Beyond Here and Now: How Spatial Representations Support Abstract Thought

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Abstract

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The ability to think about concepts beyond our physical world is a hallmark of human intelligence. However, in contrast to things that are here and now, representing, remembering, and reasoning about abstract domains is more difficult. Many people across many cultures, languages, and ages get around this problem by grounding representations of abstract domains in space. Spatial representations of abstract domains may be so ubiquitous because they contribute to our ability to reason about them. One such representation is the mental timeline, a linear projection of time onto space, used to order events in time. The mental timeline may be so prevalent across different cultures because it supports a difficult and fragile aspect of episodic memory: remembering temporal information. In this dissertation, I used the mental timeline and temporal memory as a test case, examined with different methods at different ages, to reveal a piece of a larger intellectual puzzle concerning questions about how spatial mental

representations are leveraged as tools for learning, remembering, and reasoning about abstract concepts. The first empirical study, described in Chapter 2, investigated young children's development of linear representation of temporal order supported the development of their temporal memory abilities. The studies presented in Chapter 3 investigated whether infants, who have limited exposure to cultural artifacts that spatialize temporal information, leverage linear spatial cues to learn and remember temporal order. Finally, the study presented in Chapter 4 investigated adults' spontaneous use of spatial cues when performing memory tasks and investigated whether pupillometry and gaze movement measures provide insight into memory processes. All empirical chapters suggest representing time and, in particular, temporal order in terms of space is beneficial for temporal memory in infancy, childhood, and adulthood.

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Acknowledgments

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Dedication

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Chapter 1. Introduction

1.1 Introduction to using space to support abstract thinking

The ability to think about concepts beyond our physical world is a hallmark of human intelligence. Although we interact with our environments through our senses and actions, we often think about concepts we cannot see or touch and form mental models of abstract domains such as time, numbers, and fairness (Boroditsky, 2011). Our ability for abstract thought allows us to perform many uniquely human things: we mentally travel in time by imagining ourselves in a hypothetical future, we draw analogies between a doner kebab rotating near a heat source and the earth revolving around the sun, we consider the perspective of the person sitting across us when showing a diagram, and we understand the metaphorical expression of ideas crawling in our heads. These tasks all require us to mentally represent, remember, and reason about things beyond here and now.

Although abstract thinking is central to our lives, many people across different ages and cultures may struggle to think about abstract concepts relative to more concrete ones (e.g., Barsalou & Wiemer-Hastings, 2005; Gentner & Hoyos, 2017; Markman, 2013). One reason for this may be because, in contrast to things that are here and now, thinking about abstract concepts may have higher demands for mental representation and memory. Abstract concepts may often require grounding and contextualization in familiar knowledge or experiences (Borghi, 2020; Gattis, 2001; Granito et al., 2015; Pecher & Zeelenberg, 2018). Because many people have rich knowledge of the physical world, and ample experience interacting with and exploring it, representing abstract ideas and experiences in terms of more concrete ones may facilitate the ability to represent, remember, and reason about them (Tversky, 2001).

Space is a frequently used domain to represent abstract concepts and is considered a 'universal donor' as a domain ubiquitously recruited to represent other target domains (Gentner et al., 2001). Spatial information we observe in the world and represent in our minds may involve information about shapes, locations, paths, relations among entities, and how entities are situated in their frames of reference (Newcombe & Shipley, 2014). Our ability to mentally represent and transform this information is related to our spatial thinking skills (Uttal et al., 2013). These skills are crucial to our functioning in the world because they support skills central to our lives, ranging from navigating our environments (e.g., where should I go to find water?) to assessing threats in those environments (e.g., how close are other animals to me?). These skills are also relevant to many daily tasks that require the mental manipulation of spatial information. For example, when assessing whether our sofa would fit on the other side of the room, we mentally rearrange the space before physically moving the furniture, and when trying to find the shortest way to our destination, we mentally represent and compare the possible routes.

One reason why spatial thinking may be particularly helpful for supporting abstract thinking may be because spatial thinking skills are also relevant to tasks that are not directly related to spatial properties of our environments, such as the size of a room or the length of roads. For example, when planning our day in the most efficient way to get all our tasks done, we go through a process similar to finding the shortest way to our destination by making various arrangements in our minds and comparing them. To solve a geometry problem, we go through a process similar to imagining the sofa on the other side of the room. Our abilities to represent and mentally manipulate spatial information may therefore support our abilities to represent, manipulate, and reason about abstract information.

In line with this idea, many researchers suggest that abstract thinking is supported by analogical processes, such that we extend our representations of experiences in tangible and concrete domains to represent abstract ones (Gentner & Hoyos, 2017; Lakoff & Johnson, 1980). These representations are prevalent in linguistic metaphors, co-speech gestures, and cultural inventions across many cultures and age groups (Casasanto, 2017; Cooperrider & Núñez, 2009; Tversky, 2001; Tversky et al., 1991). For example, people use metaphorical language across many languages and cultures to describe abstract domains in terms of space. For instance, we may say that we are feeling ‘down’ to express our negative feelings, or we may describe a deadline as ‘approaching’ to communicate urgency. Such conceptual metaphors provide a relational structure in which we can ground our understanding of abstract concepts (Boroditsky, 2000; Gentner et al., 2001; Lakoff & Johnson, 1980). In other words, when we draw on our experience of a 'rough' surface in the spatial domain to describe a challenging interaction with a friend, we use a concrete domain as a source to represent a more abstract experience in the realm of interpersonal relationships. Further, when we talk about the ‘roughness’ of an interaction, we not only use this metaphor as a tool for communication but use it as a tool for engaging with and thinking about our experience (Lakoff & Johnson, 1980). Such metaphorical expressions featuring abstract concepts often feature an asymmetric relationship between the source and target domains, such that we describe abstract domains in terms of concrete ones more often than the reverse. These metaphors are communicated in language (Gentner, 2001) and also visually by diagrams, depictions (Tversky, 2001), and gestures (Kita et al., 2001). The widespread use of such conceptual metaphors, as well as the frequent use of space as a donor to structure these metaphors, suggest that spatial representations can be particularly helpful for representing abstract concepts.

1.1.1 Space as a tool for thinking

While people across many cultures use spatial metaphors to think about and communicate a wide range of abstract concepts, applying spatial thinking can particularly benefit the kind of abstract thinking that requires mentally manipulating those concepts (Atit et al., 2020). In support of this idea, decades of work demonstrate that spatial thinking abilities are strongly related to skills in domains that require learning and reasoning about abstract concepts, such as topics in science, technology, engineering, and math (STEM) (Cooperrider et al., 2016; Ishikawa & Newcombe, 2021; Newcombe, 2010). Previous research exploring the link between spatial skills and success in domains that require mental manipulation of abstract concepts converge on the idea that spatial representations are helpful for abstract thinking because they help make abstract properties of concepts more tangible by providing a structure to organize information, allowing us to communicate and reason about such concepts more efficiently (e.g., Barsalou, 2008; Gentner & Hoyos, 2017; Goldin-Meadow & Singer, 2003; Starr et al., 2020).

For instance, research exploring the relation between mental representations of number and the development of mathematical skills suggests that developing mental number line (MNL) representations supports the development of understanding of abstract properties of numbers. In a landmark study by Siegler and Ramani (2009), researchers demonstrated that children's mathematical skills can be improved through experience with linear number line representations. In this experiment, preschoolers were randomly assigned to a linear board game condition in which numbers were represented with sequentially ordered squares on a line, a circular board game condition, in which numbers were represented as squares ordered in a circle, and a control condition, in which children performed numerical activities (e.g., counting objects) instead of playing a game. Children who played the game took turns using a spinner with an experimenter, which determined the number of squares a player could advance on the board. Children were encouraged to move pieces across the game board one by one while counting out loud. Children who played the linear board game improved their performance on magnitude comparison and addition problems significantly more than those who played the same game on a circular board, and those in a control condition, who performed numerical activities (Siegler & Ramani, 2009). This pattern of results suggests that the linear board game was more beneficial for learning, potentially because it more closely resembled the desired mental representation (e.g., a mental number line) relative to the circular board. In other words, experience with an external representation of a linear progression through equally spaced squares representing numbers can help preschoolers better understand how numbers progress and relate to each other (e.g., that adding two to a number is the same as adding one to that number twice because in both cases, we advance two squares on the line). This understanding and representation, in turn, aids the ability to reason about properties of numbers and generalize those principles to tasks such as selecting the larger number among two numbers, or deciding which number adding two other numbers may result in (Siegler & Ramani, 2009).

Using spatial representations to organize abstract information in a familiar structure is beneficial beyond scientific and mathematical domains, and can facilitate memory, reasoning, and communication to support skills relevant to our everyday lives (Gattis, 2001). For instance, our ability to represent abstract domains spatially may support abilities for envisioning the future, forming autobiographical memories, and learning new word meanings (Fivush, 2011; Mullally & Maguire, 2014; Starr et al., 2020). One line of evidence supporting this comes from Starr and colleagues (2020) who hypothesized that one reason why spatial metaphors are so common across languages and cultures may be because they help children scaffold their understanding of novel words, especially in relation to more abstract domains, which are more challenging to learn for young children (Lakoff & Johnson, 1980; Starr et al., 2020). To test this hypothesis, they explored 3-to-5-year-old children's abilities in learning a novel adjective (e.g., using the word 'daxy' to mean 'high' in space or pitch) in either the domain of space (e.g., items positioned in different locations) or the domain of pitch (e.g., tones that have different pitch). Subsequently, they tested children's abilities to extend this newly acquired word to the other, untrained dimension. Children who initially learned a novel word with examples presented in the spatial domain more easily learned the meaning of and extended the novel adjective to the untrained dimension, compared to those who initially learned in the auditory domain. Further, children learned associations that were not present in their language (e.g., using words 'thin' and 'thick' rather than 'high' and 'low' to refer to pitch), which suggests that children's ability to extend the novel word to the new dimension was not due to their experiences with spatial metaphors (Starr et al., 2020). These results suggest that children can make use of cross-domain associations between space and other abstract domains to learn novel words, and more broadly, spatial metaphors may help scaffold learning in domains where experiences are more fleeting (Starr et al., 2020).

The two developmental studies highlighted here exemplify that 1) strengthening spatial representations of number through experience with activities that highlight the structure of the desired representation can aid mathematical thinking (Siegler & Ramani, 2009) and 2) learning concrete meanings of novel words help scaffold children's abilities to learn about the more abstract meanings (Starr et al., 2020). The first study involves explicitly increasing exposure to and familiarity with spatial representations of an abstract domain, while the second suggests that young children can spontaneously take advantage of cross-domain associations between space and pitch to scaffold their learning of novel words. In the next section, I discuss the role of biology and cultural experiences in the development of spatial representations of abstract domains.

1.1.2 The development of spatial representations of abstract domains

How do we form spatial representations of abstract domains that may aid our abilities to think about them? Some of these representations seem to emerge as part of our biology. Studies exploring the origins of these representations suggest that magnitude representations among the domains of space, time, and number may be present in the first days of postnatal life (de Hevia et al., 2014). In landmark work by de Hevia and colleagues (2014), researchers conducted three experiments with human newborns for the presence of associations between 1) number and time mapped onto spatial extent (length of a line), 2) number (number of syllables in the auditory stimuli) mapped onto spatial extent, and 3) time (duration of auditory stimuli) mapped onto spatial extent. During the familiarization phase of these experiments, newborns were exposed to auditory and visual stimuli. In the subsequent test phase, the dimensions of numerosity, duration, and visual extent either changed in the same direction (both increasing or decreasing) or in opposite directions (one increasing, the other decreasing). The researchers hypothesized that if newborns are sensitive to the common structure of different magnitudes, they should respond differently to changes in the two dimensions based on the direction of the change. In other words, if newborns associate the extension of auditory duration with the extension of lines on a screen, they should prefer to look longer at the test trials in which the change in magnitudes are congruent (e.g., longer line and longer duration). For all experiments, newborns preferred the novel test trials only when magnitudes changed in the same direction. These results suggest that these newborns expected the dimensions of numerosity, spatial extent, and temporal duration to change in the same direction rather than opposite directions, indicating a spontaneous, early emerging association among these domains. These findings provide evidence that representations of space, time, and number are interconnected from the early stages of postnatal life, before the experiences with language and cultural metaphors, and before extensive exposure to the natural correlations between these dimensions (de Hevia et al., 2014).

Early representations of time, number, and space in 9-month-old infants have demonstrated similar results, such that infants' representations of space and more abstract domains such as time and number automatically engage and align with one another, supporting the idea that we may be biologically endowed with a functional overlap that results in associations between these domains (de Hevia & Spelke, 2010; Lourenco & Longo, 2010). These associations are also observed for representations of pitch, such that 4-month-old infants map pitch onto space similar to adults, for example, they associate tones higher in pitch with objects placed higher in space (Dolscheid et al., 2014). Because these associations are also observed in children and adults (Bonato & Umiltà, 2014; Dehaene et al., 1993; Dolscheid et al., 2011; Srinivasan & Carey, 2010), these findings suggest that humans do not need explicit instruction or extensive experience with the physical world to map magnitude representations of abstract domains such as number or time onto space (Lourenco & Longo, 2010; Srinivasan & Carey, 2010).

Beyond demonstrating a presence of magnitude mappings among these dimensions, studies exploring early-emerging, spatial representations of abstract domains suggest that these representations can aid cognition early in life (Srinivasan & Carey, 2010). For instance, in a series of experiments by Srinivasan and Carey (2010), infants and adults were presented with pairs of visual stimuli varying in length (e.g., images of cartoon caterpillars or lines on a screen) and tones with varying duration. These pairs were either congruent (e.g., longer caterpillar and longer tone) or incongruent (e.g., shorter caterpillar and longer tone). For both 9-month-old infants and adults, the congruent pairs were more easily remembered relative to incongruent pairs. The early emergence suggests that this functional overlap may emerge in part as part of our biology rather than being constructed through experience with cultural experiences such as hearing language that applies to both domains (e.g., 'long' and 'short') (Srinivasan & Carey, 2010). Further, these results suggest that like children and adults, infants also benefit from these associations (e.g., better encoding and retrieval of pairs of stimuli).

If spatial representations of abstract domains present before extensive linguistic and cultural experiences, why may activities such as playing games with a linear number line improve our ability to think about mathematical concepts? One reason for this may be that despite early associations between space and some abstract domains, much of our representations are shaped by our cultural experiences (e.g., Bonato et al., 2012; Boroditsky, 2001; Casasanto, 2008; Tversky et al., 1991; Zebian, 2005). While spatial representations are common across many cultures (e.g., representing days on a calendar), they show variability across cultures (e.g., calendars may have different orientations in different cultures). Experiences such as reading, writing, using calendars or abacuses, and learning linguistic metaphors can modify or strengthen spatial representations of abstract domains such as time, number, and pitch (e.g., Autry et al., 2020; Dolscheid et al., 2011; Göbel et al., 2018; Shaki et al., 2009; Tillman et al., 2018). Because there is an influence of culture on the formation of many of these representations, children often build these representations gradually.

Further, using spatial thinking for mentally organizing abstract information may require adapting and transferring spatial schemas across different domains (Gattis, 2001). For example, to understand what the metaphorical expression ‘the holidays are behind us’ means about temporal relations between events, we must not only understand front-behind relations in the spatial domain but must transfer what we know about the front-behind relations in space to our understanding of temporal order. Experience with cultural artifacts may therefore gradually contribute to our abilities to leverage such representations to aid our cognition. In line with this idea, previous research suggests that children are less likely to represent abstract domains in terms of space spontaneously (Tillman et al., 2018). For example, in a study conducted by Tillman and colleagues (2018) children and adults were asked to arrange stickers representing different time periods, such as 'yesterday,' 'today,' and 'tomorrow,' on a card, either with prior spatial priming using horizontal or vertical primes or without spatial priming. While adults showed no difference in arrangements across the priming conditions, most preschoolers placed stickers in nonlinear configurations when they did not receive spatial priming but showed an increase in the proportion of linear arrangements in both spatial prime conditions. These results show that even when preschoolers can represent temporal order linearly, whether they spontaneously do so is highly variable (Tillman et al., 2018).

Previous research also suggests that children are less likely to devise strategies such as spatial cues to support their thinking for difficult tasks (Bulley et al., 2020). In a study conducted by Bulley and colleagues (2020) children 4 to 11 years of age were shown stickers hidden under opaque, identical cups and asked to find the stickers after a delay period. The children were also given a marker pen which they could use to mark the cups to help them find the stickers after the delay. The results showed that the rate at which children spontaneously used this strategy increased with age, and although none of the 4 and 5-year-olds spontaneously used the strategy, they were more likely to use it if prompted by an experimenter (Bulley et al., 2020). These results suggest that young children may need more explicit prompting or explanations of how various strategies may aid their thinking before flexibly and spontaneously using such strategies. The findings from these studies support the idea that the spontaneous use of strategies that may aid cognition, such as memory strategies, may be learned from cultural practices (Vygotsky & Cole, 1978).

1.1.3 The development of abstract thinking

Because spatial representations of abstract domains and the ability to leverage these representations to aid thinking may develop slowly, it is interesting to explore the link between the gradual acquisition of such representations and their relation with children's abilities to remember and reason about abstract domains. Thinking about abstract concepts is more difficult than thinking about concrete ones for people of all ages, and building robust knowledge and representations of abstract concepts is particularly challenging for children (e.g., Brooks et al., 2018; Siegler & Ramani, 2009; Tillman et al., 2022; van Dijck et al., 2020). Young children may also have difficulty in tasks that require abstract reasoning, such as drawing analogies between two events, imagining a future scenario based on past experiences, or understanding what it may exactly mean for ideas to "crawl" into your head (Kim & Walker, 2021; Özçalışkan, 2007; Russell et al., 2011). Previous research suggests children more easily learn concrete information before extending their knowledge to abstract representations or relations (Gentner et al., 2001; Özçalişkan, 2004). For example, studies exploring children's comprehension of metaphorical language suggest that children initially think about metaphorical expressions in terms of directly observable properties (e.g., 'time flies' like a bird flies), but may gradually use their knowledge and experiences in more directly observable domains (e.g., knowing how a bird flies) to scaffold their knowledge and understanding of more abstract domains (e.g., metaphorical expressions about the passage of time) (Özçalişkan, 2004).

Because abstract thinking can be particularly difficult for children, and because children tend to more readily learn concrete properties of concepts before learning more abstract properties, spatial representations can be particularly helpful in scaffolding learning about abstract concepts and improving the ability to mentally operate on them by providing a structure in which abstract relations are represented (Gentner, 2010). Explicit use of spatial representations such as visuospatial displays and gestures can therefore help make structures within abstract domains (e.g., the relation between 'past' and 'present' times) more transparent (Cooperrider et al., 2016; Gentner, 2010; Tversky, 2014) and be useful in encouraging children to learn about the underlying structures of abstract domains.

For instance, in addition to external representations such as the number board game (Siegler & Ramani, 2009) gestures can scaffold learning by adding a spatial component to spoken language (McNeill, 1992). For example, Singer and Goldin-Meadow (2005) found that when 8 to 10-year-old children in the United States receive instruction on how to solve mathematical equivalence tasks, they benefit more from instruction combining speech and gesture when instructors convey different strategies in their speech and gesture, compared to hearing both strategies in speech (Singer & Goldin-Meadow, 2005). These gestures may more effectively demonstrate strategies for solving these problems because they highlight how the two sides of the numbers in the equation may relate to each other on either side of the equation (e.g., placing the hand under two numbers on one side of the equation and then moving the hand to the other side) (Goldin-Meadow & Singer, 2003). Similarly, prior research suggests that math teachers in Hong Kong and Japan use gestures more effectively than teachers in the U.S., potentially contributing to the superior performance of students from these countries (Richland, 2015). Particularly the 'linking' gestures (e.g., explicitly linking two different problems that can be solved using the same strategy to more concretely demonstrate the similarities between them) may be effective because they highlight the relation between two distinct but analogous representations. These results suggest that the spatial information conveyed through gestures can be a powerful tool when learning about abstract concepts such as mathematics. In addition to instructions, previous research also suggests gesturing while thinking about abstract concepts can be beneficial for the person who is gesturing. For example, U.S. children instructed to gesture while thinking about mathematical problems show a higher likelihood of thinking of novel strategies to approach the problem, potentially due to gestures making their implicit ideas about the concept more explicit (Goldin-Meadow et al., 2009; Novack & Goldin-Meadow, 2015).

Overall, the ability to reason about abstract domains and the ability to leverage spatial representations develop gradually in early childhood (e.g., Gunderson et al., 2012; Miller et al., 2020; Starr et al., 2020; Tillman et al., 2018). Accordingly, explicit use of spatial representations can improve abilities to remember and reason about abstract information in childhood. This dissertation will focus on how humans use spatial representations for temporal order to aid episodic memory abilities.

