped at 21 participants when preliminary analyses suggested that the pointing manipulation did not make the priming task more salient relative to Experiment 2A. All data cleaning and analyses for both versions of the experiment were performed in R using the lmerTest and tidyverse packages (Kuznetsova et al., 2017; Wickham et al., 2019).

## **Results**

### ***Memory Performance***

#### Experiment 2A

In the first series of analyses, we assessed whether there is a difference in memory performance between the children who were tested in the linear or nonlinear prime conditions. We analyzed memory accuracy for these different priming conditions on performance in the two

question types across all participants, using a mixed effects model (model syntax: accuracy ~ memory question type \* priming condition + (memory question type | subject\_id)).

Contrary to our prediction, there was no main effect of priming condition on memory accuracy. Children in the linear and nonlinear conditions had no difference in their accuracy for location questions,  $\beta = 0.36, p = .26$  (Linear:  $M = .90, SD = .09$ ; Nonlinear:  $M = .88, SD = .13$ ), or temporal questions (Linear:  $M = .60, SD = .20$ ; Nonlinear:  $M = .64, SD = .20$ ). As in Experiment 1, children had higher accuracy for location memory questions ( $\beta = 2.16, p < .001$ ), ( $M = .89, SD = .11$ ) relative to temporal memory questions ( $M = .62, SD = .20$ ).

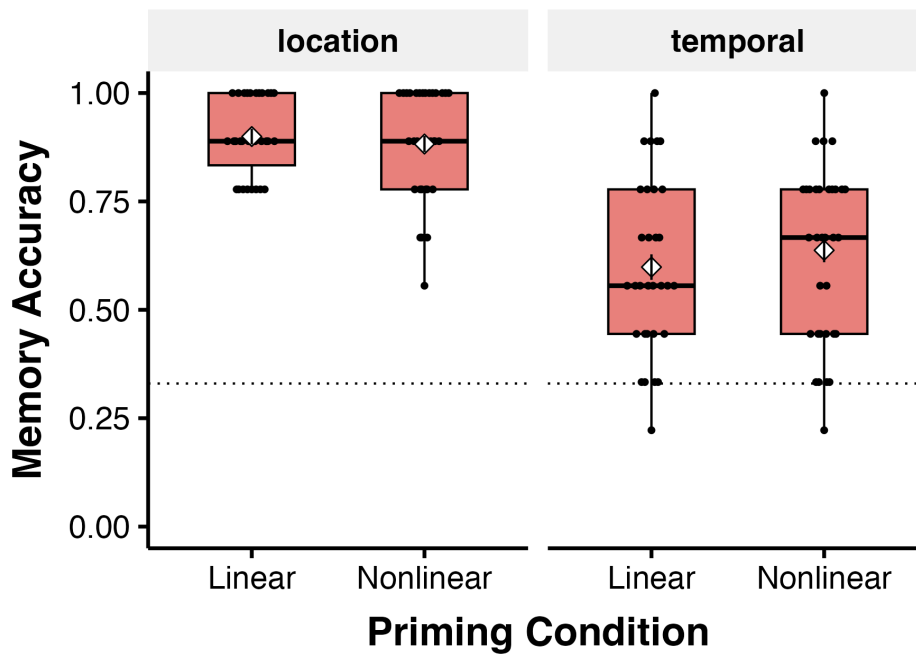


Figure 8. Memory accuracy for each question type by priming condition in Experiment 2A

### Timeline Task

Experiment 2A

We first explored whether children in the linear prime condition made more linear arrangements relative to children in the nonlinear prime condition. Overall, 21 children in the linear condition and 25 children in the nonlinear condition made two lines, six children in the linear condition and four children in the nonlinear condition made one line and, four children in the linear condition and five children in the nonlinear condition made zero lines across the two timeline task trials. Similar to Experiment 1, we found that children tested in both priming conditions predominantly made two linear arrangements across the two trials (Linear:  $\chi^2(2) = 16.7, p < .001$ , Nonlinear:  $\chi^2(2) = 24.8, p < .001$ ), (See figures 9 and 10).

