Memories of structured input become increasingly distorted across development

Tess Allegra Forest, Zahra Abolghasem, Amy S. Finn, Margaret L. Schlichting
Department of Psychology, University of Toronto
100 St. George Street, 4th Floor
Sidney Smith Hall
Toronto, ON M5S 3G3 Canada
416-978-5201

Corresponding Author:

Tess Allegra Forest
100 St. George Street, 4th floor
Sidney Smith Hall
Toronto, ON M5S 3G3
Email: tess.forest@mail.utoronto.ca

Data Availability Statement: The data that support the findings will be available on OSF following acceptance of this manuscript. The preregistration of this project can be found here: <https://osf.io/p9cbv>

Acknowledgements: This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant (RPGIN-2016-05) and SSHRC Insight Grant (435171493) to ASF; and NSERC Discovery Grant (RGPIN-2018-04933), NSERC Discovery Launch Supplement (DGEGR-2018-00252), Canada Foundation for Innovation JELF, Ontario Research Fund, and University of Toronto start-up funds to MLS. We thank members of the Budding Minds and Learning and Neural Development Labs for their continued feedback over the course of this project.

Conflict of Interest Statement: The authors have no conflicts of interest to declare.

Ethics Approval Statement: This research was approved by the Research Ethics Board (REB) at the University of Toronto.

Page Count: 39

Key words: Memory development; Statistical learning; Memory representations; Cognitive development

Abstract

Trajectories of cognitive and neural development suggest that, despite its early developmental emergence, the ability to extract patterns from the environment changes across childhood. Here, 5-9-year-olds and adults (N=211, 110 female) completed a memory test to assess what they remembered after structured exposure to a stream of shape triplets: the particular sequence in which the shapes occurred, their group-level structure, or both? After accounting for developmental improvements in overall memory, all ages were sensitive to specific transitions, while order-independent group memory was only observed in older children and adults. Thus, while young children form memories for specifics of structured experience, memory for associative gist is refined later—underscoring that adults and young children form different memories despite identical experience.

Introduction

Our memory system has the important job of enabling us to remember not only unique, one-off occurrences, but also meaningful groups of events that occur together reliably across many experiences. For example, imagine you follow a morning routine that consistently unfolds as follows: you first eat breakfast, then brush your teeth, and then finally get dressed. Next, you decide between a biking and walking commute, choosing each option about equally often. As an adult, you would likely know that after getting dressed you sometimes get your bike out of the garage, and other times walk straight out your front door. You would likely also understand that eating breakfast, brushing your teeth, and getting dressed comprise a meaningful group of events called your “morning routine”; and you would likely be flexible enough to know that even if one day you carried out these three actions in an atypical-for-you order, you would have still completed your “morning routine.” Such flexibility in behavior could arise from flexible

memory representations that emphasize commonalities across events (Gilboa & Marlatte, 2017; Schlichting & Preston, 2015). While previously demonstrated in adults, it remains an open question whether children also form such flexible memories—or, whether their memories remain more rigid, specific records tied to exact experiences.

It is well known that memory improves substantially throughout childhood (Gathercole, 1999; Gheiti & Bunge, 2012; Gheiti & Fandakova, 2020; Jabès & Nelson, 2015; Olson & Newcombe, 2014; Riggins et al., 2020) as evidenced by near-universal improvements continuing into adulthood across a variety of both lab-based memory tasks (Billingsley et al., 2002; Gómez-Ariza & Bajo, 2003; Hulme et al., 1984) and real-world memory behaviors (Bruce et al., 2000; Newcombe et al., 2000; Piolino et al., 2007). Of particular relevance to the present work are the continued improvements in episodic memory across childhood, which are likely the result of both (1) the maturation of executive functions that enable (for example) strategic encoding and retrieval (Picard et al., 2012; Shing et al., 2010), as well as (2) ongoing change in the functionality of the hippocampus (Gheiti & Bunge, 2012; Gheiti & Fandakova, 2020; Gómez & Edgin, 2016; Lavenex & Banta Lavenex, 2013), a region critical for memory (Scoville & Milner, 1957). While early discoveries may have led us to equate the hippocampus with episodic memory, modern perspectives highlight instead the role of this region in storing relational or associative aspects of experience in service of a wide range of behaviors (Burgess, 2008; Duff & Brown-Schmidt, 2012; Eichenbaum & Cohen, 2001; A. C. H. Lee et al., 2005; Moscovitch et al., 2016; Schlichting & Preston, 2015; Shohamy & Turk-Browne, 2013). Therefore, we reason that its development may have important implications for what information is extracted and stored from a statistically reliable experience.

Supporting the prediction that hippocampal development will yield fundamental changes in the structure of memories across childhood, numerous studies have demonstrated protracted development of a variety of other hippocampus-dependent behaviors. For instance, past work has shown relatively greater developmental change in recollective as compared with familiarity-based memory (i.e., for memories that evoke a sense of mental time-travel versus those that do not; Billingsley et al., 2002; Brainerd et al., 2004); and memory for associations, which requires binding together of multiple parts of an event, as compared to memory for the individual constituent items (DeMaster & Ghetti, 2013; Ghetti, 2017; Ngo, Lin, et al., 2019; Riggins, 2014; Sluzenski et al., 2006). These observations, in combination with neural investigations showing protracted structural maturation of the hippocampus (Daugherty et al., 2016; DeMaster et al., 2014; Gogtay et al., 2004; Riggins et al., 2018), bolster the notion that there are important refinements to hippocampal function that occur throughout childhood (Callaghan et al., 2021; Keresztes et al., 2017). Given this, it is no wonder that recent years have seen a growing interest in how development may bring important differences in not only the fidelity (Ribordy et al., 2013) and persistence (Saragosa-Harris et al., 2021) of memories, but also in how they are represented (Gómez & Edgin, 2016; Keresztes et al., 2018; Ramsaran et al., 2019).

One phenomenon that could give rise to developmental differences in the structure of memory representation is the earlier refinement of memory for simple associations—defined here as reflecting first-order, experienced relations—versus the later refinement of complex associations—reflecting higher-order, longer-range, or derived connections that might yield abstract memories. This staggered refinement may yield earlier memory for some aspects of our repeated experiences (for example, which activity follows getting dressed each morning) than others (like which activities together comprise your morning routine). While the development of

memories for simple associations appears to be earlier than memory for complex associations, much work has demonstrated that it is still quite protracted across childhood (Lloyd et al., 2009; Raj & Bell, 2010; Sluzenski et al., 2006). While in some contexts infants (Gómez & Edgin, 2016; Richmond & Nelson, 2009) and preschoolers (Drummey & Newcombe, 2002; Hudson et al., 1992; Ngo et al., 2021; Saragosa-Harris et al., 2021) can form simple associative memories, there is evidence for continued improvements well beyond the preschool years. For example, relational binding—through which different elements of experience become connected in memory—shows an accelerated maturational trajectory between 5 and 7 years of age (Riggins, 2014), perhaps mirroring the strengthening of within-episode connections (Ngo, Horner, et al., 2019) that has been reported over the same period. In certain task circumstances—such as remembering item-item associations under high memory loads—improvements in associative memory linked to hippocampal structure (J. K. Lee et al., 2020; Schlichting et al., 2016) have been observed even into adolescence (J. K. Lee et al., 2016). The development of such binding operations may also be particularly protracted when associations unfold over time—that is, when items do not appear together simultaneously but rather one after the other (J. K. Lee et al., 2016). Taken together, these results highlight that while simple associative memories for one-off experiences are expected to be in place by the preschool years, they continue to improve across childhood.