1.2. The link between representations of temporal order and episodic memory

The domains of space and time are tightly linked in our world. In many languages and cultures, people use space to describe duration in terms of space (e.g., "a long meeting") and use gestures when describing temporal information (e.g., pointing to the back when saying 'last week') (Burns et al., 2019; Clark, 1973; Cooperrider & Núñez, 2009). External spatial representations of time are also widespread: many people use calendars, planners, and clocks, and often use visual representations such as evolution diagrams and project timelines to represent time information (Bonato et al., 2012; Friedman, 1990). Representing and reasoning about temporal information is crucial for episodic memory, which allows us to form contextually bound representations of events that feature spatial (e.g., ‘where’) and temporal (e.g., ‘when’) context for a particular memory (or ‘episode’) (Mullally & Maguire, 2014; Tulving, 1972, 2002). Episodic memory abilities allow us to achieve many uniquely human feats such as mentally traveling in time by projecting ourselves to different points in time (Suddendorf & Corballis, 2007; Tulving, 2002) and developing autobiographical memories (Fivush, 2011; Friedman, 2004). While we can often move ourselves to different locations, the only context in which we can ‘move’ ourselves in time is through mental time travel. Because episodic memories provide context for past events, they allow for the representation of not only events in the past but also events in a hypothetical future (Prabhakar & Ghetti, 2020). The temporal context in memories also helps us understand continuity in our memories by allowing us to recall the order in which various events have happened and how particular events relate to other events that have happened around the same time (Friedman, 1990, 1993).

Because episodic memory is central to our lives and requires binding different components together, decades of work have explored the spatial and temporal components of episodic memory (e.g., Bauer et al., 2016; DeMaster et al., 2013; Hayne & Imuta, 2011; Lee et al., 2016; Newcombe et al., 2014; Ngo et al., 2019; Pathman et al., 2018; Russell et al., 2011). Much of this work suggests that even in adulthood, spatial memory (e.g., remembering where things happened) is easier relative to temporal memory (e.g., remembering when things happened) (Lee et al., 2016; Pathman et al., 2018). Studies exploring age-related improvements in episodic memory suggest that the ability to remember temporal context develops more slowly relative to the ability to remember spatial context (Ghetti & Lee, 2011; Hayne & Imuta, 2011; Picard et al., 2012). Further, studies exploring spontaneous spatial representations of temporal order suggest that children gradually build robust representations of temporal order (Tillman et al., 2018, 2022). Because people across many cultures and languages use space to represent temporal order, and because remembering temporal order is relatively difficult for people of all ages, it Is interesting to explore how representations of temporal order may aid reasoning about and remembering temporal information.

1.2.1 The Mental Timeline

Previous studies exploring how space and time are related in the mind suggest a cross-dimensional asymmetry, such that spatial information more strongly influences our representations of time than vice versa (Casasanto et al., 2010a; Casasanto & Boroditsky, 2008). This suggests that we form our representations of time through spatial representations more than the other way around. One reason why spatial representations influence representations of time may be due to the mental timeline, which is a linear, spatial representation of time (Bonato et al., 2012; Pathman et al., 2018). The mental timeline is a cross-culturally prevalent way in which people mentally represent time. For most Western adults, the mental timeline is structured such that earlier events and the past are represented toward the left side of space, and later events and the future are represented toward the right side (Bonato & Umiltà, 2014). This may be because cultural experiences, such as the direction we read and write in, influence the development of mental timeline representations, such as influencing the direction and orientation of the mental timeline. For example, for both sighted and blind individuals, there is evidence that literate individuals predominantly represent the mental timeline flowing in the same direction they read and write (Bergen & Chan Lau, 2012; Bottini et al., 2015).

Previous studies suggest that spontaneous mental organization of time is structured in terms of the mental timeline, such that adults are slower to respond when the associations are incongruent with the culturally dominant mental timeline (e.g., mapping the future to the left side of space for English-speaking adults) (Bergen & Chan Lau, 2012; Bottini et al., 2015; Chrabaszcz et al., 2024). Beyond cultural influences, spatial and temporal processing may overlap in the mind, such that disruptions in representations of space also result in disruptions in representations of time. For example, adult patients with damage to the right hemisphere of their brains who experience spatial neglect often have difficulty detecting and identifying objects or events on the left side of the space (Saj et al., 2014). In an experiment conducted by Saj and colleagues (2014), French-speaking adults were asked to learn and recall various food items a character liked to eat ten years ago and would like ten years from now. Participants without spatial neglect remembered a symmetrical number of items from these two time periods, while spatial had difficulty recalling events associated with the past, which are frequently represented towards the left side of the space for Western adults (Bonato et al., 2012; Saj et al., 2014). These results suggest that difficulties in processing space may be mirrored by difficulties in processing time. The overlap in space and time in the mind may be one reason why the mental timeline is frequently used to represent time across many cultures and why spatial representations may influence representations of time.

The mental timeline may help our abilities to think and reason about time information by grounding our representations of the more abstract domain of time in the more concrete domain of space. Such a representation provides a structure in which we can organize temporal events and structure temporal relations. In line with this idea, there is evidence that the mental timeline may be a tool for supporting our abilities to recall temporal order. For example, Pathman and colleagues (2018) found that U.S. adults and children display a strong memory advantage for remembering temporal order when a triplet of items is presented in a left-to-right spatial pattern compared to right-to-left or nonlinear patterns. This finding suggests that temporal memory was facilitated when the spatial locations and temporal order of the items within a sequence were congruent with the mental timeline and was negatively affected when the locations and order were incongruent with the mental timeline. The same benefit for encoding and retrieving temporal order for triplets that were presented from left-to-right, relative to the other orientations, was also found in children aged 7 to 9 years, an age at which children in high literacy environments start representing temporal order in terms of the culturally dominant mental timeline (Tillman et al., 2018; Tversky et al., 1991). These results suggest that once children have developed a mental timeline, they activate it when encoding and retrieving the temporal order of events (Pathman et al., 2018).

Because adults and children older than 7 years show a strong temporal memory benefit when the spatial presentation of sequences is congruent with the mental timeline, it is important to explore the link between the development of mental timeline representations and the development of temporal memory. Because temporal memory is more difficult and slower to develop relative to spatial memory, the mental timeline is an ideal test case for exploring how spatial representations may support our abilities to represent and reason about abstract concepts. Further, this memory advantage has only been shown in children who are 7 years of age and show evidence for adult-like timeline representations (Pathman et al., 2018). However, it is unknown whether the process of developing a mental timeline may support the development of temporal memory abilities, whether there are early-emerging associations for representing temporal order linearly, and to what extent adults explicitly use the mental timeline as a memory strategy.

1.3 Dissertation Approach

The goal of this dissertation is to explore how the mental timeline facilitates our abilities to encode and remember temporal order. Specifically, I explore the emergence and development of mental timeline representations and how these representations benefit temporal binding. This dissertation consists of three studies that explore the link between the mental timeline and temporal memory in infancy, childhood, and adulthood. These studies employ explicit behavioral measures from young children and adults, looking time measures from infants, and gaze movement and pupil dilation measures from adults. Together, these studies provide insight into how spatial representations of temporal order interact with temporal binding abilities, thus informing future work for exploring the use of spatial representations to facilitate temporal reasoning and episodic memory development.

The first empirical chapter investigates individual differences in the development of mental timeline representations in young children in relation to their episodic memory abilities. Many studies have shown that young children are slow to develop the ability to recall the temporal order of events, relative to their ability to recall the location of or the items and agents involved in those events (Hayne & Imuta, 2011; Mullally & Maguire, 2014; Picard et al., 2012). Between the ages of 4 and 6, children demonstrate rapid development in their episodic memory abilities, particularly their ability for relational binding, which allows for coherent, holistic representations of events (Ngo et al., 2019; Scales & Pathman, 2021). This age range is also when many children in industrialized, Western countries start formal schooling, and when many children start representing temporal order in terms of a mental timeline (e.g., linearly and from left-to-right) when asked to construct external timelines (Tillman et al., 2018; Tversky et al., 1991). However, the link between developing mental timeline representations and the development of temporal memory abilities is unexplored. This chapter utilizes behavioral measures from an episodic memory task followed by a timeline construction task to test whether individual differences in the development of the mental timeline influence the development of temporal memory abilities in 5 to 6-year-old children.

The second empirical chapter uses a habituation paradigm to assess whether spatial cues facilitate 6-month-old infants' ability to learn the temporal order of sequences. Many studies have shown space-time associations based on magnitude exist in infancy, such that young infants map 'more' time (e.g., longer duration) onto 'more space (e.g., longer line) (de Hevia et al., 2014; Lourenco & Longo, 2010; Srinivasan & Carey, 2010). However, it is unknown whether space-time representations for progressing through space and time exist in infancy such that infants can benefit from linear spatial cues when learning temporal order. This study explores whether young infants can leverage linear, spatial representations of temporal order to produce a memory benefit for recalling the temporal order of a sequence. This chapter will also provide insight into the origins and development of the mental timeline, informing whether the memory benefit from linear representations of time emerges as a product of cultural experiences such as reading, writing, or using calendars, or as a part of our biology.

The third empirical chapter uses behavioral, eye-tracking, and pupillometry measures to explore the use of the mental timeline as a memory strategy in adulthood. Previous studies have demonstrated that 7-to 11-year-old children and adults in the U.S. show a strong temporal memory benefit when the temporal order and spatial representation of sequences are presented congruent with the mental timeline (e.g., left-to-right), and show a disadvantage when they are presented incongruently (e.g. right-to-left or nonlinearly) (Pathman et al., 2018). These results suggest that these participants spontaneously make use of the mental timeline to support temporal memory. The current study explores the interaction between the mental timeline and temporal memory through two additional approaches. The first is through pupil dilation, which is related to participants' cognitive load and effort (Eckstein, 2017; Unsworth & Robison, 2018b). The relation between pupil dilation and spatial presentation of items at the encoding phase will reveal the relative cognitive load participants experience when the spatial presentation of items is incongruent with the mental timeline. The second is through gaze movements, which can provide a window into how participants mentally organize the encoded items, providing an insight into the spatial structure of their mental spaces (Martarelli et al., 2017; Masson et al., 2018; Viganò et al., 2024). Participants' gaze movements during the memory recall phase will reveal whether gaze movements are indicative of their mental representation of temporal order. Overall, the third chapter will provide insight further insight into the memory encoding and retrieval processes the mental timeline may interact with.

Chapter 2. The Development of the Mental Timeline Is Related to Temporal Memory

The study presented in Chapter 2 has been published in *Journal of Cognition and Development* (Sener & Starr, 2024) published by Taylor & Francis. The Version of Record of this manuscript has been published and is available in *Journal of Cognition and Development* on September 27, 2024, https://www.tandfonline.com/doi/10.1080/15248372.2024.2404863.

2.1 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). 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 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., 2010b). 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 and colleagues (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 and colleagues (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 and colleagues (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 kindergarteners relative to preschoolers, and higher in adults relative to both kindergarteners 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 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 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.

2.2 Method

2.2.1 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, Multiracial, *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 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 Institutional Review Board. Each family received a $5 Tango gift card and a junior scientist certificate of completion as a token of our appreciation.

2.2.2 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.

2.2.2.1 *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."

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 re-entered 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.

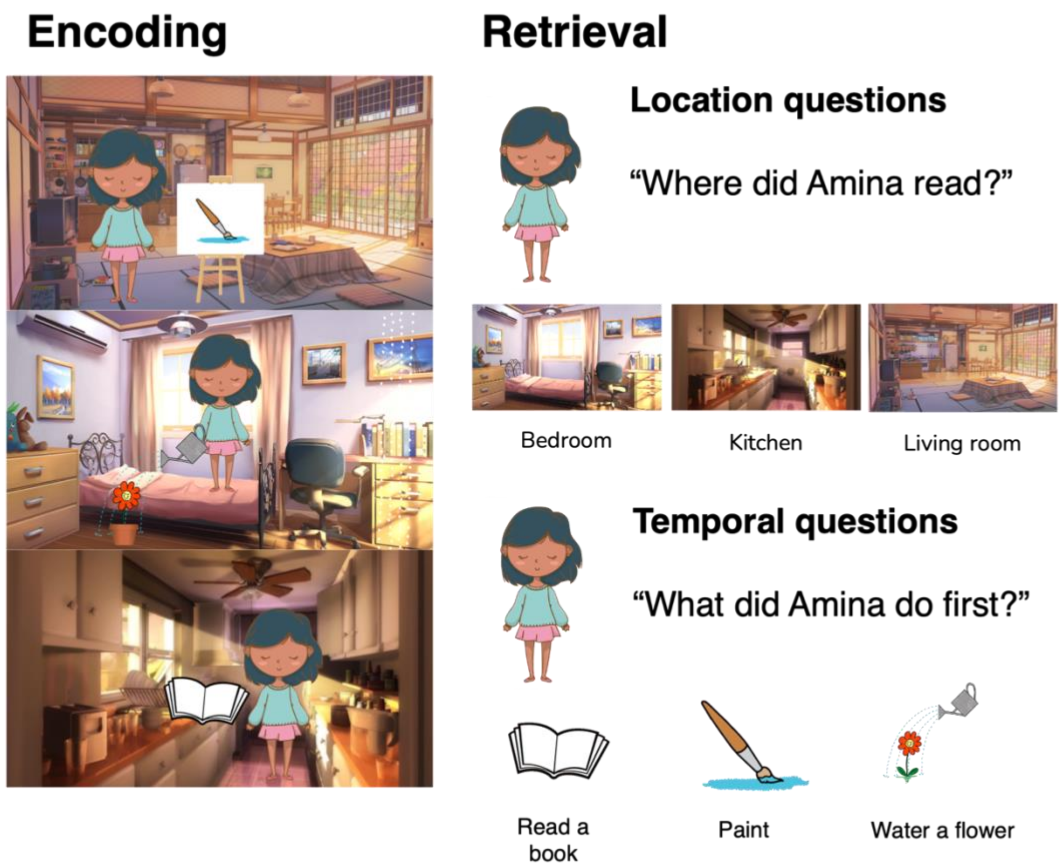

Figure 1. Schematic of the memory game. Examples of encoding scenes (left) and retrieval questions (right).

2.2.2.2 ***Timeline task.*** This task was adapted from Tillman and colleagues (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 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.

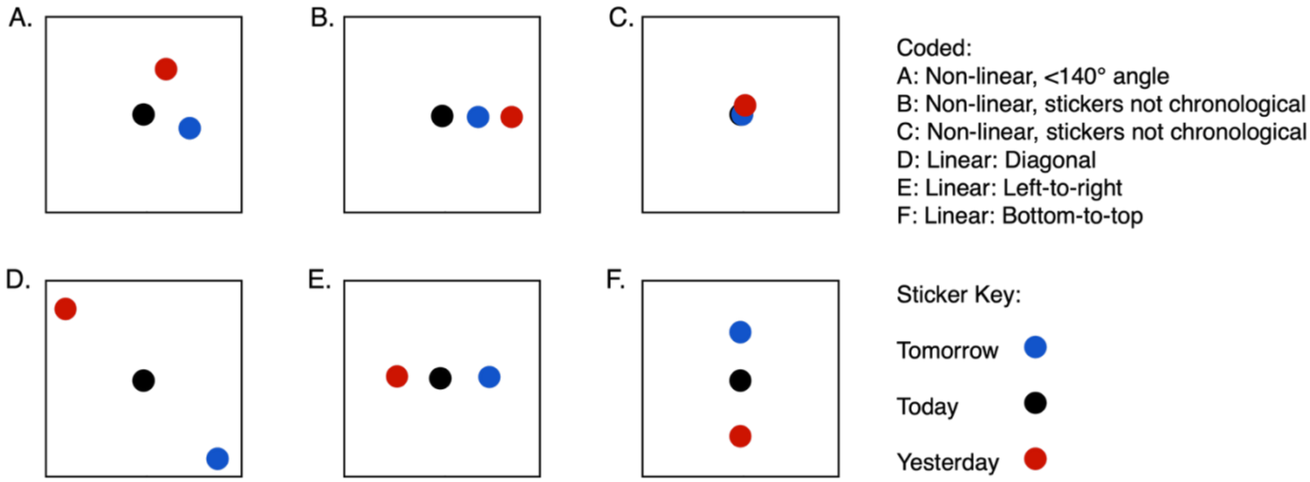

Figure 2. Example timeline arrangements.

2.2.3 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).

2.3 Results

2.3.1 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 (β = -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).

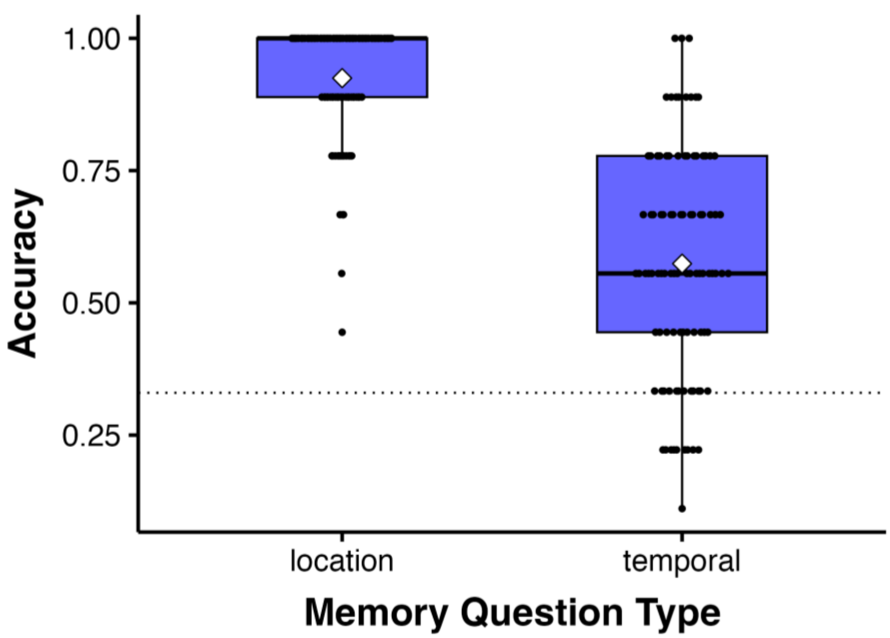

Figure 3. Memory accuracy by question type. The white diamonds represent the mean accuracy for each question type, and the black dots represent individual participants. The colored boxes represent the lower quartile (bottom) and upper quartile (top) values. The dotted line represents the chance-level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

Next, we assessed whether age was related to children's memory performance. Age was positively correlated with overall memory accuracy, $r(94) = .45$, $p < .001$, and with each memory type (location: $r(94) = .29$, $p = .004$; temporal: $r(94) = .43$, $p < .001$). Comparison of these correlation coefficients suggests that one memory type is not more strongly correlated with age than the other ($z = 1.29$, $p = .20$). These results demonstrate that both temporal and location memory are improving between the ages of 5 and 6 years.

2.3.2 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: $r(94) = -0.01$, $p = .93$; number of left-to-right lines: $r(94) = -0.06$, $p = .56$). 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; $\chi^2(1) = 0$, $p = 1$) (Tillman, 2018; Starr & Srinivasan, 2021). 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 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.

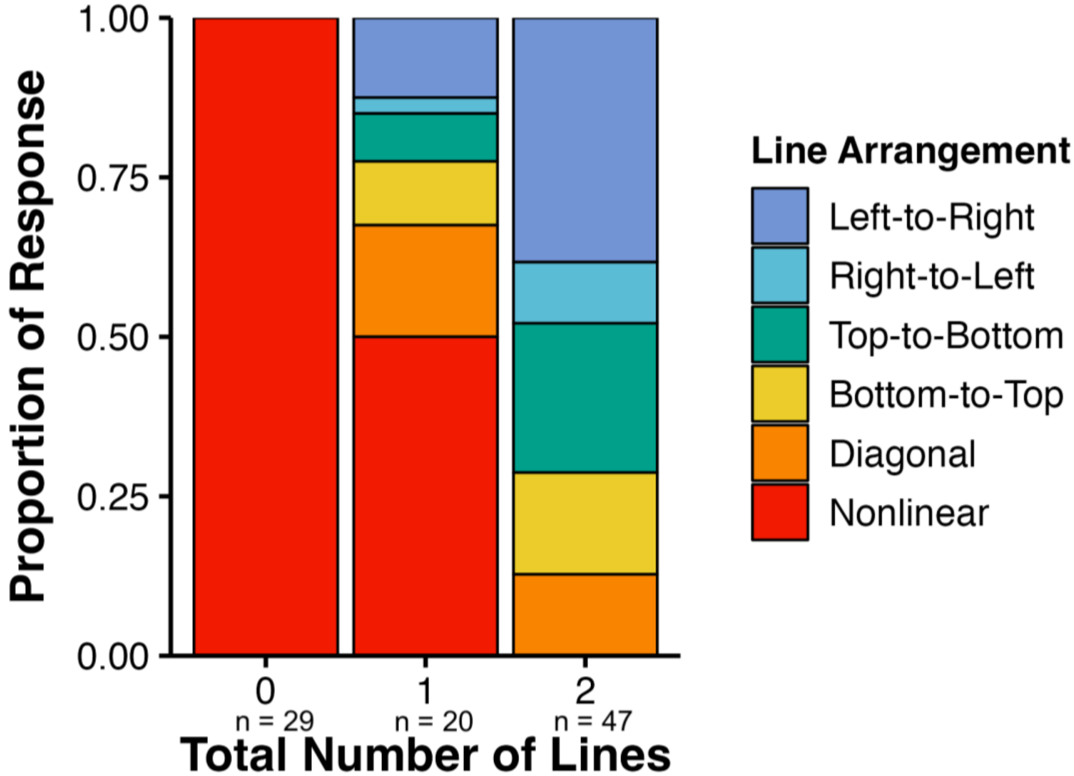

Figure 4. Distribution of timeline arrangements made by children depending on the number of lines they created across the two trials.

