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Memory for space and time in 2-year-olds

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ABSTRACT

Although the capacity to remember spatial and temporal information may develop at different rates throughout childhood, its early development has rarely been examined within the same participants, using the same task, and across different time delays elucidating retention of different aspects of early episodic memories. We used a novel tablet game to investigate memory for objects' spatial locations and temporal order in a sample of toddlers ranging in age from 2 years to 2;8 years ($M = 2;4$ years, $SD = 2$ months; $N = 73$). We examined performance both immediately after an initial and an additional demonstration, following a 20-minute delay, and 1 week after learning; performance was also assessed following a new demonstration after the 1-week delay test. Using a linear mixed model, we found that toddlers remembered spatial locations better than temporal order, and temporal memory decayed more quickly and did not benefit from reminders compared to spatial memory, underscoring that early memory fragility may depend on the type of information being retained.

1. Introduction

Early childhood is a period of rapid learning and knowledge expansion (Atherton & Nutbrown, 2013; Bauer et al., 1999; Rowe et al., 2012). During this period, the emergent capacity to recall prior experiences begins to support children's ability to explore and learn about their environment (Gopnik, 2020) as well as share their experiences (Nelson & Fivush, 2004). Episodic memory, or the ability to recall specific events, involves retaining memory for the spatio-temporal context in which they occurred (Eichenbaum, 2017a, 2017b) and it has been argued that its early development may support the capacity to accumulate and share knowledge (e.g., Bauer, 2021). To date, there is a paucity of studies with children between 2- and 3-years of age examining retention of both spatial and temporal details within the same individuals and within a single task to enable a direct comparison of memory for these details. Moreover, no studies have examined 2- and 3-year-olds' retention across multiple delays. These are significant limitations in the current literature because important improvements in memory are expected at the transition from infancy into childhood, and these differences may depend on the nature of the information being recalled.

A direct comparison of toddlers' capacity to form and retain spatial and temporal associations within the same task provides an

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avenue to elucidate the early development of associative components of episodic memory. Research in children older than 3-years shows that memory for spatial information may emerge earlier and develop faster, reaching adult-levels earlier than memory for temporal order (Lee et al., 2016; Pathman et al., 2018a), suggesting the prediction that the emergence of memory for temporal order in early childhood (e.g., <7 years) may be delayed compared to memory for spatial context. Although evidence contrasting this prediction has also been reported, such that spatial memory exhibited a more protracted development from childhood into young adulthood (Guillery-Girard et al., 2013), there were differences in cognitive demands between the tasks used to assess each memory type, making it difficult to make direct comparisons between these two aspects of memory content. Nevertheless, there is evidence of memory for spatial context (Newcombe, 2019), as well as memory for temporal order (Bauer & Leventon, 2013; Bauer & Lukowski, 2010) in infancy, which suggests the capacity to remember spatial and temporal aspects of an event may emerge at the same time. Thus, it is unclear whether an advantage of spatial over temporal memory would be evident in early development. Hence, the goal of the present study is twofold. First, we sought to examine memory for events and their association with spatial and temporal context within a single task, as well as to assess these associations over varying delays. Second, we sought to examine whether spatial and temporal memory performance on our task (adapted from Prabhakar & Ghetti, 2020) showed similar results to a previously validated assessment after multiple delays to establish whether the results converge with tasks with different motor demands.

1.1. Memory for spatio-temporal context

A nascent ability to retain spatial and temporal information regarding an experience can be detected in infancy (e.g., Bauer et al., 2000). With regard to memory for spatial information, Richmond et al. (2015) reported that during memory test trials, even 9-month-old infants looked longer at the two objects that had switched their spatial position from the encoding phase (relative to a third object that remained in the original position), indicating recognition of spatial novelty and memory for the initial positions. However, 9-month-olds showed this result only if sufficient exposure was allowed during study, otherwise only older infants (e.g., 18-month-olds) responded to the location switch with their looking behaviors. These results underscore encoding constraints to learning item-space associations in the first year of life. However, even after the first 12 months of life, toddlers show difficulty recalling memories encompassing arbitrary item-space context associations if they are tasked with remembering more than one single object-location association. For example, in a study requiring toddlers to remember in which of 4 containers a toy in one room was hidden and in which of the same 4 containers a toy was hidden in a second room (Newcombe et al., 2014), 15- to 20-month-olds did not remember the unique association between toy and container (i.e., one container hid the toy in one room and another container hid the toy in a different room, and not the other way around). Toddlers aged 21- to 26-months could recall which specific toy went in which specific container in each room only when parts of the toy were provided to cue the memory, while the older toddlers (between the ages of 34- and 40-months) performed significantly above chance on the same task without needing any cues. In another line of research, toddlers as young as 18-months accurately retrieved toys hidden across several locations in two different rooms, but not if those locations lacked visual cues differentiating them (Ribordy et al., 2013). At approximately 25-months or later, toddlers could identify the correct location of a previously hidden toy without a local cue, but only if one object was hidden in one of the locations as opposed to a different toy hidden in each location, and at 43-months they were able to recall multiple objects' locations without any cues (Ribordy et al., 2013). Finally, using functional neuroimaging methods to determine possible neural explanations for spatial memory abilities in toddlerhood, Prabhakar and colleagues (2018) demonstrated correlations between toddlers' accuracy in their recall of which room (out of two) they had encountered a novel song and hippocampal activation for the same songs in 25- to 32-month-old toddlers. Overall, this literature suggests that at about 25-months of age, toddlers may be able to form and retain memories for unique object-spatial location associations, when more than one object and more than one location are encountered. However, difficulties persist if more than one such association is being learned. Overall, this research suggests that toddlers rapidly improve their spatial memory abilities as they age and develop. Between 24 and 36 months, toddlers are successful at recalling unique associations between objects and spatial locations, even after delays (Newcombe et al., 2014).

Despite clear evidence of spatial memory between 24- and 36-months, its development continues to improve in childhood. Between 3.5- and 7-years, children show improved ability to retain multiple associations and locate 3 hidden treats among 18 locations (Ribordy Lambert et al., 2016). Although children who are 5 years or younger make more errors overall, the nature of mistakes was found to differ as a function of age with 6- and 7 year-olds choosing locations that were near the target locations when they made mistakes (instead of choosing previously visited locations), whereas younger children did not show this bias and chose both nearby and previously visited locations equally. Thus, older children not only remember locations better than younger children, but even when they cannot recollect precisely, they may retain an approximate memory for the location which might constrain the types of errors.