Among children who only made one line across the two timeline trials, children tested in the linear condition made their arrangements in all five orientations, and the distribution among these orientations was not different from chance ( $\chi^2(4) = 0.67, p = .96$ ). Children tested in the nonlinear condition made their arrangements in only three orientations, which were left-to-right, bottom-to-top, and diagonal ( $\chi^2(2) = 0.5, p = .78$ ). Among children who made two lines across the two timeline trials, children tested in the linear condition predominantly arranged their lines in left-to-right and bottom-to-top arrangements ( $\chi^2(4) = 11.1, p = .03$ ). Children tested in the nonlinear condition predominantly arranged their lines in left-to-right and diagonal orientations. ( $\chi^2(4) = 17.4, p = .002$ ). Overall, children in Experiment 2 predominantly made linear arrangements in the timeline task, and children did not differ in their likelihood in making linear or nonlinear arrangements across the priming conditions.

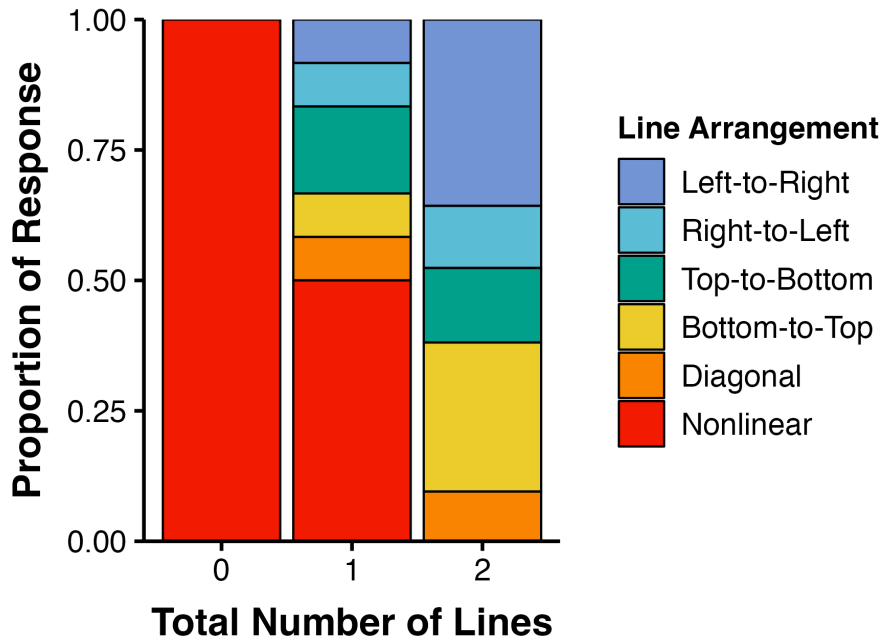


Figure 9. Distribution of timeline arrangements for children in the linear prime condition in Experiment 2A.