Later to develop than simple associative memories for experienced relations may be the more complex, abstract organization of memories linked according to their recurring elements—although there may be two ways of forming these kinds of memories, each with its own unique developmental profile. One route is to rely upon *slow* neocortical learning systems that extract only coarse, generalized memories—that is, the consistent repeated elements, but not the

idiosyncrasies—over extended time (Gilboa & Marlatte, 2017; Gomez, 2016; McClelland et al., 1995; Vlach, 2014). Importantly, such a mechanism appears to be available even to infants (Gómez & Edgin, 2016) given their demonstrated ability to extract regularities across experiences that unfold across months or years. Thus, past research has suggested that in early childhood memory representations move from general to specific with age, as established generalization mechanisms are increasingly refined for storing specifics across young childhood (Keresztes et al., 2018; Ngo, Horner, et al., 2019).

However, here we focus instead on another mechanism that would support *fast* extraction of commonalities that would maintain the underlying memories for specifics (Ngo et al., 2021) while simultaneously supporting storage of a more general representation that reflects structure repeated across many experiences. Importantly, this sort of general representation (Brunec et al., 2018; Richards et al., 2014; Schlichting et al., 2015) may be supported by the *late-developing* (Calabro et al., 2020; DeMaster et al., 2016; Gogtay et al., 2004; Langnes et al., 2020) anterior hippocampus via its connections with medial prefrontal cortex (Schlichting & Preston, 2015). Consistent with these past neural observations, behavioral evidence also suggests that children do not spontaneously store complex, higher-order relations that unfold across multiple experiences in memory until at least early adolescence (Bauer et al., 2012, 2020; Schlichting et al., 2021; Shing et al., 2019). On the whole, existing research would therefore suggest later development of memory for meaningful groupings relative to specific associations.

Taken collectively, this work predicts that there might be a period in early childhood during which memory will mirror the learner's specific experiences, but fail to reflect the more complex, order-independent group relationships. Returning to our everyday example, this would mean that perhaps both young children and adults alike could accurately report memory for a

time when they got dressed and then walked out their front door. However, unlike older children and adults, younger children would be less likely to mistake a scrambled version of their morning routine as an experienced series of actions: For instance, they would be *less* likely to erroneously report having once first gotten dressed, then brushed teeth, then eaten breakfast. Such a suggestion is consistent with perspectives characterizing memory in childhood as more rigid and less flexible than memory in adults (Barr & Brito, 2014; Brainerd & Reyna, 2004; DeMaster et al., 2016; Sloutsky & Fisher, 2004).

Here, we used a visual statistical learning paradigm—in which the hippocampus has been previously implicated in both adults (Schapiro et al., 2012, 2014, 2016) and infants and children (Ellis et al., 2021; Finn et al., 2018; Schlichting et al., 2016)—to assess the formation of memory for both the specific associations and complex order-independent relationships embedded within the same experience. We presented participants with a continuous stream of simple shapes shown one at a time. Shapes were grouped to form reliable units (here, triplets) within which the underlying associations (i.e., shape-to-shape transitions) always occurred in the same order. Therefore, in contrast to past work in which there has been variability across repetitions of the particular order at exposure (Pudhiyidath et al., 2020; Schapiro et al., 2016), here such variability is intentionally not present in the stream. There is an extensive body of literature documenting the ability of even infants to learn such statistical structures; however, due to the nature of past memory assessments, the particular representations upon which their behaviors are based remain ambiguous. Recent work in adults has shown that despite the consistency of the statistical stream and the many stimulus repetitions that might bias the system towards specifics (Kensinger & Schacter, 1999; a similar effect has been observed in children, see Brainerd & Reyna, 1996), mature learners nevertheless also express flexible, order-independent memories for the triplet

groupings (Forest et al., 2021). With respect to change over development, while past work has largely shown improvements in statistical learning ability throughout childhood (Jung et al., 2020; Raviv & Arnon, 2018; Saffran et al., 1997; Schlichting et al., 2016; Shufaniya & Arnon, 2018), the particular reason behind such behavioral gains remains unknown.

We aim to fill this gap in the literature by characterising the nature of memory representations formed through statistical learning in 5- to 9-year-olds. We separately characterize when in development children form (1) specific, rigid memories for repeated experiences, which track with the associations as they actually unfolded; and/or (2) flexible memories, which reflect complex, general associations for order-independent groupings yet deviate from actual experience. We predicted gains in overall performance across the age range, such that with development children would increasingly discriminate between old and new (never-studied) sequences. Inspired by the idea that memory for specific associations precedes their complex, order-independent relationships, we predicted that while even young children would show memory for their exact experiences from learning, only older children and adults would show memory for triplet groups that generalize to novel orderings of grouped shapes. (We note that while our conceptualization of generalization deviates from some past work (e.g., Ngo, Horner, et al., 2019; Zeithamova & Bowman, 2020), it aligns with numerous other studies in both animals and humans (e.g., Brainerd & Reyna, 2004; Richards et al., 2014) that similarly define generalization in terms of memory expression to new but similar items during a memory test; see Supplementary Materials for more in-depth consideration of this issue.) Also, in important contrast to prior work (Ngo et al., 2021), we used materials devoid of semantic information to assess the emergence of these representations in the absence of relevant prior knowledge. Moreover, participants' experience was such that specific transitions were entirely

reliable and consistent across repetitions, meaning that any behavioral evidence of memory for shuffled groups of items that co-occurred repeatedly represents a distortion of the input.

Methods

Participants

Sixty adults (mean age=19.57 years, SD=2.37) participated for credit in an introductory psychology course at a large urban university. One hundred and seventy-six children aged 5-9 years participated in exchange for a small toy or entry into a gift card raffle. Of these, 25 children (roughly evenly distributed across our age groups: eight 5-year-olds, four 6-year-olds, four 7-year-olds, eight 8-year-olds, one 9-year-old) were excluded because of failure to complete the study or failing the practice test (see **Materials and Methods, Test Phase**), leaving 151 children for inclusion in all analyses. All participants had normal or corrected-to-normal vision and reported no history of neurological impairment. Children either participated at our local science museum, in lab, or over video conferencing software (see below); all adults participated in lab.

Our sample size, methods, and planned analyses were preregistered prior to data collection ([link removed from manuscript for blinded peer-review](#)). The only deviation from our preregistration was that in light of COVID-19 restrictions, we were forced to halt in-person data collection part-way through this study; thus, we transitioned to online data collection for the remaining 63 children. Our preregistered data collection plan included 30 children at each age (year) from 4 to 9, grouped into three age groups: 4-5 year-olds (yos), 6-7yos, and 8-9yos. However, the youngest children (4yos) had too much difficulty focusing on our experiment when we transitioned to online data collection, and thus we were not able to include 4yos in our final sample. As such, our final sample included four age groups, “Younger Children” (5yos; N=30, 19 run online; 19 female), “Middle Children” (6-7yos; N=61, 10 run online; 26 female),

“Older Children” (8-9yos; N=60, 34 run online; 23 female), and “Adults” (18-30; N=60, all run in person; 42 female). Importantly, testing modality (in-person vs. online) did not impact corrected hit rate (i.e., hits – false alarms; see **Analysis Approach**) for any child age group (all p 's > 0.14) and thus any differences between online and in-person testing are not likely to explain our results. Hereafter, we report all results collapsed across testing modality.

Additionally, while the youngest age group ended up being smaller because of the move to online data collection, this cannot explain the pattern of results reported (see Supplementary Material). All procedures were approved by the Research Ethics Board at our institution.