The ability to retain item-time associations, including temporal order, may also exhibit some fragility at the transition from infancy to childhood. Infants and toddlers under 32-months can demonstrate action sequences in a given temporal order when those actions are functionally dependent (Bauer, 1992; Bauer et al., 2000). In contrast, fully arbitrary sequences of actions with no functional relation among them pose significant challenge. For example, when faced with one exposure to a non-arbitrary temporal sequence, in which the completion of an action facilitated the completion of the next action, 16- to 20-month-old infants could replicate a given sequence even after a month delay. However, 13-month-old infants required multiple exposures in order to replicate the same sequences at all (Bauer & Leventon, 2013). Early ability to retain arbitrary, non-functionally dependent, temporal associations in which there is no pre-existing or enabling relation among subsequent actions, over a delay, has not been observed until 28-months of age (Bauer et al., 1998). Importantly, Mooney and colleagues (2021) discovered an association between hippocampal activation in response to a previously learned song compared to a novel song and the temporal order of the actions that triggered that song in a touchscreen table game in 24- to 32-month-old toddlers; this finding underscores that hippocampal function can support temporal

memory at this age. The role of the hippocampus in retaining temporal associations between sequences of actions during deferred imitation has been established with studies of amnesic patients (McDonough et al., 1995). As is the case for memory for spatial details, temporal memory continues to improve beyond the age three, including marked improvements between 3 and 4 years of age (e.g., using the same task employed in this study; Prabhakar & Ghetti, 2020) and beyond (Loucks & Price, 2019; Pathman et al., 2018b; Pathman & Ghetti, 2014).

Overall, these results suggest that although memory for spatial and temporal information shows vast improvement during middle childhood, 2- and 3-year-olds demonstrate the ability to retain arbitrary information about spatial and temporal context. These early capacities may reflect sufficient integration of the dentate gyrus and CA3 into the hippocampal circuitry (Insausti et al., 2010; Lavenex & Banta Lavenex, 2013), which are responsible for precise and flexible episodic memories (Demaster et al., 2016; Ghetti & Fandakova, 2020; Lee et al., 2014).

To date, almost no studies with children younger than 36-months have examined arbitrary spatial and temporal associations using the same paradigm to test the two components within a shared learning scenario. One exception is the study conducted by Burns and colleagues (2015) involving the comparison of memory for 2D vs 3D stimuli. In this study, toddlers between 24- and 41-months of age learned a spatio-temporal sequence in which individual characters were matched with individual hats (what-what associations), with boxes (what-where associations) and with the order in the sequence they were acted upon (what-when associations). They found that children performed above chance across ages and type of layout and that only older children in the 3D task tended to remember the events configurally (remember what-where-when or nothing) underscoring a later emergence of integrated memory representations. The trajectories of memory retention for spatial and temporal features across multiple delays were not examined in this study, preventing conclusions as to whether even a subtle fragility of one component of memory representations may delay the emergence of configural memories.

These abilities may develop and emerge together but may likely have dissociable developmental trajectories observed in spatio-temporal associative abilities in older children (7- to 11-years; Lee et al., 2016, 2020). Measuring memory for spatial and temporal associations within the same task and assessing the components of success in an incremental rather than all-or-nothing fashion, will allow for a direct comparison of these abilities during toddlerhood. The retention of arbitrary associations is present during this period, but the developmental trajectory is unclear.

1.2. Memory across delays

The retention of spatial and temporal associations over a delay has been assessed substantially with very young children. There is a wealth of evidence that robust forgetting is experienced from infancy through early childhood (e.g., Bauer, 2005). The rate of forgetting in toddlerhood decreases with age and memory can be retained for longer durations. In a study with 16- and 20-month-olds, toddlers required only one exposure to replicate an imitation sequence after a delay of one month, while 13-month-olds required multiple exposures. Additionally, Bauer and colleagues (1998) found that it was not until 28-months of age that toddlers could retain and reproduce arbitrarily ordered actions immediately as well as after a two-week delay. In a similar line of work, Saragosa-Harris and colleagues (2021) found evidence that associative memory accuracy increases from ages 3 to 5 years across delays, but the age differences were even greater when examining them at the one-week delay, consistent with the idea that younger children experience more forgetting (see also Benear et al., 2021; Scarf et al., 2013 for additional evidence of age-related differences in forgetting). While there are substantial age-related differences in memory retention over delays, it is still unclear whether retention over delays differs as a function of the type of information, including spatial and temporal. A better understanding of differences in memory decline as a function of detail would provide new insight into the nature of memory content and experiences in young children.

Although there is clear evidence of strong forgetting in toddlers under 24-months, it remains uncertain the extent to which apparently forgotten memories may still benefit from re-learning as suggested by saving effects (Cornell, 1979; Morgan & Hayne, 2006). Savings effects are observed when individuals require fewer repetitions to achieve a certain level of learning if some retention persists than when they initially learned something (Ebbinghaus, 1885). Savings in memory are speculated to occur through an integration of the memory formed through relearning with a previously formed, but partially inaccessible, residual memory trace (Isurin & Seidel, 2015). It has been argued that there are greater benefits of re-learning in toddlers over 18-months, which suggests that while memories may be more likely to be lost in infancy, they may become less accessible in toddlers whose memory traces may persist in some form (Bauer, 2005). However, it is currently unclear whether the opportunity to relearn equally benefits retention of spatial versus temporal information. If an advantage is observed in the retention of spatial versus temporal information, it is also possible that memory for spatial detail would benefit more from relearning. Alternatively, if hypothesized difficulties with long-term retention of temporal information are due primarily to a retrieval failure (as opposed to a storage failure), then re-learning may be particularly beneficial for temporal information.

1.3. The present study

The primary goal of this study was to examine memory for spatial and temporal information within the same task and posing similar demands. We also sought to investigate the impact of delay and re-learning on memory for spatio-temporal information. We adapted a task from Prabhakar & Ghetti (2020), which was also used in Mooney et al. (2021). This task was developed to measure both spatial and temporal memory and will be compared to recognized associative memory paradigms to establish support for this measure. The task, a Tablet Matching Game, involved toddlers pairing 3 characters on the screen to 3 specific locations in the correct temporal order, following a demonstration. This task yielded a measure of spatial memory (determined by the number of correct spatial

locations) and temporal memory (measured by the number of characters moved in the correct order). Two versions of the task were administered to each toddler in order to maximize trial numbers. Additionally, we administered an Imitation Puzzle Task, which also required remembering how to assemble a puzzle by placing its 3 pieces in certain spatial positions and a given order. This is a previously validated task to assess memory for temporal order in toddlers as young as 18 months (Barr et al., 2016; Dickerson et al., 2013), but we sought to extract a measure of spatial memory as well in order to compare the pattern of results in this task to our own.