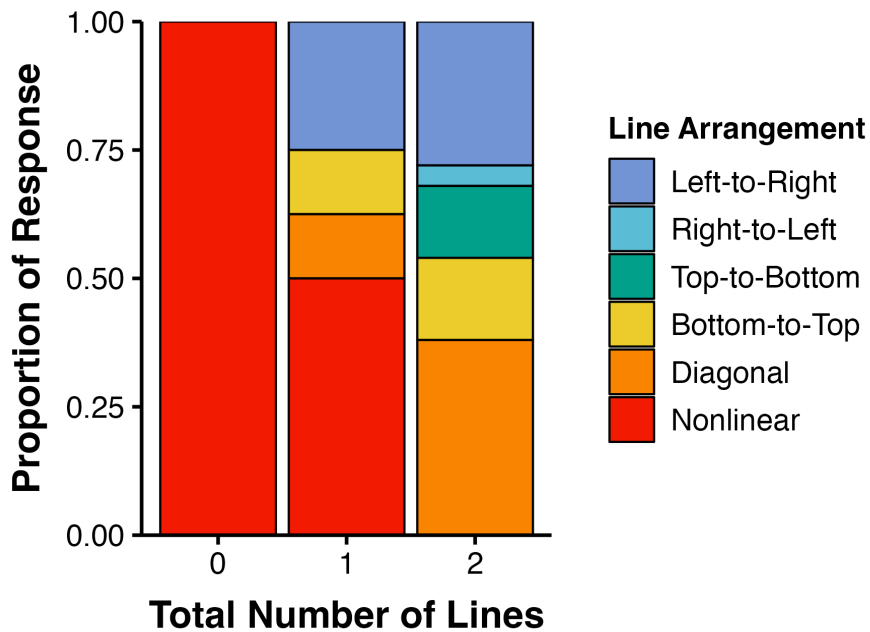


Figure 10. Distribution of timeline arrangements for children in the nonlinear prime condition in Experiment 2A.

## ***Timeline Task and Memory Performance***

### Experiment 2A

We ran an independent samples t-test to explore differences in temporal memory performance in children who made zero lines and two lines during the temporal memory task. Contradictory to our predictions, children who made two lines did not have better temporal memory accuracy (2 lines:  $M = .62$ ,  $SD = .20$ ; 0 lines:  $M = .60$ ,  $SD = .19$ ,  $t(11.6) = 0.16$ ,  $p = .88$ , or location memory accuracy (2 lines:  $M = .90$ ,  $SD = .10$ ; 0 lines:  $M = .85$ ,  $SD = .14$ ,  $t(9.7) = 1.08$ ,  $p = .31$ ) in comparison to children who made zero lines across the two timeline trials.

### ***Memory Accuracy by Task Version***

There was no difference in the temporal (2A:  $M = .60$ ,  $SD = .20$ ; 2B:  $M = .55$ ,  $SD = .24$ ) or location (2A:  $M = .90$ ,  $SD = .09$ ; 2B:  $M = .89$ ,  $SD = .09$ ) questions among the 2A and 2B priming activity conditions,  $\beta = -0.12$ ,  $p = .79$  (see Figure 11). This pattern of results indicates that the pointing manipulation in Experiment 2B did not make the priming activity more effective or salient relative to the initial, more passive version in Experiment 2A.