2.3.3 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 (β = -3.00, p < .001), but no significant effect of the number of lines made during the timeline task (β = -0.08, p = .69) or interaction between the number of lines and memory question type (β = 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 (β = - 2.76, p < .001), and a main effect of age (β = 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 (β = -0.12, p = .49). The interaction between the number of lines and memory question type also remained non-significant (β = 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 (β = 0.21, p = .02) and age (β = 0.63, p < .001) were significant predictors. For predicting location memory, only age was a significant predictor (β = 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.

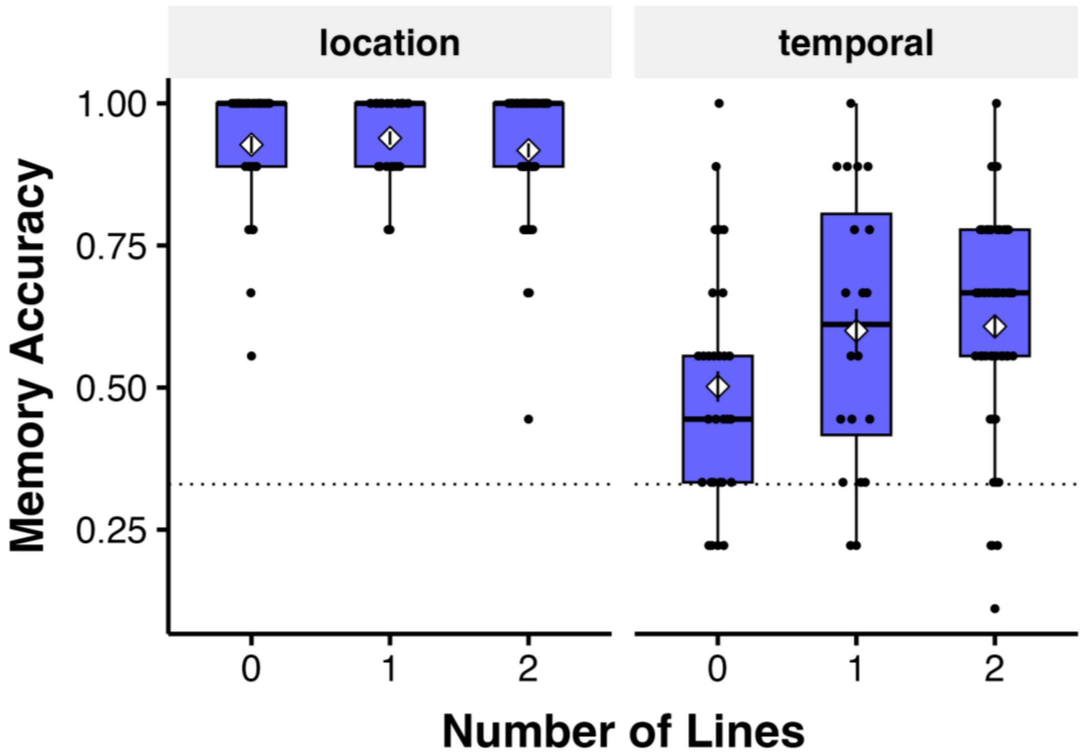

Figure 5. Location and temporal memory accuracy by number of lines. The diamonds represent the mean accuracy for each group, and the black dots represent individual participants. The colored boxes represent the lower quartile (bottom) and upper quartile (top) values. The dotted line represents chance-level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

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 (β = 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: β = -0.37, p = .12; temporal: β = -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.

2.4 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.

2.4.1 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 and colleagues (2012), experimenters assessed encoding and retrieval success by asking free recall, cued recall, and recognition questions about the same events. Picard and colleagues (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.

2.4.2 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 towards 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 towards 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 (Tversky et al., 1991; Tillman et al., 2018; Starr & Srinivasan, 2021), 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.

2.4.3 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 and colleagues (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.

2.4.4 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 to 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.

2.4.5 Summary

Chapter 2 demonstrated that the development of spatial, linear representations of temporal order supports temporal memory in early childhood. The study described in Chapter 2 used an explicit timeline construction task, which is unsuitable for use with infants. However, spatial cues representing temporal order in a linear spatial configuration may be beneficial for temporal memory before experiences with artifacts that spatialize temporal order, such as calendars. The next chapter explores the origins of the mental timeline by investigating to what extent the memory advantage may be a product of our biology versus a cultural invention that develops through experience with cultural artifacts. Specifically, this chapter investigates whether spatial cues facilitate temporal memory in 6-month-old infants.

Chapter 3. The Origins of the Mental Timeline

3.1 Introduction

Between infancy and middle childhood, the ability to form and retrieve episodic memories changes dramatically (Clayton & Russell, 2009; Mullally & Maguire, 2014). For both children and adults, remembering the order of events is more difficult than remembering the locations of those events (Hayne & Imuta, 2011; Lee et al., 2016; Pathman et al., 2018). Although the asymmetry between these components of episodic memory is present into adulthood, children are slower to develop the ability to remember "when" things happened relative to the abilities to remember "what" and "where" things happened (Ghetti & Lee, 2011; Hayne & Imuta, 2011; Lee et al., 2016). This may be because time is an abstract concept we cannot see or touch. One hypothesized way we get around this challenge is by using space to represent time, which allows us to ground our representations of an abstract domain into a more concrete one (Bonato et al., 2012; Lakoff & Johnson, 1980). In line with this idea, adults across many cultures represent time using a mental timeline, a model of time based on a linear reference frame (Bergen & Chan Lau, 2012; Bonato et al., 2012), and automatically utilize it when remembering or reasoning about temporal information (Pathman et al., 2018). Children gradually develop robust linear representations of time, which are strengthened through experience with cultural artifacts (Sener & Starr, 2024; Starr & Srinivasan, 2021; Tillman et al., 2018). For children and adults, representing time in terms of a mental timeline is beneficial for reasoning about and remembering temporal information (Friedman, 1990; Pathman et al., 2018; Sener & Starr, 2024). However, we do not know to what extent linear representations of temporal order may be a product of our biology versus a cultural invention that develops through experience with cultural artifacts such as reading direction and linguistic metaphors.

Space-time associations have been studied in two different formats. One is based on magnitude associations, such that magnitudes in the domain of time (e.g., 'more' duration of auditory stimuli) are mapped onto magnitudes in the domain of space (e.g., 'more' spatial extent of a line) (de Hevia et al., 2014; Lourenco & Longo, 2010). Magnitude-based associations between the domains of space and time are stable across development (de Hevia et al., 2014; Lourenco & Longo, 2010; Walsh, 2003). For example, prior studies demonstrate that newborns younger than 79 hours of age, 9-month-old infants, and adults all map auditory stimuli with relatively longer durations to physical lines with relatively longer spatial extents (de Hevia et al., 2014; Srinivasan & Carey, 2010). The finding that infants and newborns already associate 'more' in duration and 'more' in spatial extent suggests that space-time associations based on magnitude emerge independent of cultural experiences (de Hevia et al., 2014; Lourenco & Longo, 2010; Srinivasan & Carey, 2010).

Another format of space-time associations is based on representing temporal order in terms of a mental timeline, such that progression through time is mapped onto a linear progression through space (e.g., representing earlier events toward the left side of space and later events toward the right side, or representing future towards the front of the body and the past towards the back) (Bonato et al., 2012; Cooperrider & Núñez, 2009). There is robust evidence that cultural experiences shape the direction and orientation of the mental timeline in children and adults (e.g., Boroditsky et al., 2011; Starr & Srinivasan, 2021; Tversky et al., 1991). In open-ended timeline construction tasks in which participants are asked to place icons representing temporal events (e.g., ‘yesterday’, ‘today’, and ‘tomorrow’), literate adults and school-aged children in high-literacy environments spontaneously order these events on a line in the direction they read and write in (e.g., for most Western adults, from left to right) (Tillman et al., 2018; Tversky et al., 1991). Children demonstrate a gradual acquisition of linear representations when tested in these paradigms, such that their responses become more aligned with cultural norms (e.g., American children arranging a sequence of events on a left-to-right, horizontal line) as they gain more experience with cultural artifacts such as calendars and reading and writing (Starr & Srinivasan, 2021; Tillman et al., 2018). In contrast to older children and adults, when performing explicit, open-ended timeline construction tasks, preschool-aged children do not consistently construct linear arrangements. Further, even when these children represent temporal order linearly, they do not demonstrate directional preferences for arrangements aligned with cultural norms (e.g., left-to-right for most Western cultures) (Sener & Starr, 2024; Tillman et al., 2018). This pattern of results suggests that cultural experiences contribute to the development of the tendency to explicitly represent temporal order with linear arrangements in particular orientations.

Notably, although young children and adults without extensive exposure to artifacts that spatialize time do not consistently construct explicit linear representations of temporal order with a particular orientation, they prefer linear depictions of temporal order when choosing a visual sequence that depicts temporal order, and construct ordered representations of temporal sequences when provided with a linear template to organize temporal events in (Pitt et al., 2021; Tillman et al., 2022). For example, Tillman and colleagues (2022) assessed preschool children’s and adults’ preferences for spatial representations of temporal order in a task in which they heard short stories (e.g., “First there was an egg. Then the egg cracked. And a baby chick popped out!”). In this task, participants were not asked to create explicit representations of temporal order. Instead, participants were shown icons depicting events in each story and viewed these icons in different arrangements (e.g., left-to-right, bottom-to-top, scrambled) and were asked to choose one of two spatial arrangements that best depicted the story. The results showed that although only 5-year-old children and adults showed a strong preference for left-to-right arrangements, even the youngest children in the sample (3-year-olds) preferred ordered representations of the story over scrambled ones (Tillman et al., 2022). Pitt and colleagues (2021) found similar results with Tsimané adults, an indigenous group of farmer-foragers who live in Bolivia, most of whom have little to no formal education, very low levels of literacy, and few modern technologies (Pitt et al., 2021). In this task, the participants were asked to create explicit representations of temporal order with the help of a template. When given a linear template on which to arrange cards depicting temporal order (e.g., pictures of plantains ranging from very green to overripe), these adults systematically arranged stimuli in an ordered manner (e.g., chronologically from left-to-right or right-to-left) but did not show a preference for arrangements in any specific direction (Pitt et al., 2021). These results suggest that the tendency to spatially represent temporal sequences in an ordered, linear way may emerge independently of extensive experience with artifacts such as written language and calendars (Pitt et al., 2021; Tillman et al., 2022). In other words, a preference for linear representations of temporal order may be present in populations who do not spontaneously construct linear arrangements in explicit timeline construction tasks. Overall, tasks in which participants are asked to construct or judge spatial representations of temporal order suggest that cultural experiences such as reading and writing contribute to culturally consistent preferences for spatial representations of temporal order. However, the tendency to prefer linear representations of time over nonlinear ones is present independent of extensive experience with artifacts that spatialize temporal order.

One reason why linear representations of temporal order may be so common across cultures may be because timelines allow us to encode and remember information about the more abstract domain of time by grounding representations in the more concrete domain of space (Barsalou, 2008; Lakoff & Johnson, 1980). In line with the idea that the mental timeline aids our abilities to encode and remember temporal information, adults and children tested in high literacy environments demonstrate a strong temporal memory advantage for events presented congruent with the mental timeline, suggesting they spontaneously activate this representation when performing an episodic memory task. For example, Pathman and colleagues (2018) explored the relationship between the spatial presentation of stimuli and the ability to recall spatial location and temporal order of events in children (aged 7 to 11) and adults in the United States. They found that for all age groups in their sample, participants recalled the temporal order of events more accurately for stimuli presented linearly relative to those presented nonlinearly. Further, participants more accurately recalled the temporal order of events for linearly presented stimuli when the direction was congruent with the mental timeline (left-to-right for this sample) relative to when it was incongruent (right-to-left for this sample) (Pathman et al., 2018). These results suggest that representing temporal order linearly may specifically provide a benefit for the ability to order events in time, which is crucial for episodic memory abilities.

Previous work with 5- to 6-year-old children also shows that the development of linear representations of time may contribute to the development of the temporal aspect of episodic memory in early childhood (Sener & Starr, 2024). Individual differences in children's timeline constructions predict their temporal but not spatial memory abilities, such that at 5 to 6 years of age, children who consistently represent temporal order linearly demonstrate higher temporal memory accuracy relative to children who do not yet represent time linearly. Overall, these studies suggest that the mental timeline is tightly linked with our abilities to remember temporal order information. However, this memory benefit so far has only been demonstrated in populations in high-literacy environments and with participants who can provide explicit answers. Additionally, it is important to note that although some studies suggest that a preference for depicting temporal order with linear arrangements over nonlinear ones may emerge independent from extensive experience with reading and writing (Pitt et al., 2021; Tillman et al., 2022), the populations studied have some experience with written language and tools that spatialize time. For example, although preschoolers in high literacy environments are not readers themselves, they do have experience with written text (e.g., from storybooks, calendars, and posters in their environments). Similarly, Tsimané adults have some experience with literacy and formal schooling (Pitt et al., 2021). These experiences could potentially contribute to their preferences for ordered, linear representations of temporal order over nonlinear representations. However, if linear representations of time emerge independently of extensive experience with cultural artifacts such as reading, writing, and calendar use, the memory benefit observed in literate participants may be present in participants who have minimal experience with written text, such as infants.

Most of the existing literature exploring temporal memory in infancy has focused on abstract or ordinal sequences. These studies suggest that infants can detect and generalize patterns from novel, abstract stimuli introduced during an experiment session (Bulf et al., 2017; Koch et al., 2020; Rabagliati et al., 2019). For example, Bulf and colleagues (2017) found that 7-

month-old infants extracted high-order, rule-like patterns (e.g., AAB) from sequences of shapes presented during a habituation phase, indicated by relatively longer looking times to novel sequence patterns during the test phase (e.g., ABB). These results suggest that infants were able to learn the particular sequence to form expectations for a novel set of stimuli (Bulf et al., 2017). In another experiment, Koch and colleagues (2020) demonstrated that after exposure to a familiarization phase in which images appear in different locations on a screen in a sequence, 9-month-old infants demonstrated quicker eye movements to the locations in which the stimuli appeared, demonstrating learning of the presented sequence (Koch et al., 2020). Although these studies demonstrate that young infants can remember and generalize information from stimuli presented during an experimental session, studies exploring infants' learning of abstract or ordinal sequences are largely considered to be related to procedural memory.

Compared to abstract rule learning, less is known about young infants' episodic memory abilities for forming contextually bound representations of the temporal order of sequences of events. Abstract rule learning paradigms are related to infants' abilities to remember higher-order relations presented in the pre-exposure phase (e.g., a sequence of shapes should be presented in the order A, A, B) rather than remembering information about a particular 'episode', such as specific items within each sequence (e.g., the square appeared before the triangle) (Bulf et al., 2017; de Hevia et al., 2020; Rabagliati et al., 2019). Prior studies exploring the development of episodic memory in infancy through imitation paradigms have found that the ability to encode and retain memory for novel events develops rapidly over the first two years of life (see Bauer, 2004 for a review). For example, Meltzoff and colleagues have found that 9-month-old infants can remember and imitate simple actions after a 24-hour delay (e.g., shaking a novel toy like a rattle) (Meltzoff, 1988b). In another study, Meltzoff and colleagues found that by 14 months of age, infants could remember and imitate simple actions after a week delay (Meltzoff, 1988a). Prior studies exploring the development of episodic memory through deferred imitation paradigms, however, have also found that infants have difficulty remembering and imitating multiple actions in the temporal order they were demonstrated in (Barr et al., 1996; Bauer, 2004). For example, Barr and colleagues (1996) explored 6-to 24-month-old infants' imitation of a three-step sequence (remove the mitten from a puppet, shake the hand, replace the mitten). Although there were significant age-related improvements in how many actions infants could recall and imitate after a 24-hour delay, even the oldest infants failed to imitate all three actions in the particular order (Barr et al., 1996). Further, much of the work exploring infants' memory for ordered sequences has suggested that infants younger than approximately 20 months of age have difficulties in imitating ordered actions when the actions do not feature causal links, however, younger infants can recall and imitate ordered sequences when the actions are causally linked (Bauer et al., 1998; Bauer & Shore, 1987). For example, in an experiment conducted by Bauer and colleagues (2003), 9-month-old infants were tested on an elicited imitation paradigm, in which the two-step sequence involved pushing a toy car down a compartment, and then pushing a rod into a connected compartment, which would cause the toy car to roll down and turn on a light. In this case, the infants could push the rod before placing the car in the compartment, however, they would not be able to turn on the light if they enacted the steps out of order (Bauer et al., 2003). These results suggest that infants develop the ability to remember the temporal order of sequences in which one step is causally linked to another, several months before they develop the ability to recall the order of arbitrarily ordered sequences of actions. Overall, prior work suggests that although episodic memory capabilities are present in early infancy and infants can recall and imitate a single action as early as 6 months of age, however, memory for temporal order is challenging even in late infancy (Barr et al., 1996; Bauer, 2004; Meltzoff, 1995). Importantly, none of the existing paradigms have presented spatial cues in relation to the temporal order of events (see Bauer, 2004 for a review). Exploring the link between spatial presentation and temporal order in early infancy can, therefore, reveal whether spatial cues can facilitate this aspect of episodic memory.

If there is an early emerging, intuitive mapping between space and temporal order, infants may also be able to access and take advantage of linear spatial cues to remember temporal order. In other words, beyond the tendency to prefer linear representations of temporal order over nonlinear ones, the temporal memory advantage for events presented in terms of mental timeline may be present before extensive experience with cultural artifacts. Because prior studies probing the development of the mental timeline have all required explicit responses, the origins of the mental timeline have not been explored in infancy. The current study examines whether associations between the domains of time and space in infancy extend to linear representations of temporal order. Specifically, we explore whether linear representations of temporal sequences are beneficial for learning temporal order at 6 months of age.

In this study, infants are habituated to a triplet of images that are either presented sequentially from left-to-right or in a nonlinear order across the screen. During the test phase, all infants see two types of test trials showing the same triplet of objects presented centrally with an order that is congruent (e.g., ABC) or incongruent (e.g., ACB) with the habituated triplet. If infants can remember the temporal order in which the stimuli were presented during the habituation phase, they should discriminate between the congruent and incongruent sequences at test. Because the incongruent test trial shows a different order than presented during the habituation phase, we expect infants who discriminate between the two test trials to look longer at the incongruent trials. If infants benefit from linear spatial cues when learning temporal order, they should learn the sequence more efficiently when presented from left-to-right relative to nonlinearly and, consequently, infants in the linear habituation group should be more likely to discriminate the congruent and incongruent sequences at test. Alternatively, if the mental timeline is the product of cultural learning, there may be no differences in looking at either test trial among infants across the two habituation conditions.

3.2 Experiment 1

3.2.1 Method

3.2.1.1 Participants

The final sample included $N = 40$ participants (*M*age = 6 months, 1 day; range = 5 months, 14 days - 6 months, 29 days; $n = 24$ female). Infants were randomly assigned to the linear or nonlinear habituation conditions ($n = 20$ in each condition). Data from an additional 14 participants were removed due to outlier values for looking times at test trials ($n = 6$), experimenter error ($n = 3$), less than 2 seconds of looking for either test trial ($n = 2$), premature birth ($n = 1$), technical error ($n = 1$), or a large discrepancy in looking time (greater than 5 seconds) determined by three coders ($n = 1$). Outlier values were determined using Cook's Distance calculations, such that participants with Cook's Distance values larger than three times the mean value were removed from analyses.

All data came from participants residing in France. All infants were recruited through the Université Paris Cité Integrative Neuroscience and Cognition Center participant pool database via email and phone call invitations. Verbal and written consent was obtained from the infants' guardians prior to participation. All informed consent and data collection procedures were approved by the Université Paris Cité Institutional Review Board. Each family received a junior scientist certificate of completion as a token of appreciation.