We expected toddlers to remember spatial locations better than temporal relations and that longer time delays would result in disproportionately greater loss of memory for temporal order compared to spatial position, given the extended developmental trajectory of temporal memory. We chose our delay lengths based on those commonly used in the literature. Typically, immediate recall is measured immediately following learning (Bauer et al., 1998), use of a 20-minute delay in the neuropsychological literature has been used as a signature of long-term memory (e.g. Vargha-Khadem et al., 1997), and a week delay requires retention across naturalistic time scales (Bauer, 1996; Bauer & Hertsgaard, 1993). Finally, we proposed two alternative expectations regarding savings. If temporal memory is disadvantaged due to difficulties with integration and retrieval, it may benefit more from re-learning compared to spatial information that is more easily retrieved. However, if the development of spatial memory is more advanced, it may benefit more so from relearning compared to temporal memory.

2. Methods

2.1. Participants

We assessed 73 typically developing toddlers ($M = 2;4$ years, $SD = 2$ months; Range = 2 years to 2;8 years; 58 % Females). Participants included toddlers who were White ($n = 46, 63.1\%$), African American/Black ($n = 3, 4.1\%$), Asian/Asian American ($n = 3, 4.1\%$), Multiracial ($n = 12, 16.4\%$), and of unreported ($n = 9, 12.3\%$) racial backgrounds; as for ethnic background, the sample

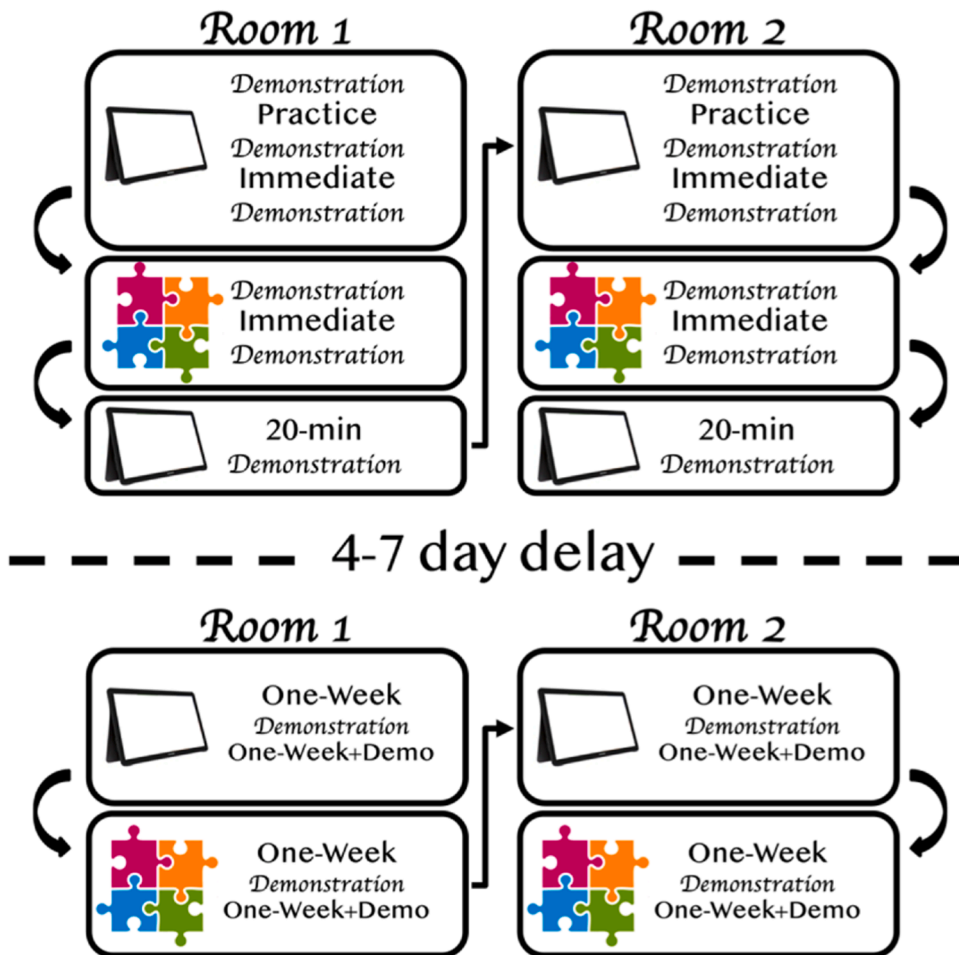


Fig. 1. : Procedure Overview. Participants completed four trials (immediate, 20-minute delay, one-week delay, one-week delay+demonstration) of the Tablet Matching Game and three trials (immediate, one-week delay, one-week delay+demonstration) of the 3-piece Imitation Puzzle Task.

included 23 (31.5 %) Hispanic/Latinx toddlers, 40 non-Hispanic/Latinx (54.8 %) toddlers, and 10 (13.7 %) unreported. Parental income was also reported as ranges of \$15,000 – \$25,000 ($n = 2$; 4.9 %), \$25,000 – \$40,000 ($n = 4$; 6.6 %), \$40,000 – \$60,000 ($n = 9$; 14.7 %), \$60,000 – \$90,000 ($n = 20$; 24.6 %), over \$90,000 ($n = 31$; 44.3 %), and unreported ($n = 7$; 4.9 %). Participants were recruited from community events or through a database of families contacted after childbirth and consented to be contacted about potential research participation. Toddlers were given a few books for their participation. Data collection was completed at the same time as data collection for Mooney et al. (2021), which employed the same task. None of the toddlers participating in this study were included in this previous study.

3. Materials and procedure

The experimental procedure included two laboratory visits. These visits were scheduled to be one week apart, $M = 6.12$ days, $SD = 1.60$ (See Fig. 1).

Session 1. During Session 1, toddlers first visited one room where they completed one version of the Tablet Matching Game, which involved learning to input a sequence of actions on a tablet to achieve a goal (turn on a song). The sequence required remembering the location of certain characters and the order with which they were placed at that location. The Tablet Matching Game began with the toddler being shown how to select the correct character image from an array of three characters (e.g., Astronaut, Doctor) and moving them sequentially, one at a time, to a location (e.g., Slide, School; see Fig. 2a–c). We ensured there was no semantic match between the characters and their locations to prevent semantic knowledge from influencing toddlers' memory (Sipe & Pathman, 2021). The experimenter demonstrated the spatio-temporal sequence without naming the specific objects or locations, but using vague references (e.g., "Let's put this here") to prevent facilitating the performance of toddlers with better vocabulary skills. After toddlers were shown the sequence, they were asked to reproduce it (i.e., immediate – after first demonstration). We informed toddlers that the song would be played if they performed the task correctly, but it was actually based only on accurate spatial recall. Based on extensive pilot data, many toddlers switched the order of two actions and thus failed to reproduce the entire spatio-temporal sequence correctly when they were first taught it. We reasoned that letting the correct spatial position of the character suffice to hear the song (i.e., perfectly spatial matching irrespective of temporal matching performance) would prove helpful in supporting toddlers' motivation to stay on task.