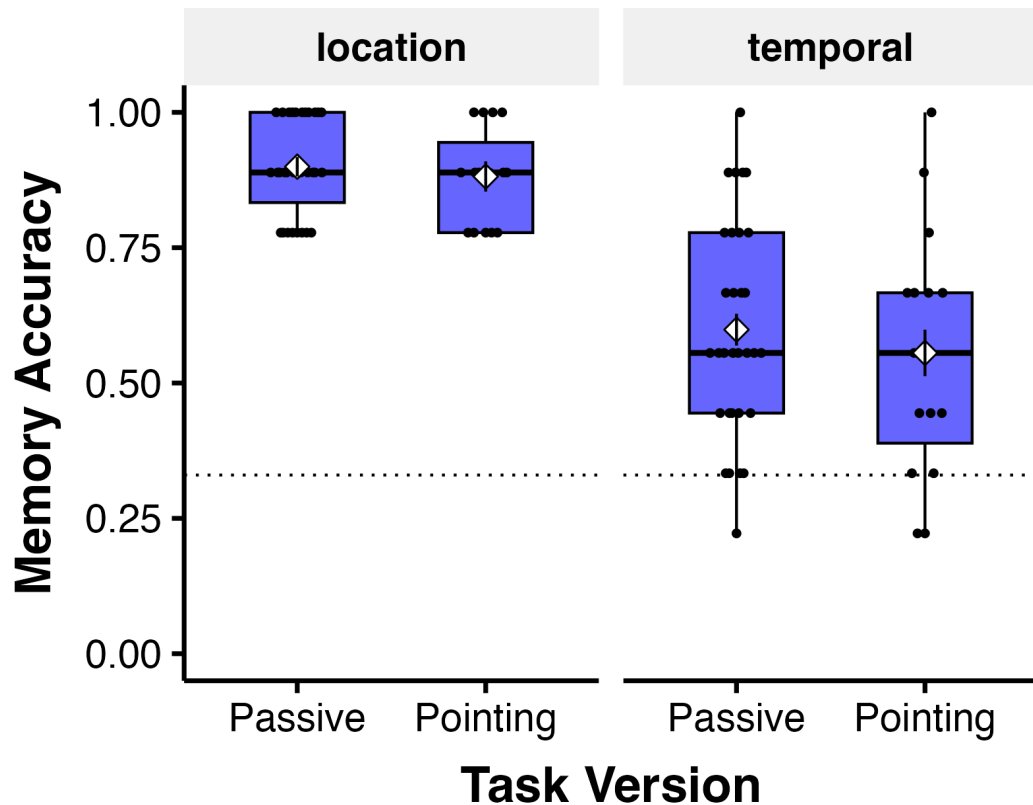


Figure 11. Memory accuracy for each question type by task version, 2A: Passive, 2B: Pointing.

### *Timeline Arrangements by Task Version*

For the timeline task, we explored whether children tested in task version 2B prime made more linear arrangements relative to children tested in task version 2A. We found that children in both task versions predominantly two linear arrangements across the two trials ( $\chi^2(2) = 2.53, p = .32$ ). Among children who were tested in task version 2B, eight children made two lines, five children made one line and none of the children made zero lines.

Among children who made one line across the two timeline trials, children tested in task version 2A showed no preference for a specific orientation (Linear:  $\chi^2 = 0.67, p = .96$ ). Children tested in the task version 2B made either top-to-bottom or bottom-to-top arrangements (Linear:

$\chi^2(1) = 0.2, p = .65$ ). Among children who made two lines across the two timeline trials, children tested in task version 2A predominantly arranged lines in left-to-right and bottom-to-top arrangements ( $\chi^2(4) = 11.1, p = .03$ ). Children tested in task version 2B, however, showed no preference for a particular orientation ( $\chi^2(4) = 3.14, p = .53$ ). Overall, across both task versions, children showed a preference for linear arrangements, and neither task version was more effective in encouraging children to make linear arrangements.

### ***Discussion***

In Experiment 2, we were interested to see whether we could encourage children to represent time in terms of the mental timeline to aid their temporal memory performance. Contradictory to our prediction, we did not find an influence of the priming condition on temporal memory performance or the proportion of linear arrangements in the timeline task.

One reason for this null result might be that because the tasks were conducted virtually over Zoom, the priming activity was not engaging enough to prime children's mental representations of time events. We think that the virtual activity was too passive to prime children's mental representations of time events. One reason why we think this activity is too passive is that there was no visuomotor engagement to our activity. In our priming activity, participants watched icons appear in either linear or nonlinear arrangements on the screen, however, in prior activities designed to prime linear representations, participants actively placed stickers on a sheet (Tillman et al., 2018). Additionally, previous work suggests that adults benefit from combining visual encoding with motor action in memory tasks in which they are asked to remember spatial information (Chum et al., 2007).

Thus, we decided to continue our data collection with a modification to the priming activity described in Experiment 2B, such that we asked children to point to the locations on the screen in which the icons appeared, to incorporate some visuo-motor engagement in this task. The results of Experiment 2B suggest that the pointing prime version of the spatial priming activity task was not more effective in priming children to think about time in a left-to-right linear order, relative to the initial, passive version. One reason for this might be that despite pointing, watching icons appear on a screen was not active enough to engage children and prime children's their mental representations of temporal order.

## **General Discussion**

Our main hypothesis for these experiments is that one reason why spatiotemporal associations are so common is because representing time in terms of space is beneficial for temporal memory. We explored the link between the mental timeline and temporal memory development through two approaches. In Experiment 1, we assessed how individual differences in the development of the mental timeline relate to temporal memory. In Experiment 2, we took a causal approach and explored whether priming children to think about time linearly would be beneficial for temporal memory.