3.2.1.2 Task

Six-month-old infants were habituated to a triplet of pictures of puppet faces either presented sequentially from left-to-right or nonlinearly across the screen. The pictures of the puppets appeared in a particular location (e.g., the left side of the screen) and remained there for 1.3 seconds. Once one picture of a puppet disappeared, there was a 0.3-second interval before the next one appeared. During the test phase, infants saw the same pictures of puppet faces presented, only in the center of the screen, with an order that was either congruent (i.e., ABC) or incongruent (i.e., BAC) with the habituated triplet (see Figure 6 for a schematic of the task). All trials displayed the sequences on a loop until the infant had looked continuously at the trial for 0.5 seconds and looked away for 2 consecutive seconds or until the trial had looped for 120 seconds. Before the start of each trial, attention-getter stimuli (i.e., a flashing shape with a ‘twinkle’ sound) appeared on the screen to orient the infants’ attention to the screen.

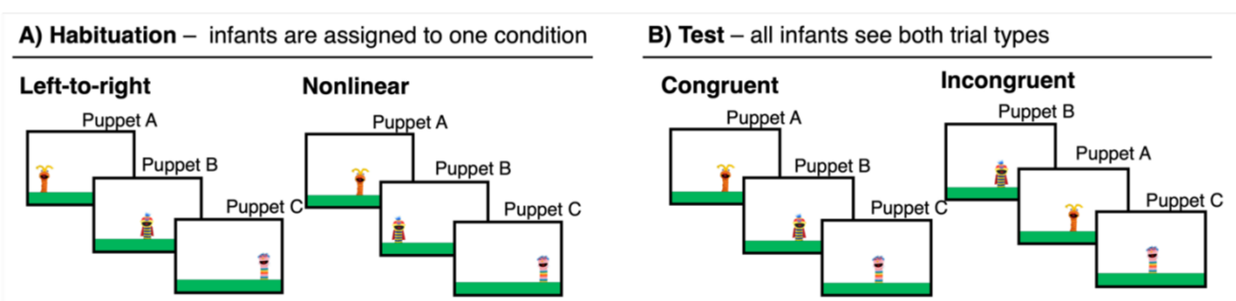

Figure 6. Schematic of Experiment 1. Depiction of the habituation (A) and test trials (B).

All infants were tested in a quiet, dark room while sitting on their caregiver’s lap. The infants and their parents were seated approximately 70 cm from a screen 509 mm in width and

286 mm in height with a 1920 x 1080 resolution. A camera positioned above the screen was angled to capture the infant's head and gaze direction. A mirror was placed behind the parent and infant to capture the infant's face and the testing screen in the video recording. The experimenter was seated behind a partition to avoid distracting the infant.

Infants viewed the habituation trials until their mean looking time for the most recent three trials was 50% or less than their mean looking time for the first three trials, or until they viewed 14 habituation trials. After the habituation phase, all participants viewed two test trials, one in congruent order and one in incongruent order with the habituated triplet. Whether infants saw the congruent or the incongruent test trial first was counterbalanced across participants. Infants' looking times for each trial were initially measured online by an experimenter during the study with the E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA) through key presses and also measured offline after the task ended by an independent coder using The Observer Video Analysis Software XT 14.0 (Noldus, Wageningen). The average of the values provided by the two coders was used for the analyses. If there were more than five seconds of difference in looking time reported between the two coder's evaluations, a third independent coder was used. After the third coder's evaluation, the two closest values were retained. If the three coders' evaluations differed by more than 5 seconds, the infant was excluded from the final analyses. All coders were blind to other coders' ratings.

3.2.2 Results

Data cleaning and analyses were performed in R using the tidyverse and lmerTest packages (Kuznetsova et al., 2017; Wickham et al., 2019). The data were analyzed using a mixed-effects model (model syntax: looking time ~ habituation condition * test trial type) + (1 | subject_id). This model returned a singularity warning indicating that one or more random effect components had near-zero variance. To address this, we simplified the random effects structure by removing the random effect of subject_id (model syntax: looking time ~ habituation condition * test trial type)). The simplified model yielded the same results as the full model. Overall, there was a main effect of test condition ($\beta = 6.77$, $p = .002$), indicating that infants looked longer at the incongruent test trial relative to the congruent test trial (Incongruent: M = 12.78, SE = 1.21, Congruent: M = 9.09, SE = 0.91). The predicted interaction between habituation condition and test trial type was also significant ($\beta = -6.15$, $p = .04$). Infants habituated in the linear habituation condition looked longer at incongruent test trials relative to infants in the nonlinear habituation condition (Linear: Incongruent: M = 14.04, SE = 1.82, Congruent: M = 7.27, SE = 1.03; Nonlinear: Incongruent: M = 11.52, SE = 1.6, Congruent: M = 10.9, SE = 1.41) (see Figure 7). Overall, 15 out of 20 infants in the linear habituation condition and 10 out of 20 infants in the nonlinear habituation condition looked longer at the incongruent test trials relative to the congruent test trials. These results suggest that only the infants habituated in the linear habituation condition discriminated between the congruent and incongruent sequences at test.

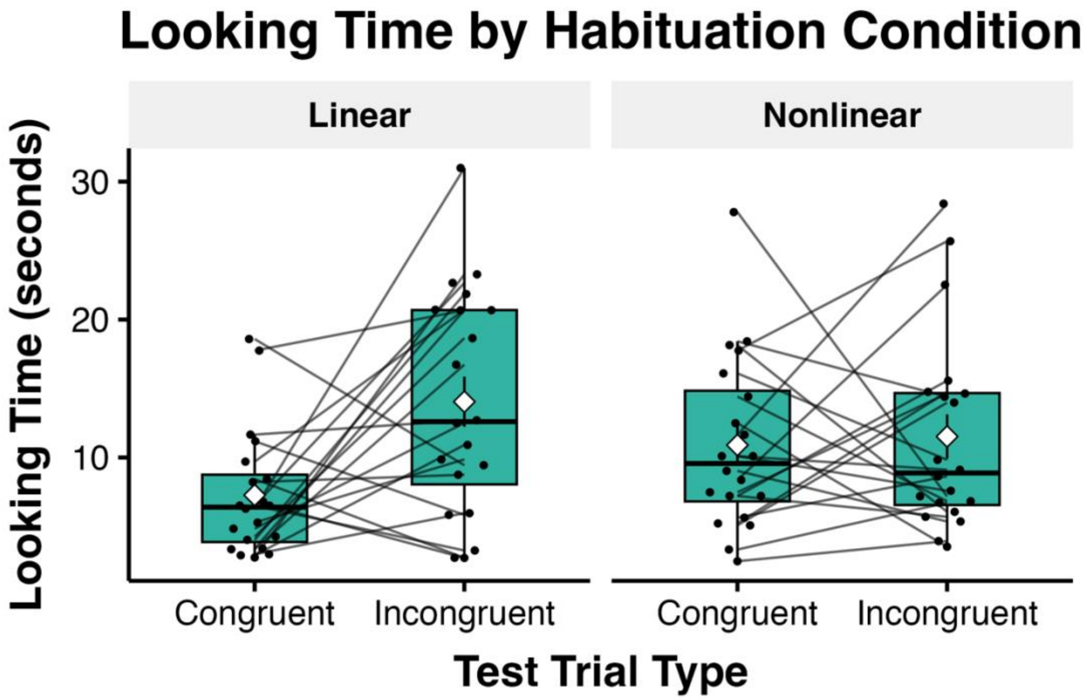

Figure 7. Looking time to test trials by habituation condition. The white diamonds represent the mean looking time for each test trial type, and the black dots represent individual participants. The lines between the dots connect individual participant's data for the two test trial types. The colored boxes represent the lower quartile (bottom) and upper quartile (top) values.

3.2.3 Discussion

In Experiment 1, six-month-old infants were habituated to a triplet of sequentially presented images of puppet faces. Infants in the linear condition saw these images presented from left-to-right, and infants in the nonlinear condition saw the images presented nonlinearly across the screen. After the habituation phase, all infants viewed two test trials in which the same images of the puppet faces were presented in the center of the screen, in an order that was either congruent or incongruent with the habituated triplet. Infants habituated in the linear condition showed a preference for incongruent test trials, indicated by longer looking times to these trials.

In contrast, infants habituated in the nonlinear condition did not show a preference for either test trial type. These results suggest that the left-to-right, linear presentation of the images bolstered infants' ability to learn and remember the temporal order of the sequence of images and thus discriminate between the two test trials when there were no spatial cues present.

Experiment 2 was run to test the robustness of the results found in Experiment 1. This experiment was designed as a conceptual replication and had some changes to the stimuli and design. In Experiment 2, the stimuli consisted of simple geometric shapes rather than pictures of puppets. We hypothesized that this change may make the task easier for the infants because the less visually complex stimuli may be easier to discriminate relative to the complex images used in Experiment 1. Experiment 2 featured a different order for the incongruent test trials than used in Experiment 1 ('ACB' instead of 'BAC'). Previous literature exploring infants' abstract rule-learning suggests that young infants have a recency bias that may influence their learning of abstract patterns (Rabagliati et al., 2019). In Experiment 1, the congruent ('ABC') and incongruent ('BAC') test trials both end on item 'C'. If the final item is more easily remembered due to a recency bias, this pattern could make the congruent and incongruent test trials more difficult to discriminate. Because Experiment 2 features simpler stimuli and an incongruent test trial order that is potentially easier to discriminate from the congruent test trial, the two experiments allow us to explore how changes to stimuli may influence the relation between temporal memory and the mental timeline in infancy, and the conditions under which infants may be able to encode the temporal order of an arbitrarily ordered sequence. Further, by testing this paradigm in two different labs on different continents, we hoped to explore the robustness of these results.

3.3 Experiment 2

3.3.1 Methods

3.3.1.1 Participants

The final sample included N = 40 participants (Mage = 6 months,16 days; range: 6 months, 3 days - 7 months, 4 days, n = 16 female). Infants were randomly assigned to the linear or nonlinear habituation conditions (n = 20 in each condition). Whether the infants saw the congruent or incongruent test trial first was counterbalanced across participants. An additional 26 infants were tested but not included in the final sample due to fussiness resulting in an inability to complete the experiment (n = 17), technical errors (n = 7), caregiver interference (n = 2), outlier values for looking times at test (n = 2), and insufficient data (under 5 seconds of looking to all test trials) (n =1). Outliers were detected by calculating the mean Cook's distance for all infants who completed the task. Participants with a Cook's distance that was more than three times the mean were removed and replaced. In addition, test pairs for which infants had less than 5 seconds of total looking were excluded from analyses. This removed one test pair from three infants, and both test pairs from one infant.

All data came from participants residing in the United States. Thirty-seven families filled out the demographic information form. Caregivers described their infants' racial-ethnic identities as: White (n = 28), Multiracial (n = 6), Asian (n = 2), and American Indian, Alaska Native, or Pacific Islander (n = 1). Most participants in our sample learned English as their first language (n = 34), and 18 infants were exposed to more than one language at home. Thirty-six families reported their income, and most (n = 35) families reported income above the area median income ($124,715 per year in 2024). Some families reported education information for more than one caregiver, resulting in information from 74 caregivers. Most caregivers (n = 66) reported education levels equivalent to a college degree or higher.

All infants were recruited through the University of Washington participant pool database via email and phone call invitations. Verbal and written consent was obtained from the infants' guardians prior to participation. All informed consent and data collection procedures were approved by the University of Washington Institutional Review Board. Each family received a $10 Tango gift card and a junior scientist certificate of completion.

3.3.1.2 Task

Infants were habituated to a triplet of geometric shapes that were either presented sequentially from left-to-right or nonlinearly across the screen. During the test phase, infants saw the same triplet of geometric shapes presented centrally with an order that is congruent (e.g., ABC) or incongruent (e.g., ACB) with the habituated triplet (see Figure 8 for a schematic of the task). The structure of the experiment was essentially the same as for Experiment 1, with a few differences: in Experiment 2, we used simple geometric shapes as stimuli rather than the images of puppets. Further, infants saw two pairs of test trials instead of one. Each trial ended when the infant had accumulated a looking time of 5 seconds for a trial and looked away for 2 consecutive seconds or when the trial had looped for 60 seconds. Finally, the incongruent test trials followed an 'ACB' pattern, rather than the 'BAC' pattern used in Experiment 1.

All infants were tested in a quiet, dark room with no windows. Infants were tested either sitting in a highchair or on their caregiver's lap if they were not comfortable sitting in a highchair. When the infants were in a highchair, the caregiver was seated on one side of the highchair, slightly behind the infant, to discourage the infants from looking at the caregiver.

Whether the caregiver sat on the left or right side of the highchair was counterbalanced across infants. One infant sat on the caregiver's lap and not on a highchair.

The stimuli were displayed on a screen with dimensions 368.3 millimeters width and 309.88 millimeters height with 1024 x 768 resolution. Infants sat in a highchair or their parent's lap at about 80 centimeters from the desk on which the monitor was mounted on a flexible arm mount. The monitor was then positioned between 550 and 600 millimeters from the infant. Disco music played during the trials through speakers that were placed behind the monitors at sound levels no louder than a quiet conversation. Infants' looking time was measured by an EyeLink 1000 eye tracker (SR Research, Ontario, Canada) with a sampling rate of 500 Hz. Gaze location and fixations were automatically detected by the eye tracker. The trial start and end procedures were triggered automatically by the eye tracker throughout the experiment, except for the attention-getter stimuli (i.e., a flashing shape with a 'twinkle' sound) in between trials. If an attention-getter was present and the infant did not look at the screen, the experimenter manually started the next trial after 10 seconds. Because the eye tracker projects the gaze location data for off-screen looks, the final data file filtered gaze data corresponding to locations outside the screen coordinates.

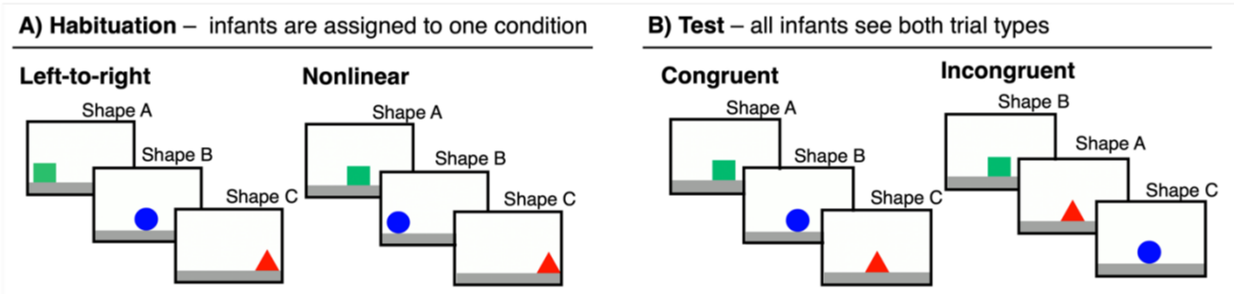

Figure 8. Schematic of Experiment 2. Depiction of the habituation (A) and test trials (B).

3.3.2 Results

Data cleaning and analyses were performed in R using the tidyverse and lmerTest packages (Kuznetsova et al., 2017; Wickham et al., 2019). The data were analyzed using a mixed-effects model (model syntax: looking time ~ habituation condition * test trial type + (1 | subject_id). Overall, there was no main effect of test trial type on looking time (β = 1.03, p = .09). However, the predicted interaction between habituation condition and test trial type was significant (β = -1.69, p = .05). Infants in the linear habituation condition had a larger difference in looking time between the two test trial types relative to infants in the nonlinear habituation condition (Linear: Incongruent: M = 8.25, SE = 0.5, Congruent: M = 7.22, SE = 0.32; Nonlinear: Incongruent: M = 7.32, SE = 0.34, Congruent: M = 7.99, SE = 0.57) (see Figure 9). For the first test pair, 13 out of 20 participants in the linear condition and 8 out of 19 participants in the nonlinear condition looked longer at the incongruent test trial. For the second test pair, 11 out of 18 participants in the linear condition, and 10 out of 18 participants in the nonlinear condition looked longer at the incongruent test trial (note that infants only needed to have valid data for one test trial pair to be included in the analyses). Similar to Experiment 1, infants habituated in the linear condition were more likely to discriminate between the congruent and incongruent sequences at test.

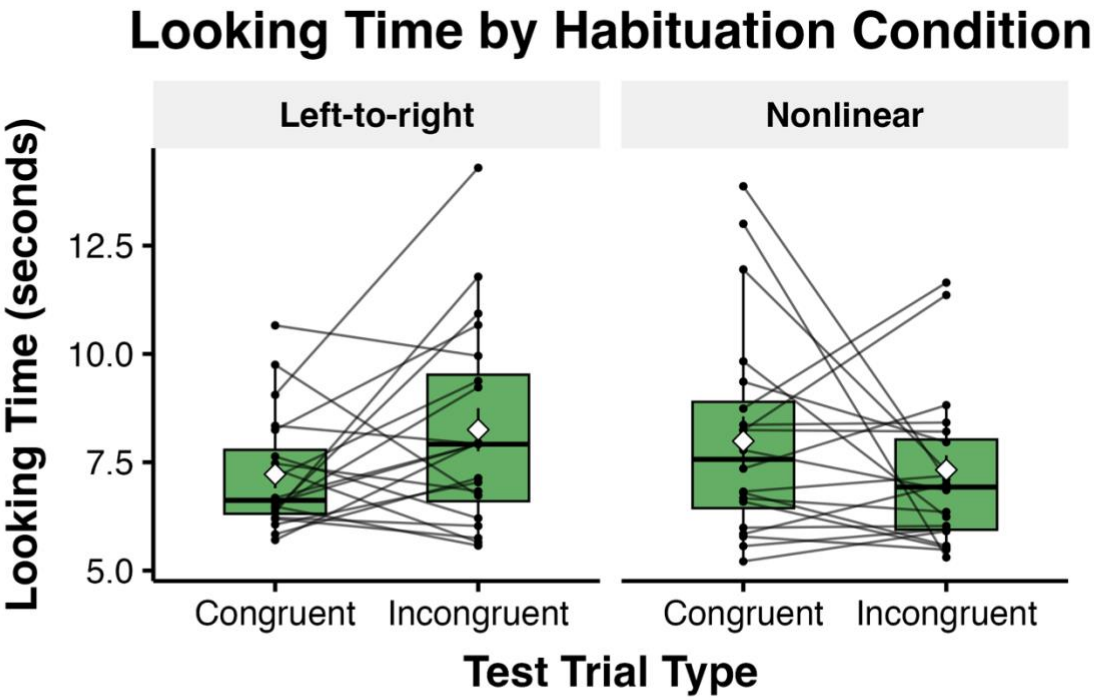

Figure 9. Looking time to test trials by habituation condition. The white diamonds represent the mean looking time for each test trial type, and the black dots represent individual participants. The lines between the dots connect individual participant's data for the two test trial types. The colored boxes represent the lower quartile (bottom) and upper quartile (top) values.

3.3.2.1 Combined Analysis

The results from Experiment 2 paralleled those found in Experiment 1. Infants habituated in the linear condition showed a preference for incongruent test trials, indicated by longer looking times at these trials, whereas infants habituated in the nonlinear condition did not show a preference for either test trial type. To explore the influence of the experiment version on looking times, we ran a model with data from the two experiments combined (model syntax: looking time ~ habituation condition * test trial type + experiment version + (1 | subject_id). Overall, there was a main effect of experiment version on looking time at test. Infants in

Experiment 1 looked longer at the test trials relative to infants in Experiment 2 (β = -3.24, $p <$ .001). There was also a main effect of test trial; infants looked longer to incongruent test trials (β = 3.89, $p < .001$) and a main effect habituation condition such that infants assigned to the nonlinear habituation condition had higher looking times to test trials (β = 2.25, $p = .05$). Finally, the hypothesized effects observed in the individual data sets were also present in the combined data set. There was an interaction between habituation condition and looking times to test trials, such that infants assigned to the nonlinear habituation condition had significantly lower looking times to incongruent test trials (β = -4.03, $p = .01$).

For both habituation and test trials, and across both conditions, infants in Experiment 2 looked at the trials for shorter durations than infants in Experiment 1. This difference in looking duration influenced the number of infants who met the habituation criteria and the number of habituation trials infants in each experiment viewed. Thirty-six infants in Experiment 1 but only 16 infants in Experiment 2 met the habituation criteria. Importantly, there was a minimum of 5 seconds of looking time criteria implemented for Experiment 2 to prevent trials from ending prematurely due to loss of the eye from the eye tracker (e.g., because the infant partially blocks one eye or the tracking sticker with their hand). Because of this requirement, if infants looked for a mean duration lower than 10 seconds in the first three trials, they could not have met the habituation criteria, which may have artificially inflated the number of habituation trials infants viewed. Overall, infants in Experiment 1 completed a median of seven habituation trials, and infants in Experiment 2 completed a median of 14 trials.

3.3.3 Discussion

Experiment 2 results generally replicated those found in Experiment 1. We found that infants habituated with sequences presented linearly, from left-to-right discriminated between the congruent and incongruent trials at test, indicated by their preference to look longer at the incongruent test trials. Infants habituated with sequences presented nonlinearly, however, did not discriminate between the two test trials. These results suggest that linear spatial cues may aid young infants' ability to encode the temporal order of stimuli.