Location recall accuracy was calculated by the number of correctly placed characters out of 3. Since more than one character could be placed in the same location, chance performance was 0.33. Order recall accuracy was calculated as the number of characters chosen in the correct order. Chance performance level once again amounted to 0.33 after accounting for the dependency in temporal order trials. This chance comparison was calculated differently than chance for spatial memory, however, because the toddler's first choice in the sequence determined their possible chance performance and because the third choice entirely depended on the first two choices (i.e., it was impossible to assign the same order to multiple objects). If the first choice was correct, then chance across the task was 0.415 (i.e., the mean of 1/3 in the first trial and 1/2 in the second). If the first choice was the second-choice character, then the second choice was automatically incorrect and chance is 0.167 (i.e., the mean of 1/3 in the first trial and 0 in the second trial). Finally, if the first choice was the third-choice character, then the second choice could be correct or incorrect and chance corresponds to 0.415 (i.e., the mean of 1/3 in the first trial and 1/2 in the second trial). We averaged those three possible chance levels (0.415, 0.167, and 0.415) and determined 0.33 was the average potential chance level. Once the first practice attempt (immediately after first demonstration) was complete, the sequence was shown to the toddler again to provide an additional learning opportunity. After the experimenter completed their second demonstration, there was an immediate testing timepoint for the toddler (i.e., immediately after second demonstration). Together, the experimenter and participant then completed their third demonstration to ensure the toddler was exposed to the correct sequence again regardless of their immediate testing performance. After a delay of approximately 20 min, toddlers were tested on their ability to complete the Tablet Matching Game without a demonstration immediately preceding (20-minute delay). Following this 20-minute delay timepoint, the experimenter once again completed the correct spatio-temporal sequence to ensure the toddler was exposed to the correct sequence regardless of their performance on the delay timepoint, this provided a final learning opportunity at Session 1.

During Session 1, toddlers also completed a 3-piece Imitation Puzzle Task (Barr et al., 2016), which was administered following the third demonstration and before the 20-minute delay test of the Tablet Matching Game. Two different imitation task puzzles were presented (e.g., boat, flower) in each room. Stimuli consisted of 3 abstractly shaped pieces attached via magnets to a magnetic 11" x 14" dry erase board. The pieces were initially placed in three of the four corners of the board, closest to their correct location to facilitate

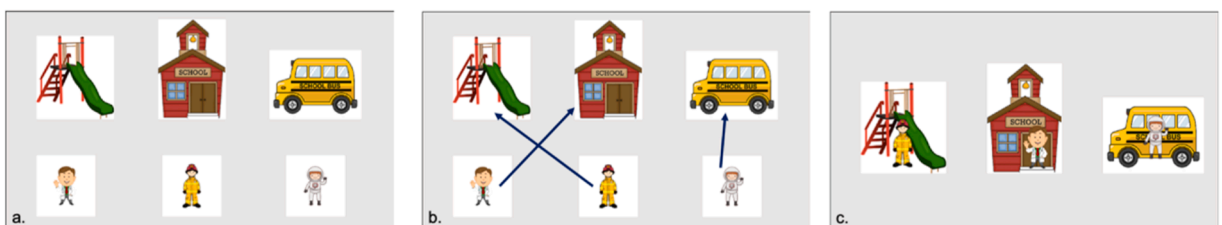


Fig. 2. Character-location matching tablet game. a. Toddlers are shown an array of three professional characters and three arbitrary locations. b. A specific matching procedure is performed in a specific order. c. Characters are matched to their prospective locations.

the toddlers' movement of the magnetic pieces. During Session 1, toddlers were first shown the correct assembly (spatio-temporal order) of each imitation puzzle (see Fig. 3), with the experimenter verbally emphasizing the order that the pieces are selected and moved (e.g., "first, this piece goes here"). Subsequently, toddlers were asked to complete the Imitation Puzzle Task (e.g., "can you show me how to make the puzzle?"; immediate recall), and then a final demonstration of the procedure was performed by the experimenter to ensure equal exposure to the correct sequence of assembly for all participants. Location accuracy recall was calculated as the number of puzzle pieces placed on the correct section of the board. We elected to use this method to assess accuracy, as opposed to the point in which the individual puzzle pieces touched other puzzle pieces (Subiaul et al., 2016) to reduce the motor demands of the task and make it more comparable to the Tablet Matching Game. Results using the original method are reported in the [Supplemental materials](#) (Supplemental Fig. 1). Order accuracy recall was calculated as the correct number of pieces selected in the correct order.

After completing these tasks in the first room, toddlers were given a break before visiting a second room. There, toddlers followed the same procedures of the first room with a new version of the Tablet Matching Game and with two additional puzzles not used in the first room (e.g., train, boat). We counterbalanced across participants which version of the Tablet Matching Game and which puzzles were completed in the first and second room.

Session 2. After reacclimating toddlers with the lab, they once again visited the first room, and completed the Tablet Matching Game after a delay (one-week delay). After they demonstrated their recall, the experimenter demonstrated the correct sequence and toddlers were provided with one more opportunity to complete the sequence (one-week+demonstration).

The Imitation Puzzle Task was completed after the Tablet Matching Game once again and toddlers were initially asked to assemble the puzzle (one-week delay) without first observing a demonstration. After the toddlers' attempt, the experimenter demonstrated the correct puzzle assembly, and then toddlers were instructed to assemble the puzzle one final time (one-week+demonstration). After completing these procedures in the first room, they moved to the second room where they completed the other versions of the task in the same manner. First and second rooms, as well as tasks completed in each room, were the same across Session 1 and Session 2.