### *Memory Development*

In both Experiments 1 and 2, we found that memory for locations of events is significantly better than memory for the temporal order of events at 5-to-6 years of age. This result 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; Picard et al., 2012; Lee et al., 2016; Prabhakar & Ghetti, 2020). Further, previous work with 4-to-6-year-old children had tested the difference in the development of these two

types of memory using a task with highly complex events and multiple recall conditions such as free recall and cued recall (Picard et al., 2012). Our findings show that this asymmetry in development of temporal and spatial memory is also evident in a simplified task. These results suggest that at 5-to-6 years of age, children may have difficulties binding all components necessary for a complete episodic memory and may not be able to recall a simple order of events accurately.

Previous studies suggest that memory for temporal order is more difficult than memory for location information into young adulthood (Pathman, 2018). Although remembering temporal order information is more difficult than remembering location information at all ages, the gap between memory performance for temporal and location memory narrows with age, and temporal memory develops at a faster rate than location memory between early childhood and young adulthood (Pathman et al., 2018; Picard et al., 2012). Multiple factors could contribute to the rapid development of temporal memory abilities between early childhood to adulthood, such as general maturation of brain regions as well as the development of the use of strategies that help temporal memory, such as drawing on the mental timeline to recall temporal order.

### *Development of the Mental Timeline*

One of our main interests was to explore individual differences in the development of the mental timeline. Consistent with previous work, we found that most children in our sample spontaneously represented time in a linear arrangement (Tillman et al., 2018). Our results suggest that as children start to represent temporal events in linear arrangements more consistently, they also develop an increased preference for the culturally conventional, left-to-right linear arrangement. In our sample, children who were only making one linear arrangement did not show a preference towards any specific line orientation, whereas children who were

consistently making lines across the two trials started showing a preference for left-to-right oriented lines.

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 (Tillman et al., 2018; Tversky et al., 1991). Our analysis, however, also explored how consistent individual children are in this process. Our results indicate that 5- to-6-year-old children display a varied progression to building adult-like mental linear representations of time, rather than showing a clear change from not representing time linearly to making consistent linear representations.

Children in our sample were highly variable in whether they consistently made linear arrangements and whether the orientations of these lines were consistent across the two trials. A high proportion (21%) of children in our sample made a mix of linear and nonlinear arrangements across the two trials. Even in children who made two lines across the two timeline construction trials, about half of the children made different orientations of lines across the trials rather than using the same orientation on both trials. A small percentage (14%) of children in our sample made two left-to-right lines across the two timeline trials, which is the culturally dominant timeline for this sample. This pattern of results could be showing two developmental stages among children who are making lines across both timeline trials. About half of these children are making a mix of arrangements in different orientations, while half of them are showing a more adult-like representation that is consistently in the same direction across the two trials. These results suggest that the development of a robust mental timeline may be less neat and more protracted than previously thought. It is possible that children are trying multiple linear arrangements, or some linear and some non-linear arrangements while developing their mental

representations of time. In the future, studies could further focus on individual level data to better understand this variability.

Our results from the timeline task provide insight into individual variability that has not been captured in previous analyses, which have focused on group-level differences in proportions of children's linear arrangements. It is important to note that the spatial orientations of the testing medium we used for the timeline task is different than the one Tillman and colleagues used. While they used a paper on a desk in front of a child, we used icons on a screen, which made the spatial orientations of the task materials as well as the perception of the axes relative to the viewer different. For example, while making a vertical arrangement on a piece of paper involves moving in a sagittal direction, this is not the case for making the same arrangement on a screen. Despite the differences in in-person versus virtual testing formats, the patterns from our sample were very similar to patterns from previous American samples (Tillman et al, 2018). The similar patterns across these testing formats show that these results are robust to changes in format.