The reason for lower looking times to test trials in Experiment 2 may be related to the geometric stimuli and the use of eye-tracking rather than manual coding. Infants are known to prefer to look at stimuli featuring faces, and looking times measured with eye-trackers tend to have lower looking times relative to manual gaze coding due to tracking gaze location with higher precision. Indeed, these differences were not specific to test trials.

3.4 General Discussion

The main hypothesis motivating these experiments is that if there is an early emerging mapping between space and temporal order, young infants should spontaneously take advantage of spatial cues to learn temporal order. In two experiments, we explored the link between different spatial representations of temporal sequences and 6-month-old infants' ability to learn temporal order. In both experiments, we found that infants habituated to the temporal sequences with left-to-right, linear spatial cues looked longer at incongruent test trials, suggesting that they learned the sequence during the habituation phase. In contrast, infants habituated with nonlinear spatial cues did not show a preference for either test trial. Our results suggest that the temporal memory advantage for events presented in terms of the mental timeline may be present before extensive experience with cultural artifacts.

3.4.1 Interaction of the Mental Timeline with Temporal Memory

Our main question of interest was to explore whether linear spatial cues benefit young infants' ability to learn temporal sequences. In two experiments, 6-month-old infants were habituated to a sequence of three images, either presented linearly or nonlinearly across the screen. The infants then viewed test trials showing these images only at the center of the screen, either in an order that was congruent or incongruent with the habituated sequence. We predicted that if there is an early emerging association between temporal order and linear spatial representations, infants should be able to learn the sequence more easily when presented linearly relative to when presented nonlinearly. In both experiments, we found only the infants assigned to the linear habituation group learned the temporal order of the habituated sequence and discriminated between congruent and incongruent test trials. Beyond exploring an early-emerging association between space and temporal order, the current study suggests that linear spatial representations of temporal order are advantageous for learning temporal sequences early in life.

The temporal binding aspect of episodic memory is difficult into adulthood (Pathman et al., 2018) and slower to develop than other aspects of episodic memory (Hayne & Imuta, 2011; Picard et al., 2012). Both children and adults show a temporal memory benefit from spatial cues presenting temporal order congruent with the mental timeline (e.g., from left to right for individuals from Western cultures) and are more accurate in recalling temporal order when spatial cues are presented linearly (e.g., from right to left) relative to when they are presented nonlinearly (Pathman et al., 2018). The current study demonstrates that spatial cues that benefit temporal order memory in children and adults are also beneficial in infancy and constitutes an important first step in exploring the continuity and development of the interaction between the mental timeline and temporal memory.

3.4.2 Experiment comparison

Although the predicted interaction between habituation condition and looking time to the test trials was significant in both experiments, there were some differences in the patterns of these results, such that infants overall looked for shorter durations to both habituation and test trials in Experiment 1. This difference is likely due to the less engaging stimuli and the use of an eye tracker rather than manual coding of looking time, in Experiment 2.

One reason for the smaller effects and overall lower looking times observed in Experiment 2 may be the stimuli used. In Experiment 1, infants saw stimuli that consisted of puppet faces, which were more visually complex, and more social relative to the simple geometric shapes used in Experiment 2. The reason for using simple geometric shapes in Experiment 2 was to account for the possibility that the visually complex stimuli may be more difficult for young infants to individuate and encode and that the use of simpler stimuli may make this task easier. However, because infants may prefer to look at social stimuli (Gluckman & Johnson, 2013) it is possible that the simplified stimuli made the task less interesting for these infants, who might have become less likely to look at the trials. Despite having smaller effects in Experiment 2, we observed the predicted results in both studies using different sets of stimuli. It is possible that simple yet attractive stimuli (e.g., simple geometric shapes with faces drawn on them) could make this task easier for infants and produce stronger results.

Another reason for the lower looking times in Experiment 2 may be due to the methods by which looking time was measured. In Experiment 1, we measured looking time using online coding during the experiment and offline coding from a video after the experiment. In Experiment 2, we measured looking time using an eye-tracker by calculating the duration of looking data within the screen coordinates. Because eye-trackers precisely track gaze locations, looking duration measured by an eye-tracker is less likely to include looks that are near but not directly on the screen (e.g., a fixation that is on the corner of the monitor), and studies using eye-trackers typically report shorter looking times . However, it is more likely that a coder interprets these fixations as 'on-screen', which could potentially increase the total looking duration, although the presence of multiple coders should minimize this issue. At the same time, eye-trackers can lose track of the infant's eye, due to reasons such as the infant covering part of the tracked eye with their hand, or covering the camera with their feet.

Another difference between the two experiments is the order in which elements were presented in the incongruent test trials. In Experiment 1, the incongruent test trial followed a 'BAC' pattern, and in Experiment 2, an 'ACB' pattern. Because there are differences in the overall looking times for Experiments 1 and 2, it is difficult to interpret whether the order in which the incongruent test trials were presented influenced how easily the infants were able to differentiate between the two test trial types. Future work could explore whether a violation of the learned temporal order earlier or later in a sequence influences infants' ability to distinguish these congruent and incongruent test trials when task stimuli are identical.

3.4.3 Directional preferences

For both children and adults, the direction and orientation of spatial representations of time are reinforced by cultural and linguistic experiences (e.g., Boroditsky et al., 2011; Starr & Srinivasan, 2021; Tillman et al., 2018; Tversky et al., 1991). For example, literate adults' mental representations of time are consistent with the direction in which they read and write (Fuhrman & Boroditsky, 2010; Ouellet et al., 2010; Tversky et al., 1991). For example, adults who read and write from left-to-right predominantly associate earlier events and the past with the left side of space, and later events and the future with the right side of space (Bonato et al., 2012). Those who read and write from right-to-left show the reverse association, mapping the future to the left side of space (Fuhrman & Boroditsky, 2010), and those who read both from top-to-bottom and left to right are equally likely to show associations in both orientations (Bergen & Chan Lau, 2012). Similarly, the orientation and direction of calendars, and linguistic metaphors that vary across cultures, such that speaking a language in which metaphors for time frequently refer to earlier events as 'up' and later events as 'down' influence the orientation, direction, and strength of such associations (Fuhrman & Boroditsky, 2010; Starr & Srinivasan, 2021). Studies exploring the development of temporal representations further emphasize the role of experience, such that young children are more varied and flexible in the direction and orientation of their representations of time relative to adults, both in their explicit representations (Tillman et al., 2018, Starr & Srinivasan, 2021) and spontaneous co-speech gestures (Burns et al., 2019). Infants, however, do not have experiences in reading, writing, using calendars, or linguistic metaphors for time and have limited exposure to co-speech gestures and written text.

Nonetheless, prior studies exploring early emerging, magnitude-based representations suggest that neonates and infants may map abstract domains, such as number onto space from left-to-right, even before cultural experiences that spatialize these domains. For example, neonates and infants may spontaneously associate 'few' items with the left side of space and 'many' items with the right side of space (Bulf et al., 2016, 2022; de Hevia et al., 2014). Additionally, previous literature exploring abstract rule learning in infancy suggests that spatial cues may influence infants' ability to extract information from stimuli (Bulf et al., 2022). For example, Bulf and colleagues (2022) demonstrate that the spatial organization of stimuli influences 7-month-old infants' ability to learn rule-like patterns, such that infants can learn these patterns when they are presented from left-to-right, but not when they are presented from right-to-left. Although these studies were conducted with neonates and infants in Western countries, these participants have no or minimal experience with their orthographic cultural environments, which suggests that infants may map abstract domains onto space with a preferred direction and may benefit from spatial cues with a specific orientation when learning higher-order, rule-like patterns before they gain experience with cultural artifacts.

Some researchers suggest that the presence of this early left-to-right bias suggests that humans might possess an early-emerging tendency to represent abstract domains in a left-to-right spatial manner (Bulf et al., 2016, 2022; de Hevia, 2021). This tendency may be due to a biological advantage for visual exploration of external space in a horizontal, left-to-right manner early in life, which may favor these early spatial preferences for these associations (Bulf et al., 2022; de Hevia et al., 2014). This biological advantage may exist due to right hemisphere dominance in visuospatial tasks and the relatively quick development of the right hemisphere, which may result in a bias favoring a leftward exploration of visual space (de Hevia et al., 2012). It is also important to note that directional preferences observed in older infants may also be due to early exposure to cultural experiences, such as observing people around them engage in directional behaviors such as reading, writing, organizing items, or engaging the infants with picture books from left-to-right (Arioli et al., 2022; Bulf et al., 2016, 2022; Nuerk et al., 2015). It is possible that both of these accounts play a role in shaping this bias observed in these studies.

Based on prior literature suggesting that left-to-right orientation may be related to early space-time mappings based on magnitude, and because the left-to-right mental timeline is the culturally dominant orientation for the infants in our samples, we started our exploration by contrasting spatial cues that present temporal order organized from left-to-right with those present it nonlinearly. However, in contrast to the left-to-right habituation trials, nonlinear trials provide a less predictable structure for the sequences and are dissimilar to the natural progression of physical movement. In other words, if representing progression through time as a progression through space is related to representing it linearly, it may be more difficult to represent a nonlinear progression through time because, in the physical world, objects and entities do not move nonlinearly on a horizontal axis (e.g., left-right-middle). Although our habituation trials do not suggest physical movement because they depict three separate entities, it is important to explore whether infants are better able to extract the temporal order of events when spatial cues are presented specifically oriented from left-to-right, or whether the difference observed between these two conditions stems from a difference in the predictability of the spatial structure. In the latter case, there should be no difference in infants' ability to learn temporal sequences from linear spatial cues presented from left-to-right, right-to-left, or in either direction on the vertical axis. Future work could explore the relation between spatial cues and temporal memory with longitudinal samples and with infants from diverse cultures that use different orthographies to distill the role of biology and culture in the emergence of directional preferences. Despite our results not distinguishing the role of predictability, linearity, and orientation of spatial cues in aiding temporal binding, the current results provide an important first step in confirming their relation starting in the first few months of life.

3.4.4 Conclusions

Our experiments demonstrate that French and American infants at 6 months of age benefit from linear spatial cues when learning temporal order before they gain extensive experience with cultural artifacts. We demonstrated this effect in two experiments conducted by two different labs on two different continents, using different stimuli and data collection methods. The replication of this effect across the two experiments suggests that these results are robust. These results demonstrate that the tendency to map temporal order onto a line is present before cultural learning of mental timeline, and the temporal memory benefit from mapping temporal order onto a linear timeline is beneficial for temporal memory early in life.

3.4.5 Summary

Chapter 3 explored whether the temporal memory benefit from spatial cues may be present before extensive experiences with cultural tools and demonstrated that infants benefit from linear, spatial cues when learning and remembering temporal order. Chapter 2 demonstrated that children's linear representations of temporal order in an explicit timeline construction task predicted their temporal memory abilities, suggesting developing linear representations of temporal order supports memory for temporal order. Combined, the two chapters suggest that spatial, linear representations of temporal order are beneficial for encoding and remembering temporal order in tasks for which explicit spatial cues are not present in both infancy and early childhood. However, less is known about the processes involved in this memory benefit, and in particular, whether the mental timeline is used as a memory strategy as linear timeline representations become more robust. The next chapter investigates how exactly this interaction may come online in adults engaging in memory encoding and retrieval. The between the mental timeline and temporal memory in adults has been measured with behavioral paradigms. The current study uses eye-tracking and pupillometry measures to gain more insight into the cognitive processes beyond memory accuracy measures.

Chapter 4. Adults use The Mental Timeline as a Memory Strategy

4.1 Introduction

Episodic memories are central to many aspects of our lives, ranging from contextualizing our personal history to making decisions about future events. To have a complete episodic memory, we must form a holistic representation of the 'what,' 'where,' and 'when' of a particular event. To do so, we bind these different components, such as the temporal and spatial context in which an event occurred (Ngo et al., 2019). We then use these representations to form autobiographies and guide current and future behaviors (Fivush, 2011; Suddendorf & Corballis, 1997). For example, we may have rich, contextualized representations of our lives that allow us to have a 'personal history' (e.g., I was a sophomore in college when I first entered a psychology lab) and we frequently use our memories of particular experiences to prepare ourselves for similar experiences. However, some aspects of episodic memory are more difficult than others. For example, distinguishing elements of highly similar events is more difficult relative to dissimilar events (Kirwan & Stark, 2007; Ngo et al., 2019), and remembering 'when' events happened is more difficult than remembering 'where' those events happened (Lee et al., 2016; Bauer et al., 2012). These processes of differentiating between similar events or remembering the temporal context of events allow us to guide many vital tasks, such as remembering whether we already took a dose of our daily medicine on that particular day.

The temporal component of episodic memory may be the more difficult relative to locations because time is abstract. Unlike objects, agents, and locations, time cannot be directly perceived by the senses. Even in adulthood, remembering the temporal order of events is more difficult than remembering the objects, agents, or locations involved in those events (Sakon &

Kiani, 2022). To get around this problem, people across many cultures and languages use spatial representations of time to support their abilities to reason about and remember temporal information. Many cultural tools, such as calendars, planners, and evolution timelines, are external, spatial representations of temporal order, and can help temporal reasoning (Friedman, 1990). For example, calendars can help us understand how close we are getting to a deadline each day, and an evolution timeline can help us infer the order in which various species evolved. Similar to these external representations of temporal order, we may spontaneously use mental representations of temporal order to aid temporal cognition. One way in which people use space to represent temporal order is through the mental timeline, a linear projection of time onto space (Bonato et al., 2012).

4.1.1 The Mental Timeline

For most Western adults, the mental timeline is structured such that earlier events and the past are represented toward the left side of space, and later events and the future are represented toward the right side (Bonato & Umiltà, 2014). These associations (e.g., earlier-left, later-right) are evident in both explicit timeline construction tasks (Tillman et al., 2018) and reaction time tasks in which participants evaluate temporal information (Ishihara et al., 2008). The direction and orientation of the mental timeline are influenced by multiple cultural experiences, such as reading and writing direction (Bergen & Chan Lau, 2012; Bottini et al., 2015). One specific way in which the mental timeline may benefit temporal cognition is by supporting memory for the temporal order of events. Recent research suggests that older children and adults spontaneously draw on the mental timeline for encoding and retrieving information about temporal order. For example, Pathman and colleagues (2018) explored whether the direction and linearity of stimulus presentation modulated memory for spatial information (e.g., recalling where an item appeared on the screen) or temporal information (e.g., recalling when an item appeared within a sequence). In this task, participants first viewed triplets of images during the memory encoding phase. The spatial and temporal order was manipulated such that these triplets of images were presented from left-to-right, right-to-left, or nonlinearly across the screen. After a delay, participants began the memory retrieval phase, in which they were shown some of the encoded images individually and asked to recall either the spatial location or the temporal order in which the image appeared during the encoding phase. The results demonstrated that the participants were highly accurate in recalling the spatial location of the encoded images for all trial types, however, they displayed 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 (Pathman et al., 2018). 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. Overall, these results suggest that the mental timeline influences how humans represent and remember temporal information.

However, it is unknown whether children and adults deliberately exploit the mental timeline to remember temporal information, in the form of a mnemonic strategy. Because memory for temporal order is less accurate relative to memory for spatial locations for people of all ages (Pathman et al., 2018) using the mental timeline as a strategy for temporal memory can leverage the stronger memory for spatial information to improve episodic recall. Measures providing insight into cognitive processes such as increased attention, or reconstruction of previously encoded information are ideal candidates for exploring how mental timeline representations come online during the encoding and retrieval of temporal information. Using measures such as pupil dilation and gaze movement in addition to behavioral measures can provide further insight into how the mental timeline provides a benefit for remembering temporal order.

4.1.2 Eye-tracking Metrics

Pupil dilation is an established method for assessing cognitive processes such as attention, mental effort, and memory load (e.g., Kahneman & Beatty, 1966; Micula et al., 2022; Papesh et al., 2012; Unsworth & Robison, 2018) and internal states, such as arousal, surprise, or mind-wandering (Preuschoff et al., 2011; Unsworth & Robison, 2018a). For example, changes in pupil dilation during working memory tasks indicate individuals' engagement with the task, such that greater pupil dilation is associated with greater engagement and more information held in working memory, whereas constriction or flattened pupil responses are associated with becoming disengaged (Johnson et al., 2014; Kahneman & Beatty, 1966; Robison & Unsworth, 2019; Unsworth & Robison, 2018a). Pupil dilation not only indicates effort and memory load during working memory tasks but changes in pupil dilation during the encoding phase can also predict subsequent successful recall for both recognition and free recall paradigms (Micula et al., 2022; Papesh et al., 2012). These patterns suggest greater dilation during encoding is associated with improved memory, potentially due to increased attention to engagement with the task during the encoding phase. Because pupil dilation responses have high temporal resolution, using this method can reveal how mental timeline representations come online when encoding temporal order. For example, fluctuations in pupil dilation during encoding can reveal differences in difficulty (e.g., are temporal stimuli presented in terms of the mental timeline easier to encode?) and differences in pupil dilation patterns across different trials may reveal the amount of information maintained in memory (e.g., is greater information maintained following trials for which there are spatial cues present?).

Beyond measures indicating attentional and memory load, we can explore the relation between the mental timeline and temporal memory through associations through gaze position during the recall phase. Previous research suggests that eye movements provide insight into the memory retrieval processes (Hannula et al., 2007; Holm & Mäntylä, 2007; Wynn & Schacter, 2024). For example, when retrieving previously encoded stimuli, participants may make eye movements consistent with their eye movements during the encoding of those stimuli (Holm & Mäntylä, 2007). In a study conducted by Holm and Mäntylä (2007), participants completed a memory task with an eye-tracker, in which they were presented with a set of complex visual stimuli during the encoding phase and shown a mix of previously viewed and novel scenes during the recognition phase. The results showed that during the recognition phase, participants were more likely to fixate on the same regions they had looked at during the encoding phase when they successfully recognized a previously encoded scene. These findings suggest that gaze movements provide insight into the reconstructive processes during memory retrieval and may reflect the participants' mental representation of the encoded stimuli. Further, previous work suggests that eye movement patterns consistent with mental representations are also present when people are thinking about concepts that do not have spatial properties, such that eye movements reveal how adults may spatially represent concepts such as time, number, and colors (e.g., Chrabaszcz et al., 2024; Martarelli et al., 2017; Masson et al., 2018; Viganò et al., 2024). For example, Chrabaszcz and colleagues (2024) have found that speakers of Russian (which is written from left-to-right) and speakers of Hebrew (which is written from right-to-left) show opposite patterns in their gaze behavior when hearing verbs spoken in the past or future tense. While speakers of Russian looked more to the left when they heard past tense verbs relative to when they heard verbs spoken in the future tense, speakers of Hebrew looked more to the left when they heard future tense verbs relative to when they heard verbs in the past tense (Chrabaszcz et al., 2024). These results are in line with other studies showing that for adults in high literacy environments, reading and writing direction influences the orientation of the mental timeline (Fuhrman & Boroditsky, 2010; Tversky et al., 1991). These eye movements congruent with the culturally dominant mental timeline in these groups suggest that eye movements can reveal space-time associations in terms of the mental timeline when processing stimuli about the past and the future. Overall, previous studies exploring eye movements suggest that gaze movements during a task can provide insight into both memory reconstruction processes and the geometry of mental representations for concepts without inherent spatial properties (Chrabaszcz et al., 2024; Martarelli et al., 2017; Viganò et al., 2024). Gaze movement patterns during retrieval of temporal order information can therefore reveal insights into the reconstruction of the encoded information and the process by which the mental timeline may provide a benefit for temporal memory.

4.1.3 Current Study

In the current study, we explore the memory benefit for temporal information presented in terms of the mental timeline using behavioral accuracy, pupillometry, and eye-tracking measures. Specifically, we investigate 1) whether the spatial presentation of the stimuli influences mental effort and attention during memory encoding and 2) whether participants spontaneously organize the temporal order of triplets in terms of a mental timeline. By combining pupillometry and gaze measures we aim to provide additional information about how the linearity and direction of the spatial presentation interact with temporal memory processes. Adult participants in the U.S. were asked to complete a spatiotemporal memory task adapted from Pathman and colleagues (2018). In this task, triplets of images were presented in spatial orientations that are either congruent (left-to-right) or incongruent with the mental timeline (right-to-left, nonlinear) of this sample. We operationalized location memory as a memory for the location an item is presented on the screen (e.g., the right side) and memory for temporal memory as the memory for the temporal order of an item in the triplet (e.g., the second item), the same way these two types of memory were operationalized in Pathman and colleagues (2018).