4. Results

For the Tablet Matching Game, accuracy rates were calculated for memory for correct spatial locations (i.e., rate of correct placement of characters at the correct location) and memory for temporal order (i.e., rate of correct order with which characters are moved to be placed in locations, regardless of correct spatial matching). We conducted a linear mixed model (see Fig. 4) evaluating the effects of age as a continuum, delay (immediate/after learning, immediately after an additional demonstration, 20-minute delay, one-week delay, and one-week+demonstration), and detail type (spatial location or temporal order). Our model intercept was set at the immediate test after 2nd demonstration and the spatial task was used in the intercept. This was done in order to assess whether differences in memory over time and between task types were reflective of a deviation from the traditionally superior memory type (i.e., location) and ensured sufficient opportunity to encode (i.e., after two exposures). Our mixed model revealed a significant effect of delay, $F(4, 912.58) = 2.46, p = .04$, and of detail, $F(1, 899.71) = 11.14, p = .0009$. This indicates that children perform better on

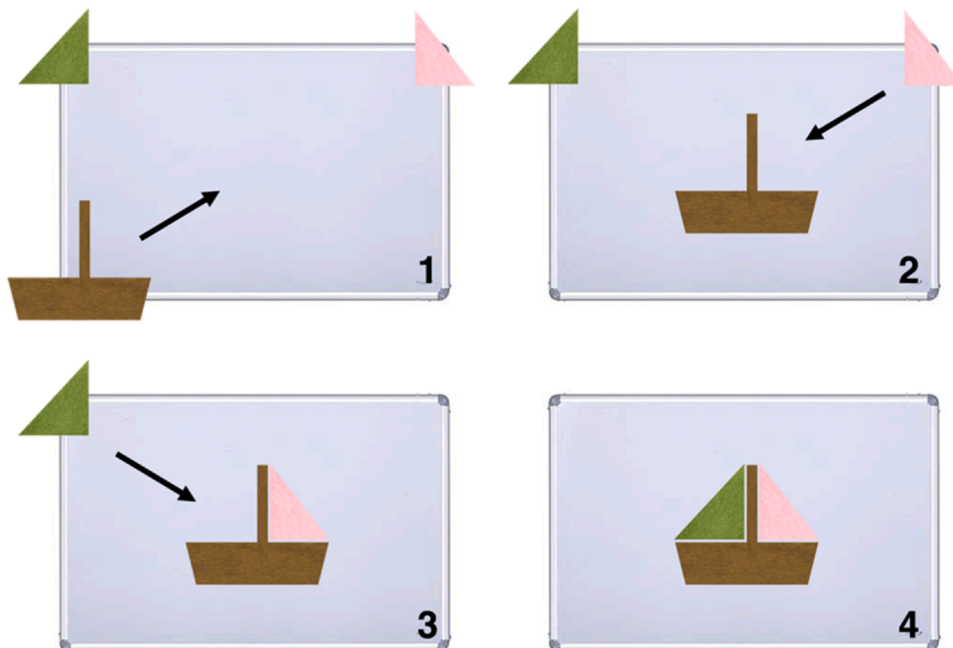


Fig. 3. 3-piece Imitation Puzzle Task. Toddlers are shown a 3-piece puzzle sequence on a magnetic white board with felted magnetic pieces. Complete puzzles represented known objects (e.g., boat, plane, flower, etc.).

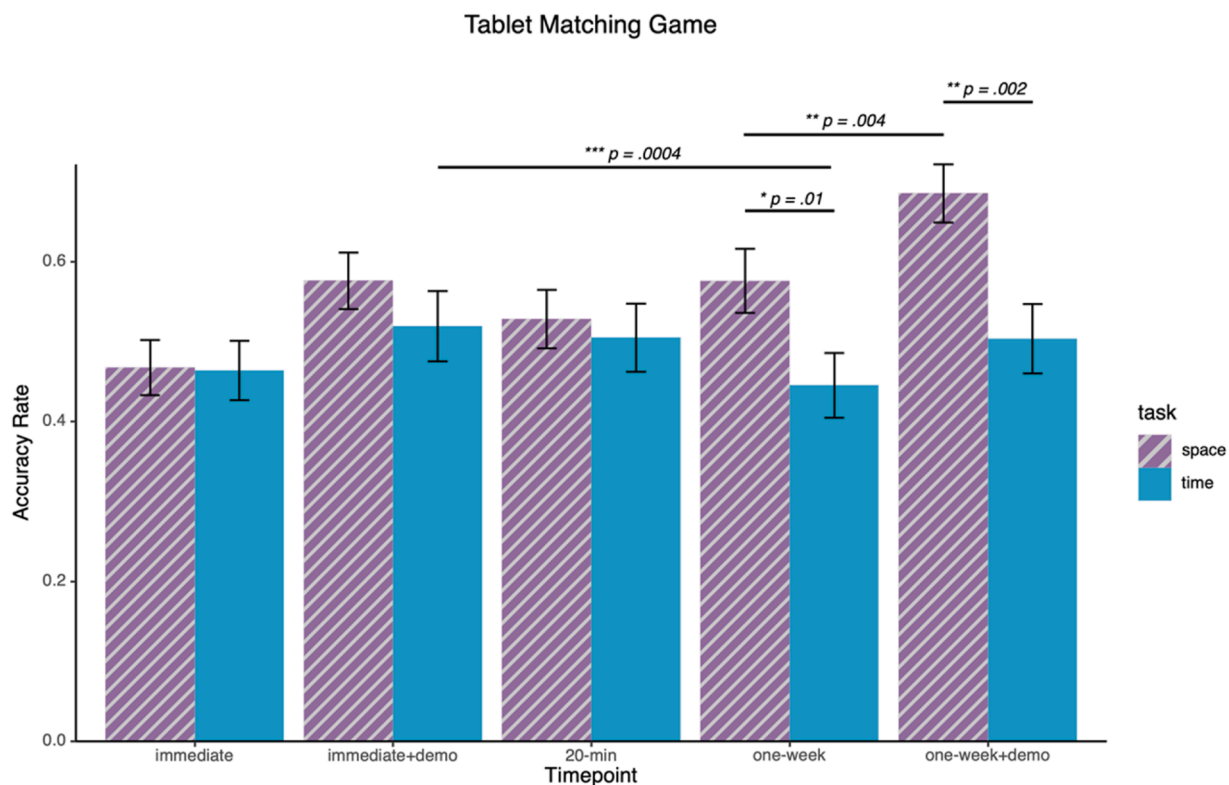


Fig. 4. Tablet Matching Game Accuracy. Results from mixed model. Toddlers performed better on spatial memory details compared to temporal memory details, specifically after a one-week delay. Timepoints consist of: immediate (recall following learning), immediate+demonstration (recall following a demonstration of the correct sequence), 20-min (recall 20 min after learning), one-week (recall one-week after learning), and one-week+demonstration (recall following a final demonstration of the correct sequence).

memory for locations, $M = 0.54$; $SD = 0.37$, than for the order with which individual characters visited the locations, $M = 0.47$; $SD = 0.41$. However, there was also a significant interaction between delay and detail ($F(4, 899.25) = 2.56, p = .037$) that was driven by several findings. First, spatial memory was better than temporal memory only after a delay (one-week delay $t(1901) = -2.59, p = .01$), and after relearning (one-week delay+demonstration; $t(1899) = -3.15, p = .002$), whereas no differences were found in the immediate test, $t(1898) = 0.25, p = .80$, the test following a second demonstration, $t(1896) = -1.25, p = .21$, and in the 20-minute test ($t(1897) = -0.19, p = .85$), suggesting that the advantage of spatial memory is evident only after delay (i.e., one-week delay). Moreover, temporal memory declines significantly from immediate+demonstration to the one-week delay, $t(1908) = -3.53, p = .0004$, but that was not the case for spatial memory, $t(1910) = -0.84, p = .40$.