Materials and Procedure

Stimuli were nine uniquely colored shapes. Shapes were presented one at a time on a black background for 800ms (200ms ISI). Unbeknownst to participants, the shapes were grouped into sets of three shapes (“triplets”) which were always presented in the same, fixed order; for example, shapes A, B, and C would always appear in the order “ABC.” Triplets were matched in average luminance, and could appear in any order with the stipulation that no triplet was allowed to directly follow itself (i.e., “ABC” could be followed by “DEF” or “GHI” but not “ABC”). There were no differences in ISI between shapes within and across triplets, so any learning about triplet structure could not be due to additional (e.g., temporal) cues. Stimuli were presented to participants on either an iPad (in-person sessions, for all age groups; programmed for a custom app using Swift) or their home computer screen (videoconferencing sessions with a live experimenter, for all age groups: programmed using Psychopy (Peirce, 2009) and JsPsych (de Leeuw, 2015)).

Exposure. First, participants watched a stream of shapes for ~4.5 minutes (30 presentations of each triplet). Participants received instructions to “*Simply watch the shapes and pay attention!*”

If children stopped paying attention, they were reminded to “*Keep paying attention so you can answer my questions at the end!*” Such reminders were never necessary for adults.

Test Phase. To assess what participants had learned about the triplets during exposure, participants next made old-new judgments for test sequences made up of the exposure shapes. There were five types of test sequences (described below), and test sequences were presented in a random order for each participant. There were a total of 30 test trials, six per sequence type. In all cases, three shapes were presented back-to-back with the same timing as the exposure phase (800ms stimulus, 200ms ISI). After each test sequence, participants indicated whether or not the sequence they just saw was part of what they had seen earlier (i.e., answer the question, “*Do you think this is part of what you saw before?*” with response choices “yes” or “no”). Adults responded themselves, by tapping either option (“yes” or “no”) on an iPad screen, and the experimenter responded for child participants to ensure correct mapping between their selection and the touch (in-person sessions) or key (videoconferencing sessions) response. This prompt was rather vague by intention, so as not to imply to participants that there were different kinds of similar lures present in the test. While the response prompt was worded as a yes/no question to support participants’ understanding, we will refer to “yes” responses as “old”, and “no” as “new” to align with terminology typically used in this sort of memory test.

Before the test, all participants completed two practice test questions which used letters from the alphabet (as in past statistical learning research; Finn & Hudson Kam, 2008; Forest et al., 2019; Jung et al., 2020). This practice was completed to highlight to participants that we were not asking whether they had seen any of the shapes *individually* before, but that we were asking whether the shapes appeared *together* in the same order that they had during exposure. The first practice test item presented the letters “A”, “B”, “C” one at a time in intact, alphabetical

order; the second practice test question presented the letters “A”, “I”, “E” (not in alphabetical order). Thus, participants should have responded “yes” and “no,” respectively, when asked if each sequence is part of what they would hear in the alphabet. Children who responded incorrectly to either sequence were asked why they had responded as such, and corrected. The experimenter then repeated the incorrectly answered sequence verbally, and children were prompted to respond again. Children who responded incorrectly again were excluded from all analyses (N=25, as noted above), and another participant was run in their stead. Participants continued to the test phase immediately after the practice test.

Test types. There were five different test sequence types. The first type (“triplet” sequences) were the same triplets shown repeatedly at exposure. For these sequences, participants saw three shapes that had comprised a triplet during exposure, in the same order they had appeared during exposure. Thus, participants should indicate these test sequences are “old.” Participants were tested on all three exposure triplets, twice each, for a total of six trials in this condition.

The next type (“control” sequences) were six test sequences which were constructed to be as new as possible relative to exposure. These sequences (e.g., “EAI”) thus maintained as little old signal as possible from position (one shape was shown in the same within-triplet position as during exposure), transition (no transitions were held intact from exposure), or group information (no shapes from the same triplet). Accordingly, participants should respond “new” to these test sequences, regardless of the type of representation they have stored. Each of these test sequences were created using the same shapes that had been present during exposure, and thus the shapes themselves were not novel. All shapes appeared exactly twice across the six control sequences. Each of the six control sequences were presented just once during test for a total of six trials in this condition to ensure that they were new for each presentation.

The remaining three test types were each designed to maintain one type of statistic from exposure while minimizing the match in every other statistic. We refer collectively to these test sequences as “lures”. The inclusion of these lures allowed us to compare responses across types to understand which statistics are guiding memory decisions for each age group. Participants completed six unique trials of each lure type. Mirroring the control sequences, for each lure type we also distributed shapes across test sequences such that all shapes appeared exactly twice in the six lures of each type.

The first lure type (“position” lures, six test sequences presented once each) was made up of three shapes from different exposure triplets. The reasoning behind including these types of lures was to assess the possibility that items appearing in a particular position could be “tagged” with their within-triplet position (Hsieh et al., 2014; Kikumoto & Mayr, 2018; Pathman & Ghetti, 2015); and thus to a certain degree could become interchangeable with other same-position shapes in memory. In position lures, each shape in the test sequence therefore maintained its position relative to its own triplet (e.g., “AEI”, where “A” is a first position shape, “E” is a second position shape from a different triplet, and “I” is a third position shape from yet another triplet; for brevity we refer to this position ordering as “1-2-3”). No transitions between shapes were maintained relative to exposure, and none of the shapes were from the same triplet. As such, both the number of intact transitions and number of shapes from one triplet are low, and if participants treat these sequences as old, they are likely representing information about the ordinal positions of individual shapes from exposure.

The second lure type (“transition” lures, six test sequences presented once each) included two shapes from the same triplet and one shape from a different triplet, in an order that was allowable during exposure (e.g., “BCD”). These test sequences maintained the highest

transitional probability value possible for three shapes that were not a triplet, while minimizing position information (no shapes in their original position; three of the six sequences used a 2-3-1 order, the other three used a 3-1-2 order; visualized in *Figure 1b*) and the number of items from the same triplet (two). These test sequences therefore present shapes in the same order as they appeared during exposure, but do not comprise a reliable triplet. It is important to note that these sequences are technically old, as participants would have seen this order of shapes during learning, but only half as often as a triplet (15 times per transition lure for each participant vs. 30 times per triplet). However, because we are primarily interested in the difference in responses to lure type across age, rather than adjudicating responses as “correct” or “incorrect,” we are including them with our lure sequences because they do not represent the reliable triplet groupings participants were exposed to most frequently (for a similar approach see Forest et al., 2021). Thus, if participants respond “old” to these transition lures, they are likely representing the specific transitions experienced during exposure.

The last lure type (“group” lures, six test sequences presented once each) included three shapes from the same exposure triplet, but in a shuffled order (e.g., “BAC”). These sequences had the highest possible number of shapes from one triplet (three), but maintained no transitions from exposure, and only one position relative to exposure (three of the six sequences used a 1-3-2 order, the other three used a 2-1-3 order; visualized in *Figure 1b*). Thus, if participants are representing order-independent information about the groups that shapes appeared in during exposure, they should respond “old” to these items.