#### *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 predictions for Experiment 1, we found that the individual differences in the strength of children's mental timelines predicted their temporal memory performance. Relative to children who made zero lines, children who made two lines in the timeline task were significantly more accurate on temporal memory questions. The largest difference in temporal memory performance in Experiment 1 was between children who made zero lines and children who made two lines in the timeline task. Importantly, though children who made two lines performed better on temporal

memory questions, all children performed equally 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 the difference in performance on the temporal memory questions are likely driven by the linear mental representation of time.

Although their temporal memory performance was not significantly different than either the zero-line or the two-line group, children who made one linear arrangement in the timeline task performed most like children who made two linear arrangements in the temporal memory questions. It is possible that these children are benefiting from starting to form linear representations of time during temporal memory recall, although these differences are not as pronounced as children who are starting to consistently representing time linearly.

In our analyses, we also explored whether the orientation of the mental timeline influenced temporal memory performance. We assessed whether this temporal memory advantage was driven by linear arrangements of any orientation, or specifically the culturally conventional, left-to-right oriented linear arrangements. Among children who represented time linearly across both timeline task trials, children who made two left-to-right arrangements did not show a memory advantage relative to children who made two linear arrangements in a different orientation. Overall, our results imply that the benefit to temporal memory in this context comes from thinking about time linearly, rather than having the culturally dominant, left-to-right mental timeline. Although we did not find an effect of line orientation on temporal memory performance, previous work has demonstrated that older children and adults benefit from spatial representations of time that are congruent with the mental timeline orientations that are the conventional in their culture, rather than any linear orientation (Pathman et al., 2018). These results suggest that developing mental spatial representations of time is beneficial for temporal

memory development; as children start building a consistent mental timeline, they are also drawing on it to support episodic memory for temporal order.

### *Priming the Mental Timeline*

Our results from Experiment 1 show that children who have more linear representations of time also have better temporal memory, and that at 5-to-6 years of age, children are highly variable in their development of their mental timeline. Building on our Experiment 1 results as well as prior research highlighting the flexibility of children's mental representations (Tillman et al., 2018), we aimed to investigate whether we could use spatial priming to encourage children to activate the mental timeline. Although children who have more consistently linear mental timelines are drawing on the mental timeline to remember temporal information, it is possible that for children for whom the mental timeline is not yet consistent, engaging the mental timeline is not a strategy they use spontaneously. Further, investigations into the use of mnemonic strategies in children demonstrate that young children are unlikely to spontaneously use mnemonic strategies such as verbal rehearsal, although they benefit when prompted to use them (Schneider & Sodian, 1997). At 5-to-6 years of age, a robust mental timeline representation is still in development for many children, which could make it difficult for them to use the mental timeline as a strategy to remember temporal order.

In Experiment 2, we explored whether priming children to represent time in a linear, left-to-right order would have a positive influence on temporal memory. However, the results from Experiments 2A and 2B suggest that our priming activity was not effective in influencing children's temporal memory. Contrary to our predictions, we did not see a difference in temporal memory accuracy between children who were tested in the linear and nonlinear priming conditions. Additionally, there was no influence of priming condition on the proportion of linear

arrangements children made in the timeline task. One possibility for these null results is that priming the mental timeline does not affect memory performance. Another possibility is that our priming task was not effective in encouraging children to think about time in terms of space.

A recent study by Tillman and colleagues (2018) provides evidence that priming activities involving object manipulation can successfully influence mental timeline representations in 4-to-6-year-old children. In this study, children were shown an arrangement of three differently colored blocks, oriented either in a horizontal or vertical line, and then asked to place stickers in an orientation that matched the blocks. This activity was effective in increasing the proportion of linear arrangements children made in a subsequent timeline task, and specifically in increasing the proportion of lines that were oriented in the same direction as the spatial primes. These results demonstrate that children's mental timeline constructions can be influenced through a priming activity in which they watch and physically manipulate objects.