Finally, there were no differences between the immediate timepoint and at one-week delay+demonstration performance in the temporal portion of the task, $t(1912) = -0.73, p = .47$, yet memory for spatial locations was better after re-learning compared to initial learning, $t(1325) = 2.918, p = .004$, indicating that a reminder after a delay was effective only for spatial details. There was only a non-significant trend of older toddlers outperforming younger toddlers, $F(1, 186.49) = 3.12, p = .08$. Participants performed above chance, on average, across all trials, $t(1972) = 16.39, p < .001$.

Additionally, we conducted a repeated measure linear mixed model evaluating the Imitation Puzzle Task (see Fig. 5). For this task, we investigated spatial proximity only (See supplemental materials for spatial orientation and proximity analyses). Consistent with the previous literature on this task (Dickerson et al., 2013), we investigated approximate location accuracy of pieces as a measure similar to the spatial demands of the Tablet Matching Game and seemingly less difficult in terms of motor demands. The linear mixed model again evaluated the effects of age, delay (immediate, one-week delay, after one-week+demonstration), and detail type (location or order) in the context of spatial proximity. Our mixed model revealed a significant effect of delay, $F(2, 665.90) = 13.86, p < .001$, and of detail, $F(1, 672.10) = 194.88, p < .001$. There was also a significant interaction of delay and detail ($F(2, 663.35) = 4.84, p = .008$). As in the Tablet Matching Game, there was no significant effect of delay for spatial trials ($t(1, 671) = 1.55, p = 0.63$, whereas for temporal order, toddlers performed significantly better at the immediate timepoint compared to the one-week delay, $t(1, 667) = 6.07, p < .001$, and the one-week delay+demonstration, $t(1, 669) = 3.60, p = 0.005$. Unlike the Tablet Matching Game, toddlers remember more about spatial location than temporal order starting from immediate assessment in the Imitation Puzzle Task, $F(1, 194) = 5.95, p < .001$.

Finally, the one-week delay+demonstration memory was not significantly greater than memory at the one-week delay, $t(1, 666) = -2.36, p = 0.17$. The difference between the immediate recall and the one-week delay+demonstration recall indicates significant

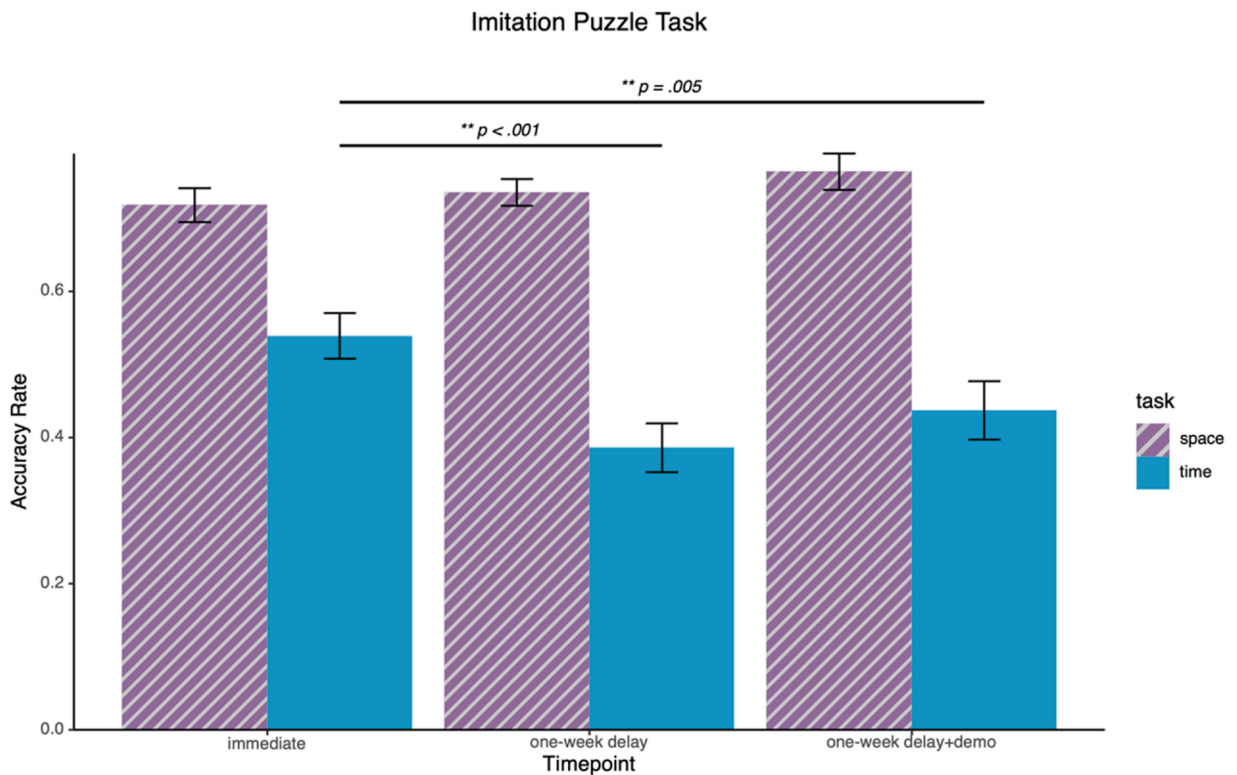


Fig. 5. Graph of Imitation Puzzle Task. Results from mixed model. Toddlers performed better on the immediate recall, than on either the one-week delay or one-week delay+demonstration. Toddlers also performed better on location accuracy than on temporal order. Timepoints consist of immediate (recall following learning), one-week (recall one-week after learning), and one-week+demonstration (recall following a demonstration of the correct sequence).

temporal memory decline across delays that does not benefit from reminders or savings.

In addition, there was a significant effect of age, $F(1, 66.89) = 9.50, p = .003$. This is indicative of older toddlers performing better than younger toddlers, which did not interact with any of the other variables. Participants performed above chance, on average, across all trials, $t(1742) = 21.34, p < .001$. Results obtained using an alternative coding scheme for spatial memory are reported in the [Supplemental Materials](#) (Supplemental Results and [Fig. 1](#)).