Figure 1. Experimental Design. a) Exposure phase. Three, three-shape triplets appeared one at a time in a pseudo-random order, such that each triplet repeated 30 times and could not immediately follow itself. Triplets were matched for average luminance. b) Example test sequences from each condition. At test, participants indicated whether test sequences representing five test types (colored boxes) were part of what they had seen during exposure (center schematic; same as panel a). Control sequences (yellow) maintained no information from exposure (three shapes from different triplet groups, with no maintained transitions and one maintained position; unambiguously “new”); triplet sequences (purple) perfectly maintained all structure from exposure (three items from one triplet in the same positions with all transitions maintained; unambiguously “old”); position lures (orange; always position 1-2-3), group lures (red; either position ordering 1-3-2 or 2-1-3; 2-1-3 is visualized in the figure) and transition lures (magenta; either position ordering 2-3-1 or 3-1-2; 3-1-2 is visualized in the figure) each held one type of information constant relative to the triplet structure from exposure. Dashed lines show how shapes in each sequence were re-arranged relative to exposure to create the test sequence types.

Analysis Approach

Analyses were preregistered unless otherwise noted. First, we confirmed that within each age group, participants could discriminate triplets from control sequences. Indeed, pairwise *t*-tests revealed that there was a significant difference in old responses to triplets and control sequences in all age groups (all *t*'s > 2.88, all *p*'s < 0.007, corresponding to all points in *Figure 2* being significantly above 0), indicating that across our sample participants had memory for the triplets. As such, all age groups were included in all further analyses.

Next, we asked whether overall performance differed across age groups. To do so, we calculated the corrected hit rate for each participant by subtracting their proportion of “old” responses to control sequences (false alarms) from their proportion of “old” responses to triplet sequences (hits). We then compared corrected hit rate using a one-way ANOVA with age group (Younger Children, Middle Children, Older Children, and Adults) as a between-subjects factor, and corrected hit rate as a within-subjects factor. Pairwise, two-sample t-tests were then used to compare the corrected hit rate across age groups. We also performed a parallel analysis that considered development of hits and false alarms separately. Described in more detail in the Results, older participants were significantly better able to discriminate between triplets and control sequences than were younger participants. Thus, while we report the overall patterns of old responses to all test types separately for transparency (with age both considered by group as well as continuously; see Supplementary Material), our primary analyses were designed to control for overall differences in memory strength across age groups.

Specifically, our main research interest was understanding how the pattern of “old” responses across lure trial types differed with development, beyond any general improvements in discrimination between triplets and new sequences. Therefore, to control for developmental differences in memory for the exposure stream more generally, we normalized responses to the lure types relative to each overall age group’s memory. Specifically, we subtracted each participant’s proportion of old responses to the control sequences from their proportion of old responses to each lure condition (lure-control) separately. We then divided this number by the average triplet versus control difference for that age group. This resulted in a lure discrimination value, expressed as a proportion of the maximum possible discrimination for that age group, given the most unambiguous memory comparison (i.e., triplet versus control). In this way, we

could understand whether participants judged each of the lure types (position, transition, and group) as older than the control items (indicated by a score > 0), in a manner normalized relative to that age group's maximum discrimination for triplet and control sequences. A score of 1 would mean participants treated a particular lure type as just as old as their age group treated old sequences (on average); negative values would indicate participants treated a lure type as newer than their age group treated control sequences.

We then compared these normalized difference scores across ages using a 3x4 ANOVA with age group as an across-subjects factor, and lure type as a within-subjects factor. Follow-up ANOVAs were then run on each age group separately to ask whether performance for lure type reliably differed. Then, to ask whether participants in each age group represented any information about position, transitions, or group membership, performance on each lure type was compared to 0 using t-tests.

Finally, participants gained most of their experience with the shapes during the exposure phase, and so we reasoned that test performance will primarily reflect learning from exposure. However, it is possible that both (1) additional experience during the test phase could shift participants' responses and (2) the impact of this additional experience could be greater for younger learners. As such, we performed a series of follow-up (and not-preregistered) control analyses to ensure that the pattern of results presented below is relatively constant across the test. These results are presented in the Supplementary Material. Briefly, and in line with previous work (Forest et al., 2021), our findings confirmed that test phase experience is not likely to explain the pattern of results reported below.

Results

Overall memory improves with age

Having verified that each age group could discriminate triplet from control sequences at above-chance levels (see **Analysis Approach**), we next compared the corrected hit rate across ages. Memory significantly varied with age (*Figure 2*; main effect of age group on corrected hit rate; $F(3,207)=11.59, p<0.001$): While memory in younger (5 yrs) and middle (6-7 yrs) children did not significantly differ (Welch's two-sample t-test; note that this does not assume equal variance for each group and thus does not result in an integer value for degrees of freedom; $t(66.13)=1.16, p=0.25$), older children (8-9 yrs) outperformed younger ($t(66.40)=3.30, p=0.002$) and middle ($t(118.97)=2.40, p=0.02$) children, and adults outperformed all children (all t 's >2.42 , all p 's <0.02). Such a finding of improvements across childhood replicates the limited extant literature on these relatively late developmental gains in statistical learning (Jung et al., 2020; Raviv & Arnon, 2018; Schlichting et al., 2016). Interestingly, an ANOVA separately interrogating old responses to triplet versus control sequences across age indicated significant age-related gains in the ability to correctly identify triplets as "old" ($F(3,207)=15.91, p<0.001$) but not reject control sequences as "new" ($F(3,207)=0.83, p=0.48$). Such a result suggests that overall developmental differences in memory for statistical structure may be driven by an increased ability to recognize something as matching the experienced structure, rather than a decreased tendency to report something as appearing when it did not.

Triplet memory improves with age

Figure 2. Triplet memory improves with age. Corrected hit rate (y-axis; raw proportion of old responses to old sequence – raw proportion of old responses to control sequences) as a function of age group (x-axis). Horizontal lines represent the group means, boxes represent 95% confidence intervals, and semi-transparent dots represent individual participants' scores. Younger children and middle children's scores were not significantly different from one another; all other pair-wise comparisons were significant at $p < 0.05$ (not marked on chart). Dashed line at 0 represents no difference in responses to triplet and control sequences.

Children's memory judgements reflect specific transitions before groupings

Investigating the raw proportion of “old” responses across our test types revealed a significant interaction with age group, such that responses became increasingly differentiated across development (these data are reported in full in the Supplementary Material, “**Memory judgements to each test type increasingly differentiate over development**” and depicted in *Supplementary Figure 1*). Here, we focus on our main question of how old responses across lure types differ with age to examine how memory representations may change with development. We compared normalized responses to each lure type across all four age groups. A 3x4 ANOVA indicated that, as expected, there was no significant main effect of age group ($F(3,207)=0.62$, $p=0.61$), confirming that our normalization effectively removed general age-related differences; there were also no significant age effects when each lure type was considered separately (all F 's < 1.18 , all p 's > 0.32). Moreover, there was a significant main effect of test type ($F(2,414)=43.56$, $p<0.001$)—such that position lures were treated as the newest, followed by group lures, and then transition lures—that was significant within each age group considered separately (all F 's > 4.65 , all p 's < 0.01); however, test type did not significantly interact with age ($F(6,414)=0.86$, $p=0.52$). Therefore, after controlling for overall memory differences (and

overall differences in “old” responses to triplets), the relative oldness of the different lure types did not significantly shift across development.

Importantly however, the above analysis does not ask whether each factor on its own shows evidence for influencing memory decisions within each age group. Put another way, do participants make significantly more old responses to certain types of lures relative to control sequences? And does this differ by age? To address this, our next planned comparison examined the response profile of different lure types to zero in each age group independently.