Our first question explores whether the spatial presentation of the stimuli influences mental effort and attention during memory encoding. To answer this question, we explore participants' changes in pupil dilation during the memory encoding phase. We assess differences in mental effort and attention during the encoding phase as a function of the spatial presentation of the stimuli by measuring changes in pupil dilation. We also test whether pupil dilation during encoding predicts recall accuracy. Exploring changes in pupil dilation for successfully recalled or forgotten items will reveal information about the memory processes the mental timeline may support. For example, it is possible that despite increased attention during encoding, the trials for which triplets are presented in spatial orientations incongruent with the mental timeline are more difficult to maintain in memory over time. It is also possible that once participants increase their attention in the encoding phase, they can recall the order of the items successfully. We predict that participants will have larger pupil dilation when encoding triplets presented in spatial orientations incongruent with the mental timeline (right-to-left and nonlinear) due to increased attention. We also predict that when controlling for trial direction, participants will be more accurate in recalling the temporal order of items in trials for which participants experienced larger pupil dilation.

Our second question explores whether participants spontaneously organize the temporal order of triplets in terms of a mental timeline. To answer this question, we explore participants' gaze movements during the memory retrieval phase. Exploring gaze positions will reveal whether participants spontaneously reference the mental timeline when recalling the temporal order of triplets, revealing insights into the strategies adults may use when remembering the temporal order of the items. For example, participants may be mentally organizing the order of the triplets in terms of a mental timeline and shift their gaze toward the left when recalling an item that was presented earlier in the triplet and shift their gaze toward the right when recalling an item that was presented later in the triplet, even when the items were presented from right-to-left, or nonlinearly (e.g., right-left-middle). It is also possible that participants primarily encode the spatial location of the objects, which may bias their recall of the temporal order of the object. For example, for a trial in which the objects in a triplet were presented from right to left, participants might shift their gaze toward the right when recalling the first object because it was presented on the right side of the screen and incorrectly recall that item was presented later in the triplet. We predict that most participants will shift their gaze toward the left when remembering earlier events and shift their gaze toward the right when remembering later events. This gaze pattern would indicate a mental reorganization of the stimuli, suggesting that participants are drawing on the mental timeline to recall temporal order, regardless of the spatial organization the triplet items were presented during the encoding phase.

Overall, patterns in pupil dilation and gaze movements can provide insights into how adults may engage the mental timeline when encoding and remembering temporal order by informing changes in cognitive load during the memory encoding process and the mental organization of temporal information during the memory retrieval process.

4.2 Method

4.2.1 Participants

The final sample included 33 participants (*M* = 22.79 years, range: 18 – 43 years, *n* = 27 female, *n* = 4 male, *n* = 2 non-binary). Data from two additional participants were excluded due to participants not following instructions (*n* = 1) and answering more than 10% of the attention check questions incorrectly (*n* =1). Data from one participant includes only one block, due to technical difficulties during the second block of the experiment. All included participants filled out a demographic information form. Participants described their racial-ethnic identities as: White (*n* = 17), Multiracial (*n* = 7) Asian (*n* = 8), and African American (*n* = 1). Most participants spoke English as their first language (*n* = 32), and more than half (*n* = 14) spoke more than one language.

Participants were recruited from the University of Washington's Research Participant Pool (*n* = 30) and through emails within the University of Washington (*n* = 3). Participants recruited through the Research Participant Pool received class credit, and participants recruited via email received an $8 digital gift card. Participants provided verbal and written consent prior to participation. All informed consent and data collection procedures were approved by the University of Washington Institutional Review Board.

4.2.2 Materials and Procedure

4.2.2.1 Memory Task

4.2.2.2 Stimuli. The stimuli in the memory task were images selected from the Bank of Standardized Stimuli (BOSS) database (Brodeur et al., 2010). An experimenter initially selected a set of 210 images for stimuli, and another experimenter then assessed whether the stimuli set was balanced in terms of item category (e.g., food items, animals, household items). The selected images were matched for luminance using the SHINE-color toolbox to make them suitable for pupillometry (Dal Ben, 2023). Two independent experimenters reviewed the modified images matched for luminance and removed images that were no longer easily recognizable from the stimuli set (n = 5). The triplet of images presented at each encoding trial were randomly created from the list of 205 images to create 50 triplets (n = 25 for each encoding block) at the beginning of the experiment for each participant, totaling 150 images viewed during the encoding phase. The triplets were made unique for each participant such that if some triplets were easier than others (e.g. because two semantically related objects appeared together) these would be randomized across participants.

4.2.2.3 Encoding phase. During the encoding phase, the participants first saw a fixation cross at the center of the screen, presented for 2000 ms. They then viewed images of a triplet of objects presented one at a time, each present for 1500 ms with a 500 ms interstimulus interval in between to allow time for the pupillary response (see Figure 10 for a schematic of an encoding trial). These images appeared at distinct locations on the screen, presented either from left-to-right, right-to-left, or nonlinearly. The nonlinear trials had four possible presentations (middle-right-left, middle-left-right, right-left-middle, left-right-middle). The final image in the triplet was followed by a mask image (scrambled image resembling a static screen) presented for 2000 ms. The participants then saw the same triplet of images presented with the same timing structure. For 80% of the trials, the images in the second triplet appeared in the same order and location for the first and second time the participants saw the images. For 20% of the trials, the second time the participants saw the triplet of images, these images appeared in a different location than the first time. At the end of each encoding trial, the participants were asked to answer whether the first set of images they viewed was exactly the same as the second set of images they viewed. These catch trials were implemented to ensure that the participants were paying attention to the task. During the practice trials, the participants were instructed that the displayed images would always be the same and that they should pay attention to the order and location in which the images in a triplet appear.

4.2.2.4 Retrieval phase. For each retrieval block, participants saw 20 retrieval trials, in which one object from each 'same' trial from the encoding phase was presented. Each trial started with a 2000 ms fixation cross, then the question text "When did you see the following object?" was displayed for 1000 ms, followed by the retrieval image which was displayed at the center of the screen for 500 ms. The participants then saw a blank screen for 1000 ms, after which the question text "When did you see the object?" and answer options (first, second, third) were displayed until the participants chose an answer. The answer options were vertically oriented to ensure the orientation of the answer options did not match the orientation of the stimuli (see Figure 10 for a schematic of a retrieval trial). Because we anticipated that the first and third items would produce larger eye movement during the retrieval phase, we structured the retrieval trials such that the majority of the retrieval images came from images that were displayed first or third in the triplet, and on the left or right side of the screen (see Table 1 for a breakdown of retrieval image order and location displayed in the included retrieval trials). Importantly, although the participants were instructed to pay attention to both the temporal order (e.g., first, second, third) and the spatial location (e.g., left, middle, right) of the images within a triplet, and completed a practice trial of both question types, they were only asked temporal order questions during test.

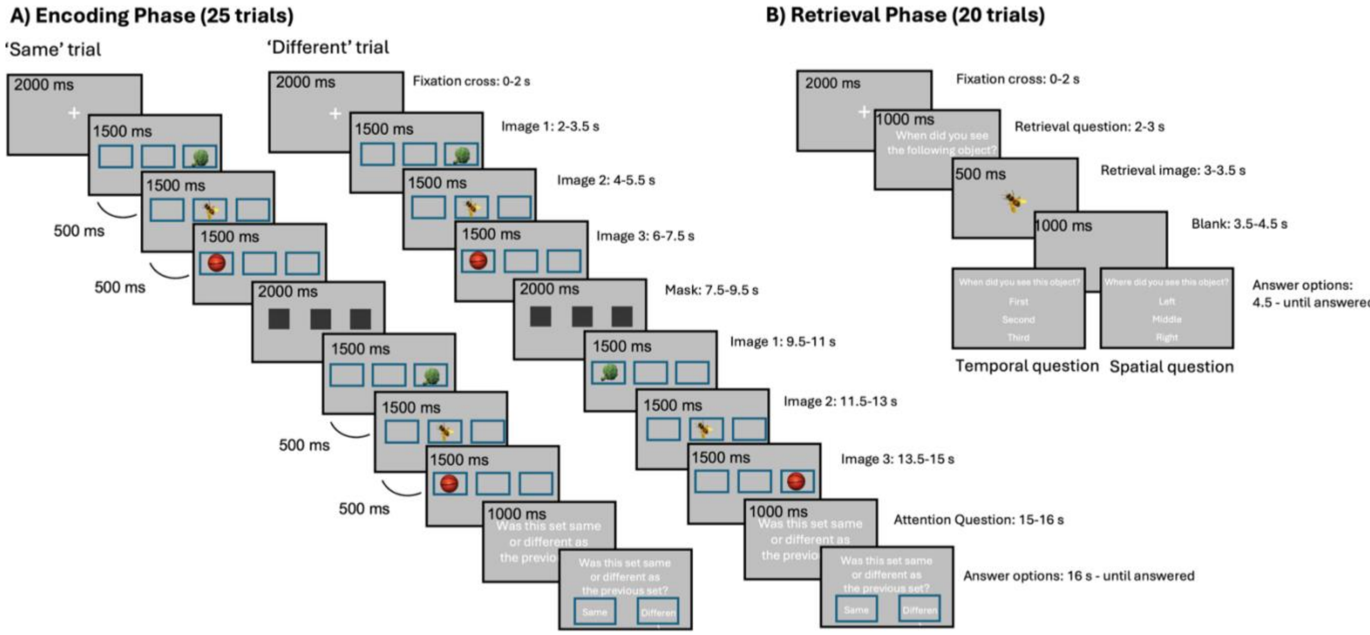

Figure 10. Schematic of the Memory Task. Depiction of the encoding (A) and retrieval trials (B).

	First	Second	Third
Left	193	88	192
Middle	110	73	122
Right	193	91	192

Table 1. The order and location of the retrieval images displayed during the encoding phase.

4.3 Procedure

All participants received task instructions from a researcher before the study. Participants were told they would view pictures of objects in groups of three and were instructed to attend to the spatial location and the temporal order of the images within triplets. They then completed four practice trials, displayed on a laptop by a researcher. These practice trials included two encoding trials, one 'same', one 'different', and two retrieval trials, one with a spatial question and one with a temporal question (see Figure 10 for an example of these trials). The participants were encouraged to ask questions during this time, and experimenters provided feedback and repeated the instructions if the participants did not answer the practice questions correctly. Once participants were situated in the eye-tracking room, they were also told to look at the fixation cross whenever it appeared, to generally keep their eyes on the screen, and to sit as still as possible during the task.

All participants were tested individually in a quiet, dark room with an EyeLink 1000 eye tracker (SR Research, Ontario, Canada) with a sampling rate of 500 Hz and a screen that was 368 mm in width and 310 mm in height with 1280 x 1024 resolution. Participants sat in a chair about 80 cm from the desk and were told to adjust their sitting position until they were comfortable and could use the computer mouse without moving to answer the questions throughout the task. Once the participant was situated, the monitor, which was mounted on a flexible arm mount, was positioned between 55 and 60 cm from the participant. Experimenters performed calibration procedures before starting the task. The experiment was programmed and run using PsychoPy 2024.1.4 with the EyeLink integration (Peirce et al., 2019).

All participants completed two encoding and two retrieval blocks, with a 3-minute break between each encoding and retrieval block. Participants were allowed to get up and move around during these breaks, however, they were not allowed to look at or engage with any other material. After each break, the experimenter performed a drift check on the eye tracker and recalibrated if necessary. After participants completed the memory task, they were given a brief survey about strategies they used during the memory task and a survey about their internal representations adapted from the Internal Representations Questionnaire (Roebuck & Lupyan, 2020). The survey data are analyzed elsewhere.

4.4 Data exclusion

4.3.1 Pupil data preprocessing

Pupil data were processed and cleaned in R using the PupillometryR package (Forbes, 2020). Pupil data were first down-sampled to 50 ms time bins, outlier data points (e.g., those corresponding to blinks) were filtered out using a median filter, and resulting gaps were linearly interpolated. Trials with 50% or more gaze data missing were removed from the analysis (n = 62 encoding, n = 22 retrieval). If a participant had 50% or more of their trials removed in a particular encoding or retrieval block, we removed all trials from that block from the analysis (n = 2 encoding). For the encoding trials, only the 'same' trials were analyzed (80% of all encoding trials). Then, we filtered the encoding trials for which participants answered the attention check question incorrectly (n = 20 trials) and the retrieval trials that featured images from these trials during encoding (n = 17 trials). The remaining pupil values were converted from artificial units to mm using values obtained from a recording with an artificial pupil of a known size.

4.3.2 Pupil dilation at encoding

Our primary period of interest for measuring pupil dilation was the initial presentation of the triplet of images. For each trial and each participant, we calculated a baseline measure of pupil dilation that corresponded to the average pupil dilation during the final 200 ms of the fixation period before the first image in the triplet. Baseline pupil dilation values that were two standard deviations above or below the mean were considered outliers and excluded from the data (n = 60 trials). Two additional trials were removed due to the experiment pausing the study to re-calibrate the eye tracker.

4.3.3 Gaze location at retrieval

Our primary period of interest for measuring gaze movements was the 1000 ms period in which participants saw a blank screen after viewing the retrieval image and before answer options appeared on the screen. Because the eye-tracker projects gaze locations for off-screen looks, we filtered all data points that were outside the screen coordinates (0.05% of the points). Response times for the recall questions that were two standard deviations above ($z \geq 2$) or below ($z \leq -2$) the mean for each participant were considered outliers and excluded from the data (n = 48 trials). We also removed outlier gaze points based on gaze location, such that gaze points two standard deviations above ($z \geq 2$) or below ($z \leq -2$) the mean coordinates were removed from analyses (0.03% of the points). This was to eliminate gaze positions captured while participants were making eye movements off the screen that were removed from the analyses.

4.3.4 Behavioral data

Retrieval trials that featured images from trials in which participants answered the attention check question incorrectly (n = 17 trials) were removed from analyses.

4.4 Results

All data were analyzed using the lmerTest, tidyverse, and zoo packages (Kuznetsova et al., 2017; Wickham et al., 2019; Zeileis & Grothendieck, 2005).

4.4.1 Recall Accuracy

First, we explored participants' behavioral responses during the retrieval phase as a function of the direction in which the triplets were presented during the encoding phase. Participants were significantly less accurate in recalling the temporal order of the images when the triplets were presented from right-to-left (β = -0.9, $p < .001$) or nonlinearly (β = -0.79, $p < .001$) compared to when they were presented from left-to-right. There was no difference in accuracy across the two blocks (β = 0.21, p = .1) (see Figure 11).

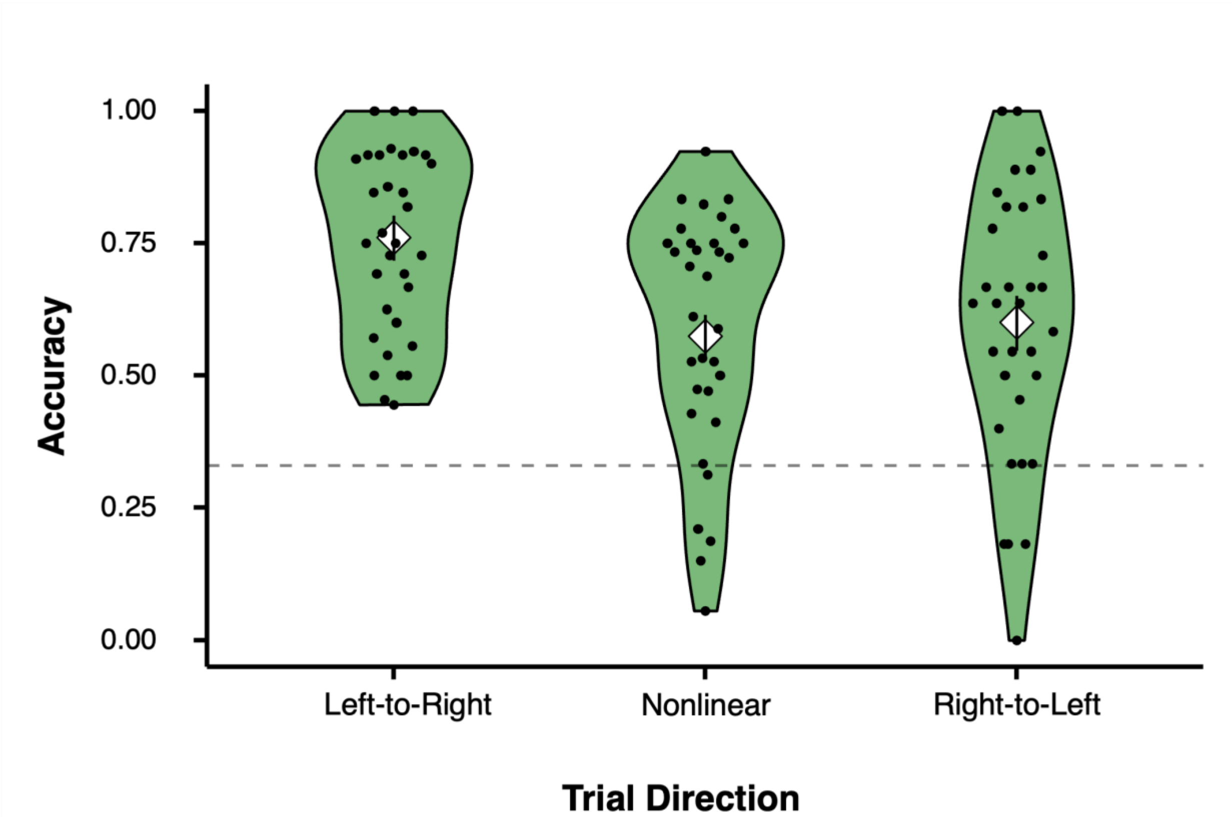

Figure 11. Temporal memory accuracy by trial direction. The diamonds represent the mean accuracy for each trial direction, and the black dots represent individual participants. The dotted line represents chance-level performance.

Because participants made more mistakes in the right-to-left and nonlinear trials relative to left-to-right trials, we explored whether participants' mistakes suggested mental organization of temporal order in terms of the mental timeline. For this analysis, we compared participants' incorrect responses for items presented first and third in the triplets and on the left and right sides of the screen. Participants were significantly more likely to mistakenly recall an image presented third in the triplet as being presented first when the image was presented on the left side of the screen, relative to when it was presented on the right side of the screen, and more likely to mistakenly recall an image presented first in the triplet as presented third when the image was presented on the right side of the screen relative to when it was presented on the right side of the screen ($\chi^2(1) = 16.03$, $p < .001$) (See Figure 12). These results suggest that the spatial location of the items contributed to participants' recall errors when they were incongruent with the mental timeline.

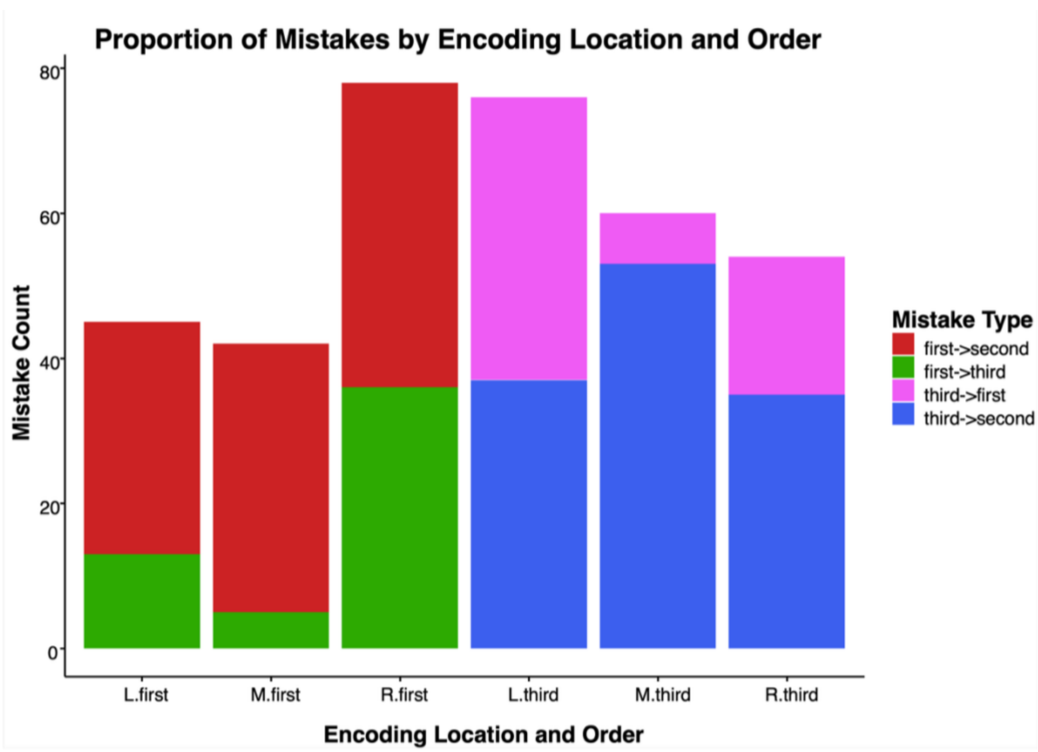

Figure 12. Proportion of incorrect responses at retrieval by encoding location and order.