All findings are reported in [Table 1](#). Performance on the two tasks was correlated. This was the case both within task (correlation between spatial and temporal memory for each task), $r_s > .30, p_s < .05$, and between tasks (imitation vs. tablet) across ages and delays, $r_s = .26, p_s < .05$.

5. Discussion

The primary goal of this study was to compare retention of memory for spatial versus temporal details within the same task and across several time intervals and opportunities to learn. The examination of the ability to retain these details is critical to our understanding of the early foundations of episodic memory ([Bauer & Lukowski, 2010](#)). In order to achieve this goal, we adapted a touchscreen tablet-based matching task ([Prabhakar & Ghetti, 2020](#)) that proved successful at engaging 2-year-olds, assessed arbitrary

Table 1

Means and standard deviations for the Tablet Matching Game and Imitation Puzzle Task across different trials.

	Tablet Matching Game				Imitation Puzzle Task			
	space		time		space		time	
Delay	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Practice	0.47	0.30	0.46	0.32				
Immediate	0.58	0.30	0.52	0.38	0.72	0.20	0.54	0.27
20-min	0.53	0.31	0.51	0.36				
One-week	0.58	0.34	0.45	0.35	0.74	0.16	0.39	0.29
One-week+Demo	0.69	0.31	0.50	0.37	0.76	0.21	0.44	0.34

Note. *M* and *SD* represent mean and standard deviation, respectively.

spatio-temporal associations, and is a promising complement to other associative memory tasks. We additionally assessed memory on an Imitation Puzzle Task requiring toddlers to place puzzle pieces in a certain spatial location and temporal order to gain evidence of the robustness of our findings on the table task.

Although there is ample evidence that the ability to remember specific events emerges in the first three years of life (Bauer, 2005; Bauer et al., 2000), very few studies have investigated the retention of spatial and temporal components within a single task and to our knowledge no study has examined 2-year-olds' retention of spatial and temporal details concomitantly across several delays. Although there is a wealth of literature supporting improvement of spatial (Newcombe et al., 2014, Ribordy et al., 2013) and temporal (Bauer et al., 1998, Bauer & Leventon, 2013) memory abilities during the infant and toddler years, more work is needed to understand early development of spatio-temporal memory and its persistence over delays. The present study aimed to begin to fill these gaps in the literature.

We expected, consistent with previous literature in older children (Lee et al., 2016; Pathman et al., 2018), that 2-year-olds would have better spatial compared to temporal order recall. With regard to delay, we expected that memory loss over delays (Bauer, 2005; Bauer et al., 1998; Bauer & Leventon, 2013) would be more pronounced for temporal details. Children performed better on the spatial memory aspect of both tasks, which is expected based on investigations of memory abilities discussed earlier (e.g., Scarf et al., 2013). A key aspect of episodic memory is the ability to bind or associate together the various elements of an experience to retain information about the co-occurrence of these elements (Eichenbaum & Cohen, 2004). Previous work indicates that limited binding of either spatial or temporal information may also contribute to difficulties with recall of early episodic memories as a whole (Burns et al., 2015; Ribordy Lambert et al., 2016). With the comparison of our Tablet Matching Game to the Imitation Puzzle Task, we expand upon previous findings (Bauer & Leventon, 2013) that memory for item-space associations may be stronger earlier in development than item-time associations. While the current study did not directly examine the hippocampus, a brain structure known to support relational binding abilities, it undergoes volumetric changes for subregions at different rates and on different timescales during development (Lee et al., 2014, 2020), with the hippocampus being particularly adept at bridging gaps or identifying differences in associations (Staresina & Davachi, 2009). Spatial details, while visually salient, may be more readily differentiated than temporal details which have fewer tangible indicators. Moreover, a previous study using the same behavioral paradigm (Mooney et al., 2021) reported a correlation between memory for temporal order across delays and hippocampal activation associated with the song played at the completion of the task; the correlation with spatial memory was not significant. It is possible that higher performance levels reduced the score range and thus the probability of finding a significant correlation with spatial memory. However, it is also possible that the availability and utilization of additional cues (e.g., landmarks at spatial locations provided by a meaningful object) may have reduced hippocampal contributions, and, more generally, retrieval demands during task completion. This is consistent with research showing that children 18-months to 5-years remember the location of hidden objects better if they are marked by a proximal landmark compared to if they are not and allocentric spatial representation is required (e.g., Ribordy et al., 2013). However, even when memory for location and temporal order were compared for tasks requiring allocentric representations, children under 5-years seemed to struggle more with recalling temporal information (Ribordy Lambert et al., 2016), suggesting that the availability of local cues may not fully explain the difference. Moreover, we note that the patterns of results for spatial memory are similar to those of the puzzle task in which no local cues were used. Nevertheless, research comparing memory for spatial, temporal and spatio-temporal associations in young children is rare, and further research with the Tablet Matching Game should be conducted to directly compare memory performance with and without meaningful or arbitrary local cues, with and without stochasticity of spatial-temporal relations. As such, we assert that the task demands are as consistent as possible across spatial and temporal memory.

We also examined whether toddlers' spatial and temporal memory performance decayed differently over time after multiple delays. The fact that levels of performance for spatial and temporal memory were comparable after the first demonstration on the Tablet Matching Game suggests that the differences observed cannot be readily accounted for by difficulties with encoding temporal information when task demands between spatial and temporal conditions are matched. Instead, these differences likely have to do with how these different aspects of memory become solidified and are then retained over time. Consistent with previous research demonstrating consistent memory loss over time (Bauer, 2008; Bauer and Leventon, 2013), the accuracy results from the Tablet Matching Game and the Imitation Puzzle Task indicate some degree of forgetting over time. Based on the current results showing no differences between spatial and temporal information at the immediate delay in the Tablet Matching Game, one could extrapolate that hippocampal contribution to encoding at this early age may operate similarly for spatial and temporal information, and that differences may emerge during storage or retrieval.

Continuous improvement of relational binding occurs throughout development, and dependence on the hippocampus is likely one of driving factors (Lee et al., 2016, 2020; Mooney et al., 2021). Recent work, investigating the interaction of hippocampal recruitment during encoding and memory performance, suggests that the degree of hippocampal utilization varies by both age, with older children recruiting the hippocampus more, and performance, with greater hippocampal activation during encoding predicting better subsequent performance (Geng et al., 2019; Ghetti et al., 2010). Differences in hippocampal activation as a function of age and performance are found during retrieval (Sastre et al., 2016) and extend into adolescence (Selmeczy et al., 2019), suggesting that hippocampal function along with its connectivity with relevant cortical regions (Tang et al., 2020) might help explain early memory retention as well. Future studies should examine how the contribution of these brain regions changes with the opportunity for repeated learning in predicting retention over varying delays at different early ages.