All age groups represent transition information. We first asked how each age group responded to transition lures, which held intact transitions but not group or position information from exposure. Thus, endorsing these sequences as older than control sequences suggests participants are representing information about the specific transitions they experienced at exposure. Indeed, all age groups had normalized transition lure scores that were higher than zero (younger children: $t(29)=2.30$, $p=0.03$, *Cohen's* $d=0.42$; middle children: $t(60)=2.38$, $p=0.02$, $d=0.30$; older children: $t(59)=6.66$, $p<0.001$, $d=0.86$; adults: $t(59)=8.31$, $p<0.001$, $d=1.07$, *Figure 4*), suggesting that, by age five, children are capable of using specific transition information to guide old-new memory decisions.

Older children and adults represent group information. Next, we examined how participants of each age treated group lures (*Figure 3*), which maintained group structure from exposure, yet deviated from the order and position in the input. Interestingly, group information influenced memory decisions in only some of our age groups. Specifically, younger children and middle children did not treat these sequences as significantly older than control sequences, as demonstrated by normalized group lure responses that do not reliably differ from zero (younger children: $t(29)=0.64$, $p=0.52$, $d=0.05$; middle children: $t(60)=0.93$, $p=0.36$, $d=0.12$). Older

children and adults, however, both demonstrated normalized group lure scores above zero (older children: $t(59)=2.76$, $p=0.008$, $d=0.36$; adults: $t(59)=4.53$, $p<0.001$, $d=0.59$), suggesting that these age groups stored order-independent information about which shapes appeared together during exposure. Together, this pattern of results suggest that it is not until around 8-9 years that children begin to represent group information. Note that because group lures were sequences of items that were *never presented* during exposure, an increase in the representation of group information—in contrast to responses to transition lures—means *more* errors to this lure type in older children and adults relative to younger and middle children. Note that this developmental increase in errors is (numerically) true both in a relative (*Figure 3*) and absolute (*Supplementary Figure 1*) sense.

No evidence for representation of position information. Finally, we examined how each age group treated position lures, which match exposure on the within-triplet position of each shape, but not group or transition structure. However, none of the age groups treated these lures as significantly older than control sequences (i.e., none of the normalized position lure scores were reliably above zero; younger children: $t(29)=-0.27$, $p=0.79$, $d=0.12$; middle children: $t(60)=-0.80$, $p=0.42$, $d=0.10$; older children: $t(59)=-1.69$, $p=0.10$, $d=0.22$; adults: $t(59)=-0.56$, $p=0.58$, $d=0.07$, *Figure 4*). In other words, none of the age groups showed significant evidence of using position information to inform their memory judgements.

Memory for different aspects of statistical structure

Figure 3. Memory for different aspects of statistical structure. Normalized proportion of old responses (y-axis) to each lure type (color) as a function of age group. Horizontal lines represent the group means, boxes represent 95% confidence intervals, and semitransparent dots represent individual participants. Grey dashed line at 0 represents value at which each lure type would be treated as new as control items. Colors mirror those used in Figure 3.

Discussion

A significant body of research has demonstrated that as early as infancy, learners are able to extract statistical regularities from their environments (Saffran, 2020; Smith et al., 2018). However, the nature of the particular representations upon which children base their behaviors remains relatively less explored. Here, we characterize how the memories formed through statistical learning differ across childhood. Consistent with previously published findings (Finn et al., 2018; Jung et al., 2020; Raviv & Arnon, 2018; Schlichting et al., 2016), we demonstrate general age-related improvements in performance underpinned by gains in the ability to correctly identify exposure triplets as “old.” We replicate past work (Forest et al., 2021) using a simplified, child-friendly paradigm to show that young adults store memories for both specific transitions and general groupings, but not within-triplet position. Crucial for understanding how learned representations shift with development, we demonstrate that while our youngest learners (age five) already represent specific transition information, only beyond age eight do learners

store complex associations about general groupings. In other words, even after experiencing the same novel structure, older and younger learners remembered something quite different—with older learners interestingly showing more memory distortion as they were more likely to make errors to shuffled groups.

Our finding that old-new memory judgements improve with age is in line with multiple literatures. Virtually all statistical learning studies comparing performance between children and adults have shown developmental improvements in participants' ability to select old sequences over lures in alternative forced choice tests (Finn et al., 2018; Jung et al., 2020; Pudhiyidath et al., 2020; Raviv & Arnon, 2018; Schlichting et al., 2016; with some exceptions, i.e., Raviv & Arnon, 2018; Saffran et al., 1997). Because our study used an old-new test that probed memory for different aspects of the triplets separately, we could further examine the nature of this improvement. We saw that while the likelihood of erroneously endorsing our most unambiguously new (control) sequences as “old” (i.e., false alarm rate) was relatively constant across development, the likelihood of correctly accepting an exposure triplet sequence as “old” (i.e., hit rate) significantly increased. While unexplored among past developmental studies of statistical learning, the general observation of greater developmental differences in hits relative to false alarms aligns with much episodic memory research in school-aged children (Demaster & Ghetti, 2013; Ghetti & Angelini, 2008; J. K. Lee et al., 2016; Ofen et al., 2012).

There are multiple possible factors that could give rise to the observed developmental differences being driven by a greater ability to correctly accept an exposure triplet as old. First, one possibility is that younger children are more likely to deem all stimuli as being old—that is, they have a more liberal “response criterion” in the face of uncertainty (Berch & Evans, 1973). However, we think this is unlikely to explain the pattern of data reported here since our observed

increase in the proportion of “old” responses was not ubiquitous, but rather seen only in a few test sequence types (even after accounting for differences in “old” responses to the control items). A second possibility is that the large number of exposure repetitions—a feature common to all statistical learning studies—is known to enhance precise, “verbatim” memory traces (Brainerd & Reyna, 1996, 2004; Poole & White, 1991). Since it has shown that the degree of repetition-related enhancements in hit rate increases over development (Brainerd & Reyna, 1996, 2004; Poole & White, 1991), this feature of exposure may accentuate developmental differences in hit rate.

With regard to what information is represented in memory across development, we first turn to our finding that memory for specific transitions is present from early in childhood. Specifically, all age groups exhibited elevated “old” responses to transition lures relative to control sequences. While transition lure sequences were not seen as frequently as triplets, participants had indeed seen these sequences during exposure; thus, endorsing them as old is correct. In general, the finding that by age five children can remember infrequent, arbitrary associations is consistent with past work (Drummey & Newcombe, 2002; Hudson et al., 1992; Ngo et al., 2021; Saragosa-Harris et al., 2021). However, other work has emphasized that children’s associative memory continues to improve well beyond this period into late childhood (Riggins, 2014) and adolescence (J. K. Lee et al., 2016). Taken together, these studies lead to the prediction that we could see an increasing tendency to represent transition information in memory. However, after correcting for overall performance differences, we found no statistical evidence for such developmental change in performance on transition. One possible explanation for this null effect could be that past work used particularly taxing memory paradigms that may yield a later developmental plateau—for example, extended associative memory differences have

been observed in cases with few (one or two) stimulus exposures (J. K. Lee et al., 2016; Riggins, 2014) or months-long delays (Friedman & Lyon, 2005). Therefore, performance may be more constant across development in our study given the extensive exposure and immediate test phase. In addition, normalizing age group performance according to old-new discrimination may have further minimized the potential to detect developmental differences: Given that the same memories could be referenced to judge transition lures and triplet sequences as old, our analysis normalizing according to the latter may have hindered our ability to detect the former.