Another recent study that successfully primed children's mental number lines, which is conceptually similar to the mental timeline, was conducted by Göbel and colleagues (2018). In this study, 3-to-5-year-old preliterate children engaged with an experimenter reading a story book, either in a left-to-right, or a right-to-left direction. They found that this priming activity influenced the direction of children's counting behavior, such that children became more likely to count objects in the same direction in which the experimenter read the storybook. However, children in their sample did not show this effect after simply viewing images of animals moving on a screen in either a left-to-right or right-to-left direction (Göbel et al., 2018). These contrasting results suggest that visual priming tasks in which children simply watch an activity may be not salient enough to prime children's mental representations of number quantities,

whereas a task in which they can physically engage with can successfully prime these representations.

The results of the Tillman et al. (2018) and Göbel et al. (2018) provide some insight into why our priming activity may not have been effective. One reason why our task was not effective could be the lack of visuo-motor engagement, which would require children to engage in this task while pairing visual information with motor movement. There is evidence that suggests people benefit from visuo-motor engagement in spatial memory tasks (Chum et al., 2007). In contrast to these previous studies in which children were successfully primed (Göbel et al., 2018; Tillman et al., 2018), children in our study were not able to physically engage with the materials in the task and instead simply watched icons appear on a screen. It is possible that motor engagement paired with the visual information in the previous activities have made them more salient and in turn more effectively influenced children's mental representations. We attempted to improve the motor component of our task through introducing a pointing manipulation in Experiment 2B. In Experiment 2A, children only watched icons appear in the boxes on the priming schema. In Experiment 2B, we asked children to point to the highlighted box before the icon appeared in it. However, conducting the experiment virtually made it challenging to control factors such as screen size and the precise location children were pointing to, potentially reducing both the consistency of the pointing manipulation and the efficacy of the priming activity. Moreover, compared to the tasks used by Tillman et al. (2018) and Göbel et al. (2018), our virtual priming activity offered less joint attention between the experimenter and the participant, potentially decreasing its saliency.

Another factor that could have influenced the effectiveness of priming activity is children's visual access to the priming stimuli. Children in our sample were only able to view the

priming schema during the recap phases of the story, rather than engaging with it for the whole duration of the activity. Perhaps children in our sample would have benefitted from longer visual exposure to the priming stimuli. It is also possible that the sequential nature of the hearing the story and then seeing the spatial primes made the connection between the priming stimuli and the story sequence less explicit.

It is possible that while the spatial priming activity did not directly influence temporal memory performance, it might have had a temporary impact on children's mental mappings of temporal events. This may have been especially expected given the results from the timeline task conducted by Tillman and colleagues (2018). However, effect of the priming activity may have been short-lived, and the longer delay between the tasks might have diminished the spatial priming effect on children's timeline arrangements. A key difference between both of the paradigms discussed and our own is that we had a memory task in between the priming activity and the timeline task. In both previous studies, children were asked to perform the target tasks immediately after the priming tasks with no distractor task in between (Göbel et al., 2018; Tillman et al., 2018). In our experiments, the delay between the priming activity and the timeline construction task is longer because children engage in a memory task between. Future studies can further explore the duration of the influence of spatial priming activities is on children's mental representations of abstract concepts.

The differences in the results and designs across these studies could help improve our understanding of what aspects of these priming activities might bolster the use of the spatial mappings and are most influential in supporting children's mental timeline development. We are currently running an in-person version of Experiment 2, in which children have access to a physical board on which they can place icons on during the priming activity. This change

overcomes some of the limitations of the online format in Experiment 2. In the in-person version of this task, children have access to the priming schema for the whole duration of the activity and can physically move stickers on the board while they simultaneously listen to the story. With this improved design, we hope to gain further insight into what types of spatial priming activities could effectively encourage children to activate the mental timeline, and whether these activities also influence how children spontaneously encode and represent temporal order.

### *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 timelines interfaces with temporal memory using both a correlational individual differences approach and a causal approach. Our results provide preliminary evidence that the development of the mental timeline supports the development of temporal memory, such that as children begin to mentally represent time linearly, they can use this framework to encode and recall temporal order information. Further, our results provide insight into various constraints of spatial priming activities and suggest that children's active engagement, as well as motor cues, might be critical in influencing mental spatial representations.

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