The development and persistence of memory ability is not the same across spatial and temporal details. Memory for space and time may employ unique cognitive processes (van Asselen et al., 2006) and brain networks (Ekstrom & Bookheimer, 2007; Staresina & Davachi, 2009). Moreover, there is evidence that spatial and temporal features may be differentially associated with different hippocampal subregions (Kyle et al., 2015; Lee et al., 2020). The significant interaction of delay and type of information revealed that

spatial memory persisted more than temporal memory after a delay. After a one-week delay, temporal memory declined significantly in both tasks, while spatial memory did not. We expected that spatial and temporal memory would exhibit different developmental trajectories in toddlerhood, with temporal memory ability developing later than spatial memory (aligning with previous research with older children and adolescents; Lee et al., 2016, 2020; Picard et al., 2012). We found that toddlers retained considerable information, but that improvement in memory after a new demonstration a week after initial learning only benefitted spatial memory. This is consistent with the hypothesis that more persistent spatial memory representations may show savings during subsequent learning opportunities. In sum, in our sample of 24- to 32-month-old toddlers, spatial memory is on average superior, resists decay, improves with age, and benefits from relearning to a greater extent than temporal memory.

The fact that a difference between memory for spatial and temporal aspects of the task was found in the immediate test in puzzle task, but not the Tablet Matching Game, underscores the potential that other factors, including motor demands necessary to demonstrate memory, may additionally contribute to the pattern of results. It is possible that toddlers' focus on placing and orienting puzzle pieces may have interfered with processing temporal information. Differences in the saliency or importance of spatial and temporal features of events may play a large role here. For example, when toddlers learn to complete the puzzle, they discover a new configuration, the figure represented in the puzzle. From that perspective, the spatial relation among the pieces is more directly in the puzzle task than the order in which the pieces are assembled (even though the order was emphasized during the demonstration). Greater salience of the resulting confirmation may be one reason why temporal memory in the puzzle task may have suffered. Additionally, toddlers may face some challenge due to the unique motor demands in each of the tasks, motor skills such as those needed to use a touch-screen tablet as well as the fine motor skills associated with moving and orienting puzzle pieces. Evidence of reduced memory for temporal information starting at the immediate test may suggest that the placement of puzzle pieces takes precedence, and the pattern of results is different in the puzzle task if performance on the puzzle task is assessed based on stricter criteria for puzzle piece placements (Supplemental Fig. 1). The failure to find reliable saving effects on the puzzle tasks similarly suggest that other demands may have interfered with performance. These considerations underscore the importance of matching motor or other memory-unrelated demands. Our Tablet Matching Game also limits the spatial locations available for choice, making it more directly comparable to the measure of temporal memory (for both measures there are only three choices in location/character). Despite these potential limitations, the Tablet Matching Game and the Imitation Puzzle Task both allowed for distinction of the retention of spatial and temporal details.

Other considerations regarding the memory development of the toddler years are the emergence of several other aspects of cognition, including the emergence of the sense of self, abstraction, and language abilities (Alberini & Travaglia, 2017). As the ability to recognize oneself and one's body as an individual entity emerges around 24 months with sense of their action on the world emerging around 14 months (Rochat, 2010), so too may emerge the ability to spatially place and recall items and events in relation to oneself. Similarly developing language abilities may impact toddlers' ability to create and maintain memories for that type of information, given the explosion of language abilities during this age. Spatial descriptors such as 'under' and 'next to' begin to emerge around 14-months of age, continuing until approximately 30-months (Shimpi & Waterfall, 2019) while temporal descriptors such as "before" and "after" emerge between 36- and 52-months (Zhang & Hudson, 2018). However, to date there is no evidence indicating whether these language abilities predate memory abilities or are dependent upon them. Future directions should include a systematic investigation of the role of arbitrary vs functionally dependent actions within a methodologically similar task as well as a systematic investigation of the role of these language abilities in conjunction with the development of spatio-temporal memory associations. We can begin to unravel the true nature of episodic memory development only by conducting a thorough review of how other cognitive skills contribute to spatio-temporal memory.

Our research aligns with existing studies on memory for spatial and temporal details in older children. For example, 3- and 4-year-olds tested with this same task exhibited recall of spatial and temporal information (Prabhakar & Ghetti, 2020), with better memory for temporal order. The continued improvements in precision, flexibility during childhood in both spatial and temporal memory tasks (Arterberry & Albright, 2020; Benear et al., 2021; Canada et al., 2020; Newcombe & Huttenlocher, 1992; Ribordy Lambert et al., 2016) suggests continued refinement of the same abilities detected in toddlers. Continuity can also be gleaned from studies examining retention over delays in older children. The ability to remember associative pairs over delays improves with age; 4- and 5-year-olds retain this memory over intervals of 5 min, 24 h, and one week. In contrast, 3-year-olds struggle to maintain such memory for a week-long delay despite initial successful recall at shorter intervals (Saragosa-Harris et al., 2021). The toddler years are pivotal, setting the foundation for these and further memory enhancements.

Ultimately, episodic memory has vast implications on how we can successfully navigate our lives. Episodic memory is necessary to navigate many daily challenges, such as memory guided planning—the ability to utilize past experiences and knowledge to develop plans in new contexts (Blankenship & Kibbe, 2019; Prabhakar & Ghetti, 2020). The relative fragility of memory for temporal compared to spatial memories provides insight on the kind of situations that may prove particularly challenging for young children. For example, it is possible that reduced memory for temporal information may help explain why young children encounter disproportionate difficulty with bridging current memory states to future-oriented thought even when the future is immediate (Blankenship & Kibbe, 2022; Kliegel & Jäger, 2007; Prabhakar & Ghetti, 2020; Ślusarczyk et al., 2018).

More generally, characterizing the developmental trajectory of spatial and temporal memory can provide insight on how different aspects of memory can guide young children as they face novel situations or learning challenges. Taken together, our findings contribute to a growing of literature on early memory functioning and confirm unique developmental trajectories of spatial and temporal memory.

CRediT authorship contribution statement

Simona Ghetti: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jasmeen Dadra:** Writing – original draft, Project administration, Formal analysis, Data curation. **Kelsey Davinson:** Writing – original draft, Project administration, Data curation. **Lindsey N Mooney:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Naoya Tani:** Visualization, Resources, Project administration, Formal analysis, Data curation.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.cogdev.2024.101443](https://doi.org/10.1016/j.cogdev.2024.101443).

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