While all age groups represented specific transitions in memory after statistical learning, group membership begins to guide memory decisions only around eight years of age. This finding underscores that the representations formed after statistical learning are not constant across development, but change such that older learners form generalized representations of their experiences, while younger ones do not. As mentioned in the Introduction, at first glance, the finding of increasingly abstracted memories with development may appear at odds with extant perspectives suggesting the opposite trajectory for “general” memories (Keresztes et al., 2018). However, much past work taken as support for the idea that memories become less general with age differs from the present approach in multiple ways. First, the majority of prior research on generalization has used semantically rich stimuli (J. K. Lee et al., 2016; Ngo et al., 2021; Riggins, 2014; Sluzenski et al., 2006), while we used simple shapes. Second and relatedly, generalization in past work often takes the form of children erroneously endorsing similar test lures as having been studied (such as endorsing a red house as “old” when participants saw an orange house), such that the memory formed generalizes to a new stimulus—leading it to be incorrectly judged as “old” (Ngo et al., 2017; Rollins & Cloude, 2018). These task features may interact: for example, age-related differences in participants’ (pre-experimental) familiarity with

the stimuli themselves may lead to the formation of lower-fidelity memory representations in children than adults (Bellana et al., 2021), which would yield more generalization errors (Vlach, 2014). In contrast, we used simple shapes to limit the impact of potential developmental differences in knowledge of the stimuli; and, as noted in the Introduction, operationalized generalization as extraction of global associative structure rather than item-level gist. Given these differences in experimental setup, it is perhaps not surprising that we likewise arrive at different conclusions.

Despite their apparent contradiction with some findings, our results of an increasing tendency to extract complex associative structure with development are consistent with numerous other behaviours that similarly rely upon the formation of associative links. Such studies have shown developmental increases in the tendency to combine across multiple memories to generate new inferences, both when self-deriving new semantic knowledge (Bauer et al., 2012, 2020), as well as inferring novel associations between items indirectly related through a common link (Schlichting et al., 2016, 2021; Shing et al., 2019). Relevant to the present work, older more than younger learners attribute shared features to items originally experienced close in time in an exposure sequence (i.e., a member of the same “temporal community” (Pudhiyidath et al., 2020), consistent with our finding that adults and older but not younger children may link together group members in memory. While on the surface some of these tasks seem quite methodologically distinct from ours, past work has suggested that learning of temporal community structure (Schapiro et al., 2016), standard statistical learning (Schapiro et al., 2012), and associative learning (Schlichting et al., 2016) all share a common neural substrate, and may therefore reflect a similar learning mechanism. As such, here, we extend past work to show that temporal grouping emerges in older children and adults even when it means distorting

the input; as well as demonstrate that such temporal structure is reflected in pure memory judgments, when overt inferences about shared features that may engage additional reasoning operations are not required.

The careful reader may have some unresolved discomfort surrounding the result of increasing group knowledge in older participants, which amounts to a greater prevalence of errors with development. Needless to say, typically we expect performance improvements across development, and so this may seem counterintuitive. However, such “developmental reversals” have been reported previously (see Gualtieri & Finn, 2021, for review), such as in the Deese-Roediger-McDermott (DRM) false-memory paradigm. It is well established that following encoding of a list of conceptually related words in the DRM task, adults erroneously endorse new, semantically related lures (e.g., endorsing “bed” as “old” when having read a list containing “sleep,” “pillow,” and “dream”) as studied more often than do children (Brainerd et al., 1995; Paz-Alonso et al., 2008). This phenomenon may be due to adults’ more densely interconnected semantic networks that give rise to the illusion of having studied words that were not presented (Brainerd et al., 2004; Brainerd & Reyna, 2004). Here, we report a parallel phenomenon of increased memory errors with development, such that generalization is operationalized as more erroneous “old” responses to shuffled group lures. We extend beyond prior work with the DRM paradigm to show that such “memory illusions” may be increasingly prevalent across development in an entirely different context: namely, even when participants acquire a novel associative structure—unrelated to established semantic networks—within a single experimental session.

The fact that transition-specific and generalized group memory follow different developmental timelines may reflect the establishment of a memory hierarchy, such that only in

older children and adults does group knowledge emerge alongside related specific memories. This idea is broadly consistent with work on the development of semantic generalization as a function of underlying associative memory (Ngo et al., 2021). Despite observing no difference in associative memory in that study, researchers found that 6-8-year-old children and adults were more likely to make semantic generalizations—that is, indicate that a studied character would prefer a semantically similar item to add to their existing collection (e.g., a piano when the character had previously been paired with other instruments) over a dissimilar one—than were 3- to 5-year-old children. Moreover, only adults’ generalization related to the strength of the underlying specific memories; in children, associative memory and generalization were independent. These findings, and others showing that memories are processed holistically (such that remembering one aspect of an event makes someone more likely to generalize their retrieval to another aspect of that event) by around age six (James et al., 2021; Ngo, Horner, et al., 2019), are consistent with the ideas put forth here, such that group knowledge depends upon specific memories only later in development. While our design was not well-suited to ask whether such dependency (i.e., whether memory for the specific transitions comprising a triplet underlies the tendency to make a memory error to a group lure comprising those items) exists in a statistical learning context, our findings are broadly consistent with the trajectory observed in past work, albeit with generalization here emerging slightly later than it did in this previous study (i.e., at eight versus six years, Ngo, Horner, et al., 2019). One explanation for this difference might be uncovered by comparing the raw proportion of old responses across lure types in our study: Doing so, we find that only younger children (aged 5 years) failed to behaviorally discriminate between triplets and transition lures ($t(29)=-0.08, p=0.93$), with a significant difference in responses to these trials first emerging around age six (all age groups middle children and older:

$t > 2.8, p < 0.007$). Given that triplets and transition lures differ in the strength of one item-item transition (0.5 for transition lures, instead of 1.0 for triplets) *and* their group membership (two same-group items for transition lures versus three for triplets), it is possible the emergence of this difference in the middle children indicates group knowledge is already impacting responses in a nuanced way beginning around age 6. Such a marker could be consistent with the speculative idea that proto-group knowledge emerges and can subtly influence behavior around the age of 6 years, paralleling the developmental timeline in other work.

Finally, we saw no evidence that any age used ordinal position as a basis for endorsing test sequences as old. The fact that here, and in past work, position was not used as a signal for oldness (even after extended exposure, Forest et al., 2021), may seem surprising given other empirical work suggesting the importance of position coding in sequence memory (Clewett et al., 2020; Kikumoto & Mayr, 2018; Pathman & Gheetti, 2015) and of boundary events in event segmentation (Dubrow & Davachi, 2013; Kosie & Baldwin, 2019; Kurby & Zacks, 2008). Indeed, we included position lures partly inspired by these literatures, and because position has frequently been held constant relative to exposure in past visual statistical learning research in adults (Luo & Zhao, 2018; Park et al., 2018; Turk-Browne et al., 2005) and children (Arnon, 2020; Jung et al., 2020; Schlichting et al., 2016). Thus, including this lure type provided a methodological link to past studies.

For all ages, position lures were easily (and correctly) deemed “new.” One possibility is that memory for the relative temporal lag at which particular items were encountered during exposure supported participants’ ability to reject such lures; and that this was true at all ages. Past work has shown memory for when in time (or in what order) some target event occurred continues to improve throughout childhood (Canada et al., 2020; Friedman, 1991; Friedman &

Lyon, 2005; Pathman & Gheetti, 2014). However, even young children show some evidence that temporal factors impact the way memories are stored: For both 4-year-olds and adults, events experienced further apart in time are easier to distinguish than events that happened closer together (Friedman et al., 2011; Pathman et al., 2013). Moreover, children (like adults) show evidence of bias towards temporally proximal (and next-in-the-sequence) items during recall (Brown et al., 1981), consistent with experiences being bound to a drifting temporal context even in childhood (Howard & Kahana, 2002). Because position lures here included three shapes that always occurred relatively far apart in time at exposure (i.e., at a high lag), they could be less confusable with true experiences than other lures. This could mean they yield an easy “new” judgment if temporal proximity is used to determine the memory status of a sequence by children.