The x-axis shows the encoding location (L = left, M = middle, R = right) and order. The legend shows actual order -> guessed order.

4.4.2 Pupil Dilation at Encoding

Our main analyses concerned two questions. First, we explored whether or right side of participants' pupil dilation during the encoding phase changed as a function of trial direction. To explore changes in pupil dilation in relation to trial direction, we analyzed the baseline-corrected pupil values during two phases of the encoding trial. First, we explored the period starting from 1000 ms after the onset of the first image, and half a second after the end of the third image, corresponding to a 5000 ms period. This one-second delay was implemented to ensure any effect we observe is in response to the stimuli displayed in the trial because changes in pupil dilation in response to stimuli emerge slowly (Hoeks & Levelt, 1993; Mathôt & Vilotijević, 2023). For the same reason, we included half a second period after the offset of the third image to capture responses to the third image (see Figure 13). Because both mental fatigue and familiarity with the experiment can influence pupil dilation (e.g., due to developing memory strategies), we used block as a fixed effect in this model (model syntax: relative pupil dilation ~ trial direction + block + (1|subject_id).

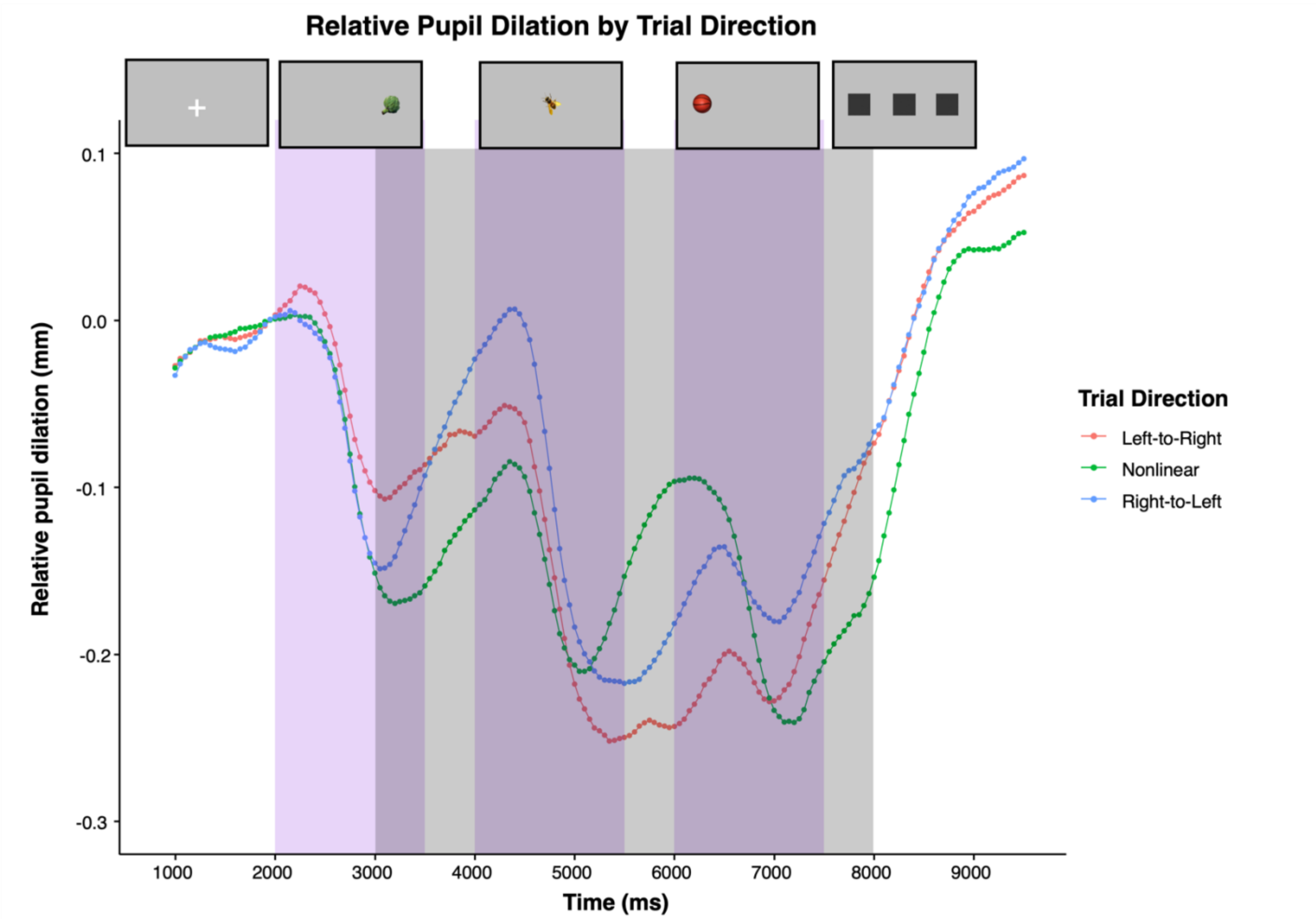

Figure 13. Relative pupil dilation over the first view of the encoding trial by trial direction. The top panel represents what is present on the screen during the time period. The areas shaded in purple represent the times at which the triplet images were displayed, and the area shaded in gray represents the period from which the values used for the analyses encompassed.

Relative to trials displayed from left-to-right, participants experienced significantly larger pupil dilation when trials were displayed from right-to-left (β = 0.01, $p < .001$) or nonlinearly (β = 0.04, $p < .001$). There was a main effect of the block, such that participants had higher pupil dilation during the second block (β = 0.005, p = .02). Because there was a main effect of block, we included block as a fixed effect in all future models. We then analyzed mean and maximum pupil dilation values as a function of trial direction. Mean or maximum pupil dilation values did not change as a function of trial direction (all βs <|0.04|, all ps > .59). This pattern of results suggests that differences in pupil dilation for different trial directions may in part be due to different dilation patterns over the course of multiple seconds, rather than an overall increase in pupil dilation.

4.4.3 Pupil Dilation After Image Viewing

Next, we explored the participant's pupil dilation after viewing the triplets, while the mask image was presented. For this analysis, we included pupil values for the time the mask image was presented, which corresponds to a 2000 ms period after the third triplet image disappears (See Figure 13). Because pupil dilation carryover effects can last 2000-3000 ms after stimulus onset, and because pupil dilation response to internal cognitive processes can take longer to arise relative to stimuli with a defined onset (Mathôt & Vilotijević, 2023), this additional exploration was to assess whether these two time periods, one of actively viewing the images and committing to memory and the other of maintaining in memory, may reveal different patterns. Similar to previous analyses, because both mental fatigue and memory strategies can influence pupil dilation and retrieval accuracy, we used block as a fixed effect in these models.

Relative to trials displayed from left-to-right, participants experienced significantly smaller pupil dilation when trials were displayed nonlinearly (β = -0.04, p < .001) but not from trials displayed from right-to-left (β = 0.01, p =.19) (see Figure 14). Similar to previous analyses, there was a main effect of block, however, it was in the opposite pattern such that participants had overall lower pupil dilation during the second block (β = -0.02, p < .001).

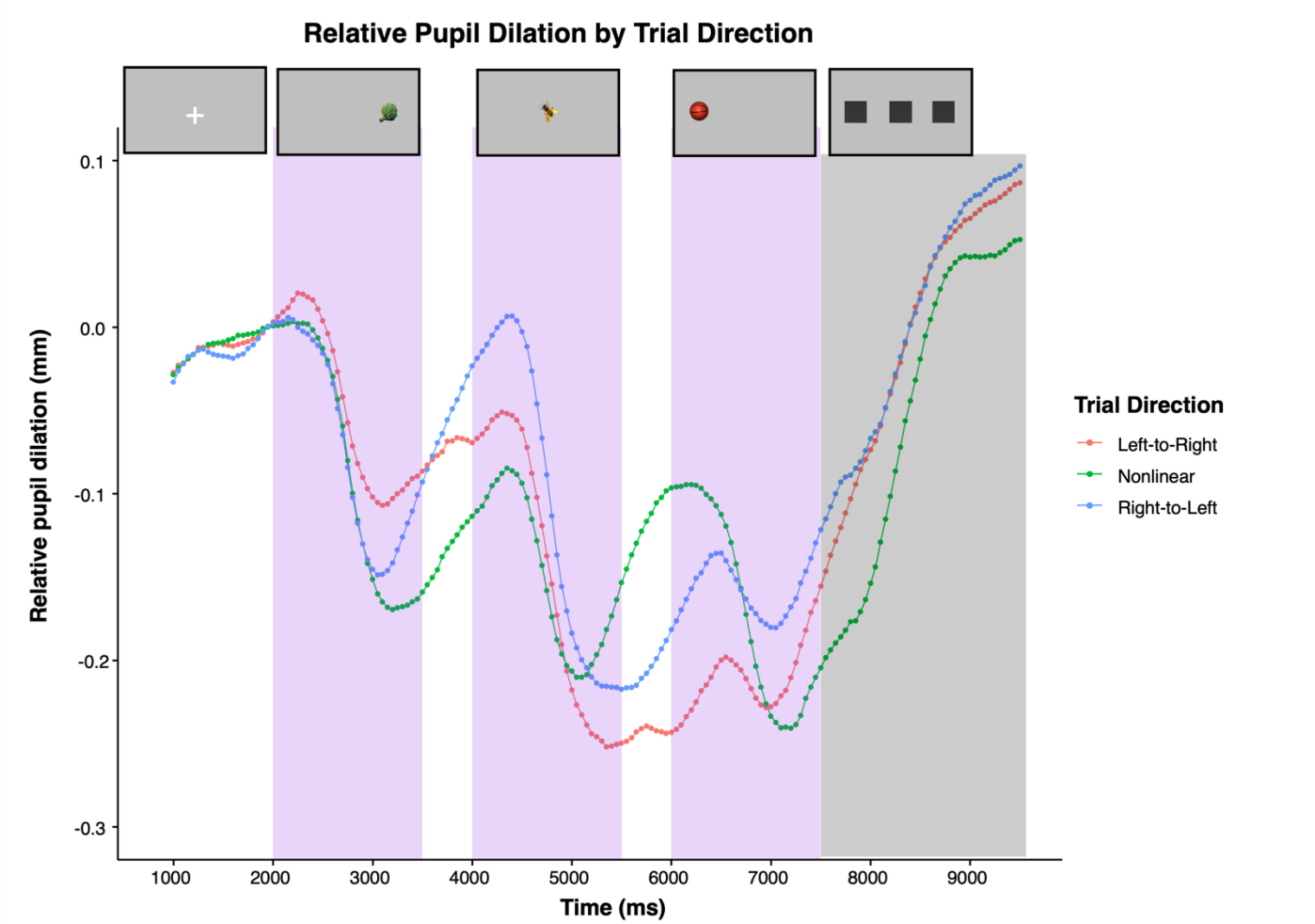

Figure 14. Relative pupil dilation after the first view of the encoding trial by trial direction. The top panel represents what is present on the screen during the time period. The areas shaded in purple represent the times at which the triplet images were displayed, and the area shaded in gray represents the period from which the values used for the analyses encompassed.

We then analyzed mean and maximum pupil dilation values as a function of trial direction. Trial direction did not influence mean or maximum pupil values during the two seconds following the initial triplet presentations (all βs <|0.05|, all ps > .06). This pattern of results suggests that differences in pupil dilation for different trial directions may in part be due to differences in sustained dilation.

4.4.4 Pupil Dilation and Memory Accuracy

Next, we explored whether mean and maximum pupil dilation during either phase (while viewing the images or after viewing the images) of the encoding trials predicted accuracy at the retrieval phase. In these models, we also included encoding order (first, second, or third) as a fixed effect, to control for the possibility that item order within the triplet may influence memory accuracy (model syntax for mean dilation: recall accuracy ~ mean pupil dilation * trial direction + encoding order + block + (1| subject_id), model syntax for maximum dilation: recall accuracy ~ maximum pupil dilation * trial direction + encoding order + block + (1| subject_id)). Mean and maximum pupil dilation values at encoding did not predict accuracy during retrieval in either phase (all βs < |1.25|, all *p*s > .08). There was a main effect of encoding order in both models, such that the images presented third in the triplet were less likely to be accurately remembered relative to those presented first in the triplet (all βs > |0.31|, all *p*s < .04).

4.4.5 Gaze location at retrieval

Our second main question of interest explored whether participants' gaze movements at retrieval suggested they spontaneously organized the temporal order of triplets in terms of a mental timeline. To answer this question, we analyzed the 1000 ms time window between the offset of the retrieval image and the onset of the answer options. We first examined participants' gaze positions to assess whether the order or location of the retrieval image during encoding influenced gaze movements during successful retrieval trials. We then compared whether gaze patterns differed between trials with accurate and inaccurate retrieval. For both analyses, we calculated rolling averages of the x and y-coordinates of participants' gaze using a 5-point moving window via the zoo package (Zeileis & Grothendieck, 2005), which averaged five consecutive points over the target duration. We used these rolling averages to smooth fluctuations in the raw data and extract broader, systematic shifts in gaze movement. All gaze analyses were also conducted using raw gaze data and by calculating displacement between gaze positions at the start and end of the 1000 ms interval. Because all methods yielded similar patterns, only the rolling average analyses are reported here.

4.4.5.1 Encoding Order

We explored participants' gaze movement for correct trials as a function of the temporal order in which the retrieval item appeared during the encoding phase (model syntax: rolling gaze x ~ encoding order + (1| subject_id). We found that the x-coordinate location of gaze position was influenced by encoding order, such that for images presented second, participants looked more toward the right side of the screen ($\beta = 5.07$, $p < .001$) relative to images presented first, however, there was no difference for gaze location for images presented third ($\beta = -1.03$, $p = .38$) (see Figure 15). *Figure 14*. Rolling average of gaze location on the x-axis during the blank screen at retrieval trials by encoding order. The top half of the plot represents more rightward gaze locations, and the bottom half represents more leftward locations.

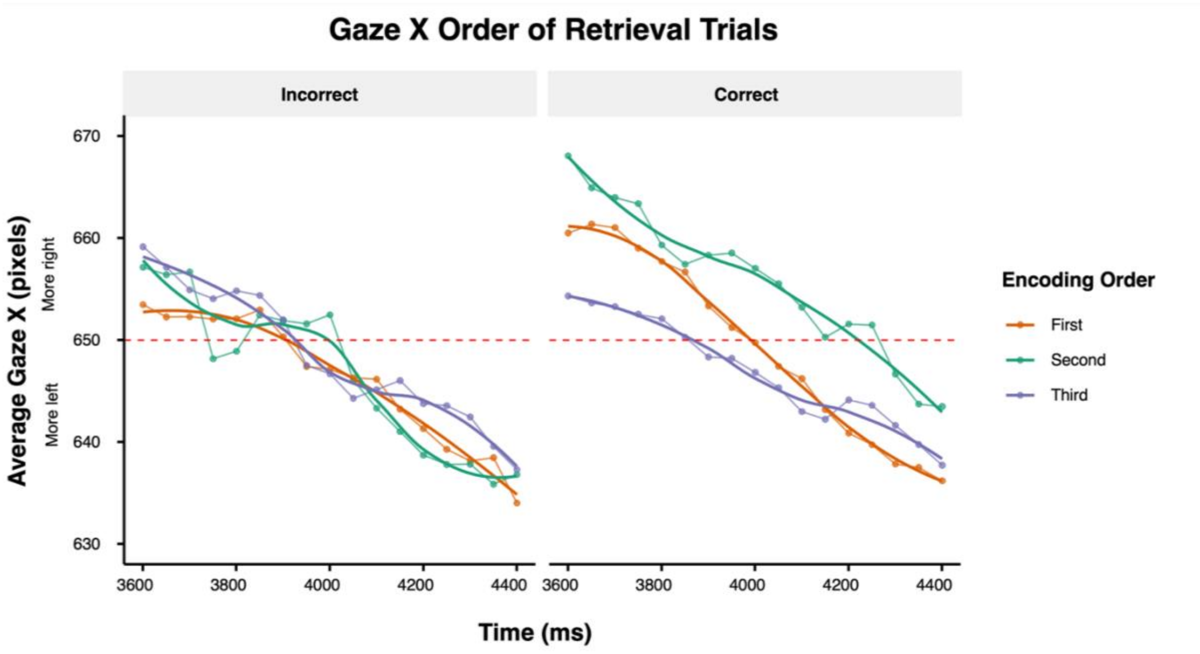

Figure 15. Rolling average of gaze location on the x-axis during the blank screen at retrieval trials by encoding order. The top half of the plot represents more rightward gaze locations, and the bottom half represents more leftward locations.

4.4.5.2 Encoding Location

We explored participants' gaze movement for correct trials as a function of the temporal order in which the retrieval item appeared during the encoding phase (model syntax: rolling gaze x ~ encoding location + (1| subject_id). We found that the x-coordinate location of the gaze position was influenced by encoding location, such that participants moved their gaze rightward when recalling retrieval images presented in the middle during encoding, (β = 5.18, $p < .001$) and for images presented on the right during encoding (β = 12.73, $p < .001$), relative to images that were presented on the left (see Figure 16).

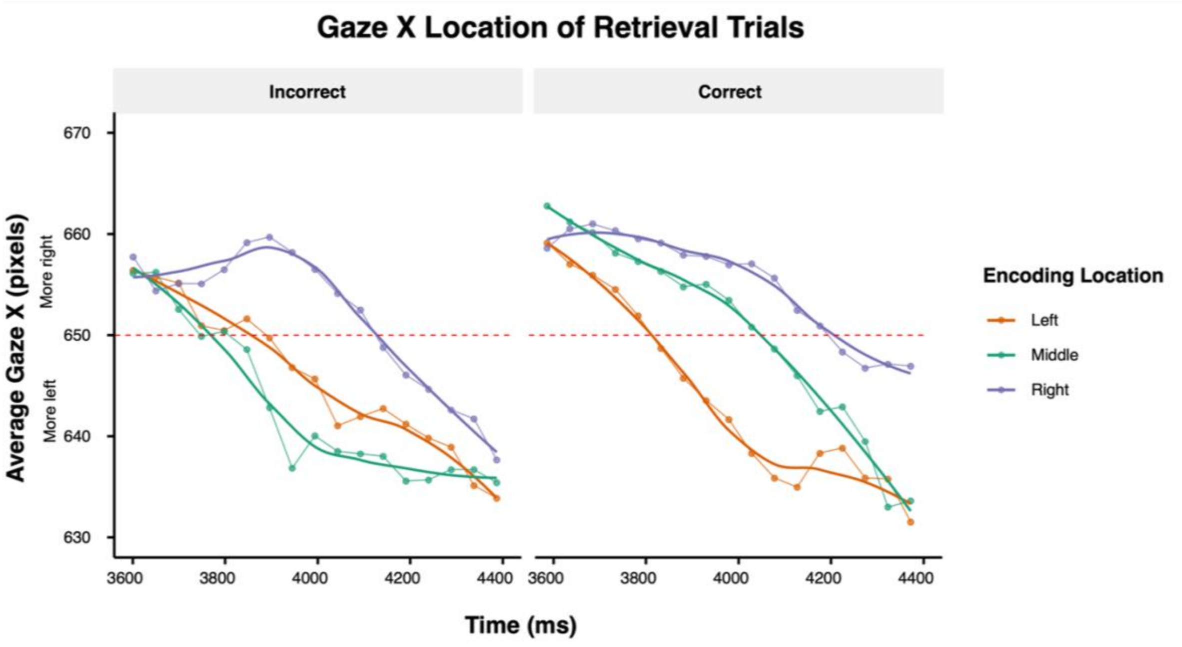

Figure 16. Rolling average of gaze location on the x-axis during the blank screen at retrieval trials by encoding location. The top half of the plot represents more rightward gaze locations, and the bottom half represents more leftward locations.

4.4.5.3 Accuracy and Gaze Location

Finally, we explored whether correct retrieval of the temporal order of the retrieval item was related to participants' eye movements. We first explored whether gaze patterns differed between correct and incorrect trials, as a function of encoding order (model syntax: rolling gaze x ~ encoding order * correct answer + (1| subject_id)). There was an interaction between accuracy and encoding order, such that participants were more likely to move their gaze rightward for retrieval images that were presented second and answered correctly relative to incorrectly (β = 7.62, p = .002), but there was no difference in gaze movement for retrieval images that were presented third and answered correctly (β = 3.72, p = .07).

Next, we explored whether gaze patterns differed between correct and incorrect trials, as a function of encoding location (model syntax: rolling gaze x ~ encoding location * correct response + (1| subject_id). There was also an interaction between accuracy and encoding location, such that participants were more likely to move their gaze rightward for retrieval images that were presented in the middle and answered correctly (β = 10.45, p < .001) and for retrieval images that were presented on the right and answered correctly (β = 10.26, p < .001)

4.5 Discussion

This experiment aimed to deepen our understanding of how the mental timeline interacts with episodic memory. Specifically, we explored the relation between the mental timeline and temporal binding by assessing American adults' behavioral accuracy, pupil dilation, and gaze movement patterns during a temporal memory task. We found that the spatial presentation of visual stimuli influences cognitive effort during memory encoding and retrieval accuracy during memory retrieval. Our results suggest that the mental timeline supports temporal memory in both the encoding and retrieval phases and may be a powerful strategy for remembering temporal order.