The present results also fit into a broader, neurobiologically informed picture of how the memory representations formed through statistical learning might evolve from infancy through childhood. Past statistical learning research has shown that eight-month-olds look longer at a visual display of shapes presented in groups that matched a previous structure versus groups which did not, despite the displays being matched in the specific transitions from exposure (Slone & Johnson, 2018). These results suggest that infants represent their statistical experience as “chunks” of items that co-occur reliably rather than as specific transitional probabilities. Such a finding may seem surprising given the present results, in which we show memory for groups—perhaps akin to the chunks observed in past work—emerges years later. However, we suggest that such a pattern is consistent with a non-linear progression in the representations formed via statistical learning across this wide developmental range. In particular, it has been suggested that there are two separate, specialized circuits for learning within the hippocampus (Schapiro et al.,

2017) that support slower learning of general groups and rapid encoding of specific associations, respectively. While we would expect based on recent findings that the hippocampus would be engaged during statistical learning in infancy (Ellis et al., 2021), it may be through a restricted circuitry relative to adults. Namely, the intra-hippocampal pathways develop at different rates (Lavenex & Banta Lavenex, 2013), indicating that perhaps only memory for general groups (via the monosynaptic pathway) would be available to infants (Gomez, 2016; Gómez & Edgin, 2016; Schapiro et al., 2017). We would then expect the ability to remember specific transitions to emerge and improve once the complementary pathway supporting rapid encoding (tri-synaptic) is established (Gomez, 2016; Keresztes et al., 2018; Lavenex & Banta Lavenex, 2013; Ribordy et al., 2013). The ultimate emergence of memory for group-level structure alongside these specific memories in older children, we predict, would mirror a different neural change: it might be related to an increase reliance on the anterior hippocampus (Demaster & Ghetti, 2013; Langnes et al., 2020; J. K. Lee et al., 2020), which has both been previously shown to occur around this developmental period and would be consistent with an increased breadth of the memory trace (Brunec et al., 2018; Ngo et al., 2021; Ngo, Horner, et al., 2019; Schlichting et al., 2016); and/or increased communications between hippocampus and medial prefrontal cortex (Calabro et al., 2020). We propose either of these neurodevelopmental mechanisms could support the storage of group membership knowledge alongside specifics in older children and adults, and explain how infant's general memories might appear similar yet be of a fundamentally different sort—both lacking specifics, and having a different neural substrate.

While future work will be needed to isolate the exact neural mechanism underlying memory representational change over development, we provide initial behavioural evidence that the fundamental ability to track the patterns around us operates differently with age. Returning to

our everyday example, we suggest children under age eight are less likely than older children and adults to accept a scrambled morning routine as something that happened previously. However, all ages would recognize that brushing one's teeth and then leaving on a bike match events stored in memory. While it is not hard to imagine that the concept of a "morning routine" allows adults to draw on their semantic knowledge to create this structure, here we have shown the same phenomenon exists with mere exposure to a simple, structured sequence of shapes—a situation devoid of meaning and perhaps less influenced by extra-experimental factors.

References

- Ahmad, F. N., Moscovitch, M., & Hockley, W. E. (2017). Effects of varying presentation time on long-term recognition memory for scenes: Verbatim and gist representations. *Memory and Cognition*, 45(3), 390–403. <https://doi.org/10.3758/s13421-016-0672-1>
- Arnon, I. (2020). Do current statistical learning tasks capture stable individual differences in children? An investigation of task reliability across modality. *Behavior Research Methods*, 52(1), 68–81. <https://doi.org/10.3758/s13428-019-01205-5>
- Barr, R., & Brito, N. (2014). *From Specificity to Flexibility*. 1023772.
- Batterink, L. J. (2017). Rapid Statistical Learning Supporting Word Extraction From Continuous Speech. *Psychological Science*. <https://doi.org/10.1177/0956797617698226>
- Bauer, P. J., Cronin-Golomb, L. M., Porter, B. M., Jaganjac, A., & Miller, H. E. (2020). Integration of memory content in adults and children: Developmental differences in task conditions and functional consequences. *Journal of Experimental Psychology: General*. <https://doi.org/10.1037/xge0000996>
- Bauer, P. J., King, J. E., Larkina, M., Varga, N. L., & White, E. A. (2012). Characters and clues: Factors affecting children's extension of knowledge through integration of separate episodes. *Journal of Experimental Child Psychology*, 111(4), 681–694. <https://doi.org/10.1016/j.jecp.2011.10.005>
- Bellana, B., Mansour, R., Ladyka-Wojcik, N., Grady, C. L., & Moscovitch, M. (2021). The influence of prior knowledge on the formation of detailed and durable memories. *Journal of Memory and Language*, 121(April 2020), 104264. <https://doi.org/10.1016/j.jml.2021.104264>
- Berch, D. B., & Evans, R. C. (1973). Decision processes in children's recognition memory. *Journal of Experimental Child Psychology*, 16(1), 148–164. [https://doi.org/10.1016/0022-0965\(73\)90069-6](https://doi.org/10.1016/0022-0965(73)90069-6)
- Billingsley, R. L., Smith, M. Lou, & McAndrews, M. P. (2002). Developmental patterns in priming and familiarity in explicit recollection. *Journal of Experimental Child Psychology*, 82, 251–277. [https://doi.org/10.1016/S0022-0965\(02\)00007-3](https://doi.org/10.1016/S0022-0965(02)00007-3)
- Brainerd, C. J., Holliday, R. E., & Reyna, V. F. (2004). Behavioral measurement of remembering phenomenologies: So simple a child can do it. *Child Development*, 75(2), 505–522. <https://doi.org/10.1111/j.1467-8624.2004.00690.x>
- Brainerd, C. J., & Reyna, V. F. (1996). Mere memory testing creates false memories in children. *Developmental Psychology*, 32(3), 467–478. <https://doi.org/10.1037/0012-1649.32.3.467>
- Brainerd, C. J., & Reyna, V. F. (2004). Fuzzy-trace theory and memory development. *Developmental Review*, 24(4), 396–439. <https://doi.org/10.1016/j.dr.2004.08.005>
- Brainerd, C. J., Reyna, V. F., & Brandse, E. (1995). Are children's false memories more persistent than their true memories? *Psychological Science*, 4(6), 359–364.
- Brown, M. R., Brown, N. L., & Caci, M. (1981). Serial Position Effects in Young Children: Temporal or Spatial? *Child Development*, 52(4), 1191–1201.
- Bruce, D., Dolan, A., & Phillips-Grant, K. (2000). On the transition from childhood amnesia to the recall of personal memories. *Psychological Science*, 11(5), 360–364. <https://doi.org/10.1111/1467-9280.00271>
- Brunec, I. K., Bellana, B., Ozubko, J. D., Man, V., Robin, J., Liu, Z. X., Grady, C., Rosenbaum, R. S., Winocur, G., Barense, M. D., & Moscovitch, M. (2018). Multiple Scales of Representation along the Hippocampal Anteroposterior Axis in Humans. *Current Biology*,