4.5.1 Behavioral results

The behavioral results of our memory task demonstrate that memory for the temporal order of items presented incongruent with the mental timeline (e.g., right-to-left or nonlinear) was significantly worse than those presented congruent with the mental timeline. These results replicate the previous findings by Pathman and colleagues (2018) and are consistent with their findings that items presented congruent with the mental timeline provide a benefit for recalling temporal order. Further, participants' incorrect response patterns suggested confusion due to the incongruence (or an expectation of congruence) with the mental timeline.

Our analysis of incorrect responses indicated that for items presented incongruent with the mental timeline (e.g., from right to left), participants became more likely to confuse its order with the order implied by its spatial location (e.g., mistakenly recalling the item presented first that appeared on the right as being presented third). Because these mistakes suggest that participants recalled the spatial location of the items even when they failed to recall the temporal order, these results also support previous findings showing that, unlike temporal memory, memory for locations is not influenced by trial direction (Pathman et al., 2018). Overall, this pattern of results suggests that one reason why people may have more difficulty when remembering the temporal order of items presented incongruent with the mental timeline may be due to a stronger memory for the spatial location of the item, and the strong association between the mental timeline and temporal order.

4.5.2 Pupil dilation during triplet encoding

We analyzed pupil dilation over two periods of interest. First, we explored participants' pupil dilation during the initial viewing of the triplet images, in which participants actively encoded the information presented in the trial. Participants showed larger pupil dilation responses to trials that were incongruent with the mental timeline relative to trials presented from left-to-right during this period. These differences were present for analyses comparing changes in pupil dilation over the full analyzed time course but not when exploring the mean and maximum pupil dilation values during this period. These results suggest that the cognitive processes while encoding the images were different across these trial types. For example, although overall pupil dilation was not higher in any trial direction when assessed by the mean or maximum dilation values, the peaks occurred at different times within the trial. For trials presented from left-to-right, participants experienced a peak after the first image, after which the relative dilation consistently decreased until after the third image was displayed. One reason for the different patterns in pupil dilation across different trial directions may be due to the relative difficulty of encoding the temporal and location information presented in the trials. In general, greater pupil dilation frequently corresponds to greater cognitive effort and greater information maintained in working memory (Hess & Polt, 1964; Kahneman & Beatty, 1966). The pattern of peaks in pupil dilation across the different trial types suggests that while the relative difficulty of encoding the images decreased in left-to-right trials throughout image presentation, participants had to increase engagement throughout the trial to encode the temporal order presented in right-to-left and nonlinear trials. These results suggest that participants had to exert the least effort to encode information when the triplets appeared linearly, from left-to-right suggesting one reason the mental timeline may provide temporal memory benefit may be through an easier encoding process for trials presented congruent with the mental timeline relative to trials that are incongruent.

Another reason for the changes in pupil dilation may be due to surprise. For trials presented from right-to-left, participants demonstrated a larger initial peak, and for trials presented nonlinearly the largest peak occurred after the second image was displayed. Importantly, while the linear trials were always presented in the same configuration, there were four different configurations in which the nonlinear trials were presented, making them the most unpredictable. Because surprise can induce pupil dilation response (Preuschoff et al., 2011), one reason for the observed differences may be due to the predictability of the presentation of the images within a trial.

4.5.3 Working memory maintenance

Next, we explored the mask period, which is a 2000 ms period after the offset of the third triplet image. Because each encoding trial included a second viewing of the images in which participants decided whether the first and second presentations were the same or different, this period may be reflective of memory maintenance and other supportive cognitive processes (e.g., rehearsal, verbal encoding) related to triplet encoding, which may arise later due to slow pupillary responses (Mathôt & Vilotijević, 2023). The pupil dilation patterns observed during this period differed from those observed during the triplet viewing period. After viewing the first set of triplet images, participants showed a smaller pupil dilation response to trials presented nonlinearly, relative to those presented linearly (e.g., left-to-right, right-to-left). One reason for this may be the relatively lower amount of information maintained for nonlinear trials. While encoding difficulty and surprise during the triplet viewing resulted in higher pupil dilation for the image viewing period, because phasic pupillary responses increase as the number of items maintained in working memory increase (Unsworth & Robison, 2018b), lower pupil dilation values for nonlinear trials during the period in which participants maintained the triplet in memory suggests participants retained a lower amount of information in working memory for nonlinear trials relative to trials in which the triplets were presented linearly.

4.5.4 Pupil dilation and memory accuracy

Our initial hypothesis was that higher pupil dilation values during encoding would predict memory accuracy during retrieval. However, we did not find a relation between pupil dilation during encoding and memory accuracy in any of the analyses. Previous research suggests that higher dilation predicts better subsequent memory due to higher cognitive effort and attention (Micula et al., 2022; Papesh et al., 2012). One reason this pattern did not emerge in our results may be due to the relative difficulty of the different trial types. Participants showed higher pupil dilation while encoding the trials incongruent with the mental timeline, potentially showing increased effort to encode the items in these trials. However, because these trials were also more difficult to recall and therefore had lower accuracy, these effects may have counteracted each other.

4.5.5 Gaze movements at retrieval

We predicted that if participants reorganized the temporal order in terms of the mental timeline, they would make gaze movements congruent with this representation such that they would look more towards the left for items presented first and more towards the right for items presented third. We found that participants' gaze patterns revealed their recall of the spatial location of the items, and to a lesser extent, their temporal order. Overall, participants made gaze movements congruent with the spatial location of where the images were presented during the encoding phase, for example, looking to the right for items that were presented on the right side of the screen. Participants also looked more to the right when recalling items presented second, relative to those presented first, though this pattern did not extend to items presented third in the triplet.

One reason that gaze patterns reflected spatial locations more than temporal order may be the salience of spatial memory. For trials recalled correctly, participants' gaze patterns did not suggest a reorganization of temporal order congruent with the mental timeline (e.g., for images presented first, second, and third, relative gaze locations oriented on the left, middle, and right). However, participants showed gaze patterns congruent with the spatial location of the images, such that for images encoded left, middle, and right sides of the screen, their gaze patterns at retrieval were oriented more to the left, middle, and right sides of the screen, respectively. Because participants' gaze movements are congruent with the spatial locations, and to a lesser extent the spatial organization of temporal order, these results suggest that the participants may be recalling the location in which they saw the images to reconstruct the memory of viewing the images to recall temporal order, rather than mentally reorganizing the images in terms of the mental timeline to then use as a reference for temporal order. Previous research suggests that spontaneous gaze movements can reveal episodic reconstruction of visuospatial stimuli (e.g., Altmann, 2004; Brandt & Stark, 1997; Johansson & Johansson, 2014). In these studies, participants recalled previously encoded stimuli with visuospatial properties (e.g., scenes of characters engaging in different activities, and relations between objects arranged on a screen). When participants recalled this information during test, their spontaneous gaze movements while viewing a blank screen indicated eye movements to the locations congruent with the recalled information. These results suggest that eye movements to the location of the encoded information can help reconstruct the memory and aid recall (Johansson & Johansson, 2014).

Because the memory question was related to temporal rather than spatial memory, and because temporal order implied by spatial location was not always congruent with typical depictions of temporal order (e.g., left-to-right for our sample), we had predicted that the gaze movements we observe in this task would be similar to those observed in tasks in which gaze movements depicted a spatial organization of non-spatial information (e.g., Chrabaszcz et al., 2024; Martarelli et al., 2017; Viganò et al., 2024). In these tasks, unlike our task, participants were tested with test items presented auditorily while viewing a blank screen, and the stimuli did not include encoded information with explicit spatial characteristics (e.g., words spoken in past or present tense, color words, number words). In these studies, participants' eye movements revealed mental organization of these domains that do not have explicit spatial properties (e.g., organizing smaller numbers on the left side and later numbers on the right side, representing earlier events on the left side and later events on the right side). However, the strength and salience of the spatial information in our task might have instead favored eye movements to the locations of the retrieval items. Overall, our results support previous findings suggesting that memory for the spatial location of items is more robust than memory for their temporal order (Pathman et al., 2018) and suggest that spatial location is a salient cue spontaneously used for remembering temporal order.

The task instructions in this study may also have influenced the observed patterns in gaze movements. To be consistent with the original study, we asked people to pay attention to both the spatial location and the temporal order of the items presented during the encoding phase. In the future, an interesting avenue of research could be to explore whether asking participants to focus on only temporal order would yield different gaze movement patterns suggesting different strategies for recalling these two dimensions.

Despite the broader patterns present in these results, participants demonstrated high variability in their memory accuracy. Some participants were highly accurate, and some performed poorly in remembering the temporal order of images presented in all three trial directions. Future studies could explore how individual differences in memory (e.g., working memory and spatial memory) and differences in strategy use may influence differences in how participants may be using the mental timeline to recall temporal order. Further, future studies could aim to control participants' engagement with the task more strictly.

4.6 Conclusions

The overall goal of this research was to improve our understanding of how the mental timeline interacts with the encoding and retrieval of temporal information. Our results replicated previous results in demonstrating that adult participants in the U.S. most accurately recalled the temporal order of previously encoded items when these items were presented congruent with the mental timeline. This memory advantage for recalling the temporal order of items presented congruent with the temporal order was evident in other measures we explored. First, participants' pupil dilation patterns during the encoding phase also demonstrated they had to allocate greater cognitive resources when encoding trials presented incongruent with the mental timeline and maintained less information in their working memory for the nonlinear trials immediately following image presentation. Next, participants' gaze movements during the retrieval phase suggested that they primarily reconstructed the encoded information by reconstructing the spatial information, rather than demonstrating a mental reorganization of the items in terms of the mental timeline. Finally, participants' recall errors indicated their strong associations between the spatial location of an item and implied temporal order consistent with the mental timeline. These results suggest that one reason why the mental timeline may provide a memory benefit for temporal order may be because spatial cues provide a benefit for encoding temporal order with lower effort and recalling it with higher accuracy. Overall, these results suggest that the mental timeline is a spontaneously used memory strategy that allows leveraging the more easily remembered spatial cues to aid the recall of temporal order.

Chapter 5. General Discussion

5.1 Chapter summaries

Using space to represent abstract domains is a cognitive tool that has been invented in many cultures and has been used for centuries (de la Fuente et al., 2014; Le Guen & Tuz Baas, 2024; Mallery, 1893; Richland, 2015; Tversky, 2001). The studies presented in the empirical chapters of this dissertation have contributed to the larger body of research demonstrating that spatial representations of abstract concepts contribute to our ability to reason about them.

Specifically, these chapters explored how the emergence and development of linear representations of temporal order benefit temporal binding in infancy, childhood, and adulthood.

In early childhood, there seems to be a co-occurrence between when children experience rapid growth in temporal memory and when they start developing the mental timeline (Ngo et al., 2019; Tillman et al., 2018). The first empirical chapter explored whether the mental timeline functions as a mnemonic device that supports the development of temporal memory. To address this question, I explored whether individual differences in the development of children's mental timeline representations are related to their temporal memory abilities. The results demonstrated that among children 5 to 6 years of age, the development of linear mental representations predicted memory for temporal order: children who spontaneously represented time linearly had significantly better temporal memory, but not spatial memory, than children who represented time nonlinearly. These results suggest that 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. These findings also demonstrated that among children aged 5 to 6 years, there exists remarkable variability in the degree to which children are representing time linearly, indicating that this age range might be a fruitful point of intervention.

The second empirical chapter examined whether associations between the domains of time and space in infancy extend to linear representations of temporal order and, specifically, whether linear representations of temporal sequences are beneficial for learning temporal order at 6 months of age. Previous studies have demonstrated that infants have capacities for episodic memory (for a review, see Bauer, 2004), can detect and generalize patterns from novel abstract stimuli (Bulf et al., 2017; Koch et al., 2020; Rabagliati et al., 2019), and can access the functional overlap between the domains of space and temporal duration (Srinivasan & Carey, 2010). However, no study assessed whether spatial cues could facilitate temporal memory in infancy. In this chapter, results from two studies conducted in two countries with different stimuli and methods showed that there may also be an early emerging, intuitive mapping between space and temporal order before extensive experience with cultural artifacts, and infants can access and take advantage of linear spatial cues to remember temporal order.

The final empirical chapter explored how adults activate the mental timeline online while encoding and retrieving temporal order in a spatiotemporal memory task. Previous studies suggest adults and children over 7 years of age demonstrate a strong memory advantage for remembering the temporal order of items when those items were presented in spatial configurations congruent with the mental timeline, relative to when they were incongruent with the mental timeline (Pathman et al., 2018). The current study explored adults' pupil dilation and gaze movements in addition to behavioral measures, to further our understanding of how the mental timeline interacts with memory encoding and retrieval processes. The behavioral measures replicated previous results, showing that adults are most accurate in recalling the temporal order of items presented congruent with the mental timeline (linear, left-to-right for this sample). Participants' pupil dilation patterns suggested that adults allocated greater cognitive effort when encoding items presented in spatial configurations incongruent with the mental timeline, and the results from the gaze analyses suggested that participants predominantly reconstructed the spatial positions of the items presented even when recalling the temporal order of items. Further, participants' incorrect responses demonstrated that the stronger recall of spatial locations made them more likely to incorrectly recall the temporal order implied by the spatial location of an item (e.g., mistakenly recalling an item was presented first if it was presented on the left). Overall, these results suggest that the temporal memory benefit from spatial cues presented in terms of the mental timeline may be due to both increased difficulty during the encoding phase and the salience of the spatial cues contributing to errors during the recall phase.

5.2 Synthesis and future directions

All three empirical chapters in this dissertation explored the link between representing time and, in particular, temporal order in terms of space and why such a representation is beneficial for memory. One potential implication of these studies is related to using the mental timeline as a strategy to support episodic memory. In the future, this work can be expanded by exploring whether mental timeline representations could be used to improve temporal memory abilities in children and adults. Results from Chapter 2 suggest that young infants benefit from spatial cues presenting temporal order linearly when learning a temporal sequence before they have experience with cultural artifacts. These results suggest that young children may also benefit from such cues, even before they explicitly start representing temporal order linearly. For example, future work could explore whether priming the use of a linear mental timeline through explicit interaction with external timelines could encourage children to use spatial representations as a strategy to encode and retrieve temporal information, and in turn, boost temporal memory performance. Similarly, future work could explore whether explicitly prompting adults to use the mental timeline as a memory strategy would provide benefits for temporal memory. Previous studies suggest that episodic binding abilities are slower to develop in childhood (Hayne & Imuta, 2011; Lee et al., 2016) and may be quicker to deteriorate in older adulthood (Kessels et al., 2007; Parkin et al., 1995). Future work could explore whether the use of memory strategies may be particularly helpful for these populations who may have increased difficulty with episodic memory (Shing et al., 2010).

The mental timeline is one way we leverage spatial associations, however, there are many others. In this dissertation, I used the mental timeline and temporal binding as a test case, examined with different methods at different ages, to reveal a piece of a larger intellectual puzzle concerning questions about how spatial mental representations are leveraged as tools for learning, remembering, and reasoning about abstract concepts. Using spatial representations as tools for thinking may be particularly beneficial early in life. Because both our abilities for learning and reasoning about abstract domains and our tendencies for forming and spontaneously leveraging spatial representations to aid thinking develop gradually in early childhood (e.g., Gunderson et al., 2012; Miller et al., 2020; Starr et al., 2020; Tillman et al., 2018). Given the relatively slow development of abstract thinking abilities and the central role of these abilities in various cognitive processes, it is important to understand the factors influencing and supporting developmental periods during which we form and strengthen representations of abstract concepts. Understanding the contexts in which different skills and strategies may be particularly beneficial for abstract thinking skills may illuminate potential methods to facilitate abstract thinking and inform how we may support these skills at different developmental stages, from infancy to adulthood.

Decades of work suggest that promoting spatial thinking can aid children's abilities to attend to and learn about spatial representations (e.g., Gentner et al., 2013; Ishikawa & Newcombe, 2021; Miller & Simmering, 2018; Pyers et al., 2010). This line of research has identified promising avenues for intervention, however, there is still much to discover about effectively supporting abstract thinking. This includes gaining a more comprehensive understanding of factors influencing the development of various spatial skills and the mechanisms through which they aid abstract thinking. This work should include both differences in cognitive factors, such as varying abilities in visualization, working memory, and language skills, and environmental and cultural effects, such as familiarity with written text and experiences in formal schooling. For example, in the second empirical chapter of this dissertation, children showed great variability in their development of linear representations of temporal order, suggesting there may be quite a lag between when children start to create linear timelines and when they consistently create timelines congruent with the culturally conventional orientation. Focusing on individual-level data, such as children's exposure to and experience with written text, could help us better understand this variability (Autry et al., 2020).

More broadly, understanding the factors contributing to early differences in children's spatial and abstract thinking abilities could help us devise ways to aid children in forming and using these spatial representations. However, the mechanisms that drive early individual differences in abstract thinking abilities and the development of spatial skills are rather elusive. For example, Gunderson and colleagues (2012) explored 5-to-8-year-old children's number line knowledge by assessing their ability to accurately place various numbers between 0 and 1000 on a line (e.g., representing the number 780 on the line). They found that the individual differences in number line knowledge predicted children's abilities to perform approximate symbolic calculation tasks (Gunderson et al., 2012). The authors discussed two possible reasons for this relation between developing linear number line representations and better performance in the approximate symbolic calculation tasks: one is that children with stronger spatial skills can better translate their understanding of numbers to a linear number line representation, and another is that children with stronger spatial skills may be better able to remember and mentally represent the mental number line they may have learned in school, thus having an advantage in leveraging this representation. It is also possible that both mechanisms contribute to the early individual differences in children's mental number lines (Gunderson et al., 2012). In the future, longitudinal studies using similar assessment tools across ages may help clarify the specific factors and mechanisms that influence early spatial development.

Studies examining other predictors of spatial skills, such as socioeconomic status, gender, and experience playing with spatial toys, provide insight into how environmental input interacts with spatial skill development (Levine et al., 2012). Children from low socioeconomic backgrounds are typically disadvantaged in spatial skills relative to their peers from higher socioeconomic backgrounds, and girls are disadvantaged in some, but not all, spatial skills relative to boys (Levine et al., 2012; Newcombe, 2020). Various factors contribute to these differences. For example, financial hardship may decrease parents' child-directed speech (Ellwood-Lowe et al., 2022) and parents may tend to engage boys in spatial play both more frequently and with better quality, relative to girls (Jirout & Newcombe, 2015, Levine et al., 2012). Research examining structural factors such as parental financial stress, access to spatial toys, cultural gender expectations, and spatial skill development can shed more light on the cultural and environmental factors influencing early individual differences in spatial skills and identify targets for intervention. Further, it is important for future work to assess whether such interventions differentially benefit individuals based on their varying abilities in visualization, working memory, executive function skills, spatial language skills, and relevant experiences, such as experience with navigating their environments. For example, previous findings from an intervention study exploring spatial sex differences conducted by Terlecki and colleagues (2008) suggest that women who had low levels of pre-existing spatial experience demonstrated slower growth in their spatial skills in response to the intervention, relative to women who had higher levels of pre-existing experience (Terlecki et al., 2008). Identifying the mechanisms by which interventions may target different skills is therefore crucial for designing interventions to benefit all children. Finally, it is vital to clarify the durability and transferability of intervention effects and identify the conditions under which these efforts are effective.

Finally, much of the work exploring the development of abstract thinking abilities could benefit from exploring ways in which abilities such as representing temporal order, numbers, or abstract relations between entities, can be assessed with similar task demands across various developmental stages. For example, in the second empirical chapter of this dissertation, it was noted that because prior studies probing the development of the mental timeline have all required explicit responses, the origins of the mental timeline had not been explored in infancy. Although this dissertation explored the interaction between the mental timeline and temporal memory in three age groups, the methods and task demands were different across the three groups, and therefore, these studies explored slightly different aspects of the mental timeline and temporal memory. In the future, using nonverbal paradigms with pupillometry and eye-tracking measures could be a promising avenue for research exploring continuity and change across development. This approach could further clarify the influence of age-related and cultural influences.

5.3 Conclusions

The empirical chapters in this dissertation demonstrated that spatial representations of temporal order support temporal memory in infancy, early childhood, and adulthood. The data from these chapters suggest that one reason the mental timeline is a ubiquitous way in which people across the world represent temporal order is that it is functionally advantageous for encoding and remembering temporal order. More broadly, these findings suggest that one reason why spatial skills are strongly related to abstract thinking abilities may be because spatial references support the ability to both represent and operate on abstract concepts.

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