- 28(13), 2129–2135.e6. <https://doi.org/10.1016/j.cub.2018.05.016>
- Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, 1124, 77–97. <https://doi.org/10.1196/annals.1440.002>
- Calabro, F. J., Murty, V., & Luna, B. (2020). Development of Hippocampal-Prefrontal Cortex Interactions through Adolescence. *Cerebral Cortex*, 30(3), 1548–1558. <https://doi.org/10.1093/cercor/bhz186>
- Callaghan, B., Gasser, C., Silvers, J. A., VanTieghem, M., Choy, T., O’Sullivan, K., Tompary, A., Davachi, L., & Tottenham, N. (2021). Age-related increases in posterior hippocampal granularity are associated with remote detailed episodic memory in development. *Journal of Neuroscience*, 41(8), 1738–1754. <https://doi.org/10.1523/JNEUROSCI.1738-20.2020>
- Canada, K. L., Pathman, T., & Riggins, T. (2020). Longitudinal Development of Memory for Temporal Order in Early to Middle Childhood. *Journal of Genetic Psychology*, 181(4), 237–254. <https://doi.org/10.1080/00221325.2020.1741504>
- Clewett, D., Gasser, C., & Davachi, L. (2020). Pupil-linked arousal signals track the temporal organization of events in memory. *Nature Communications*, 11(1), 1–14. <https://doi.org/10.1038/s41467-020-17851-9>
- Daugherty, A. M., Bender, A. R., Raz, N., & Ofen, N. (2016). Age differences in hippocampal subfield volumes from childhood to late adulthood. *Hippocampus*, 26(2), 220–228. <https://doi.org/10.1002/hipo.22517>
- de Leeuw, J. R. (2015). jsPsych: A JavaScript library for creating behavioral experiments in a Web browser. *Behavior Research Methods*, 47(1), 1–12. <https://doi.org/10.3758/s13428-014-0458-y>
- DeMaster, D., Coughlin, C., & Ghetti, S. (2016). Retrieval flexibility and reinstatement in the developing hippocampus. *Hippocampus*, 26(4), 492–501. <https://doi.org/10.1002/hipo.22538>
- Demaster, D. M., & Ghetti, S. (2013). Developmental differences in hippocampal and cortical contributions to episodic retrieval. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 49(6), 1482–1493. <https://doi.org/10.1016/j.cortex.2012.08.004>
- DeMaster, D., Pathman, T., Lee, J. K., & Ghetti, S. (2014). Structural development of the hippocampus and episodic memory: Developmental differences along the anterior/posterior axis. *Cerebral Cortex*, 24(11), 3036–3045. <https://doi.org/10.1093/cercor/bht160>
- Drummey, A. B., & Newcombe, N. S. (2002). Developmental changes in source memory. *Developmental Science*, 5(4), 502–513. <https://doi.org/10.1111/1467-7687.00243>
- Dubrow, S., & Davachi, L. (2013). *The Influence of Context Boundaries on Memory for the Sequential Order of Events*. 142(4). <https://doi.org/10.1037/a0034024>
- Duff, M. C., & Brown-Schmidt, S. (2012). The hippocampus and the flexible use and processing of language. *Frontiers in Human Neuroscience*, 6(MARCH 2012), 1–11. <https://doi.org/10.3389/fnhum.2012.00069>
- Eichenbaum, H., & Cohen, N. J. (2001). From Conditioning to Conscious Recollection: Memory systems of the brain. In *From Conditioning to Conscious Recollection: Memory systems of the brain*. <https://doi.org/10.1093/acprof:oso/9780195178043.001.0001>
- Ellis, C. T., Skalaban, L. J., Yates, T. S., Bejjanki, V. R., Córdova, N. I., & Turk-Browne, N. B. (2021). Evidence of hippocampal learning in human infants. *Current Biology*, 31(15), 3358–3364.e4. <https://doi.org/10.1016/j.cub.2021.04.072>
- Finn, A. S., & Hudson Kam, C. L. (2008). The curse of knowledge: First language knowledge impairs adult learners’ use of novel statistics for word segmentation. *Cognition*, 108(2),

- 477–499. <https://doi.org/10.1016/j.cognition.2008.04.002>
- Finn, A. S., Kharitonova, M., Holtby, N., & Sheridan, M. A. (2018). Prefrontal and Hippocampal Structure Predict Statistical Learning Ability in Early Childhood. *Journal of Cognitive Neuroscience*, 31(1), 126–137. <https://doi.org/10.1162/jocn>
- Forest, T. A., Finn, A. S., & Schlichting, M. L. (2021). General Precedes Specific in Memory Representations for Structured Experience. *Journal of Experimental Psychology: General*, 2. <https://doi.org/http://dx.doi.org/10.1037/xge0001104>
- Forest, T. A., Lichtenfeld, A., Alvarez, B., & Finn, A. S. (2019). Superior learning in synesthetes: Consistent grapheme-color associations facilitate statistical learning. *Cognition*, 186, 72–81. <https://doi.org/10.1016/j.cognition.2019.02.003>
- Friedman, W. J. (1991). The Development of Children's Memory for the Time of Past Events. *Child Development*, 62(1), 139–155. <https://doi.org/10.1111/j.1467-8624.1991.tb01520.x>
- Friedman, W. J., & Lyon, T. D. (2005). Development of Temporal-Reconstructive Abilities. *Child Development*, 76(6), 1202–1216.
- Friedman, W. J., Reese, E., & Dai, X. (2011). Children's memory for the times of events from the past years. *Applied Cognitive Psychology*, 25(1), 156–165. <https://doi.org/10.1002/acp.1656>
- Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences*, 3(11), 410–419. [https://doi.org/10.1016/S1364-6613\(99\)01388-1](https://doi.org/10.1016/S1364-6613(99)01388-1)
- Ghetti, S. (2017). Development of item–space and item–time binding. *Current Opinion in Behavioral Sciences*, 17, 211–216. <https://doi.org/10.1016/j.cobeha.2017.09.002>
- Ghetti, S., & Angelini, L. (2008). The development of recollection and familiarity in childhood and adolescence: Evidence from the dual-process signal detection model. *Child Development*, 79(2), 339–358.
- Ghetti, S., & Bunge, S. A. (2012). Neural Changes Underlying the Development of Episodic Memory During Middle Childhood. *Developmental Cognitive Neuroscience*, 4(2), 1–29. <https://doi.org/10.1158/0008-5472.CAN-10-4002.BONE>
- Ghetti, S., & Fandakova, Y. (2020). Neural Development of Memory and Metamemory in Childhood and Adolescence: Toward an Integrative Model of the Development of Episodic Recollection. *Annual Review of Developmental Psychology*, 2(1), 365–388. <https://doi.org/10.1146/annurev-devpsych-060320-085634>
- Gilboa, A., & Marlatt, H. (2017). Neurobiology of Schemas and Schema-Mediated Memory. *Trends in Cognitive Sciences*, 21(8), 618–631. <https://doi.org/10.1016/j.tics.2017.04.013>
- Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., Herman, D. H., Clasen, L. S., Toga, A. W., Rapoport, J. L., & Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences of the United States of America*, 101(21), 8174–8179. <https://doi.org/10.1073/pnas.0402680101>
- Gómez-Ariza, C. J., & Bajo, M. T. (2003). Interference and integration: The fan effect in children and adults. *Memory*, 11(6), 505–523. <https://doi.org/10.1080/09658210244000090>
- Gomez, R. L. (2016). Do infants retain the statistics of a statistical learning experience? Insights from a developmental cognitive neuroscience perspective. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1711), 20160054. <https://doi.org/10.1098/rstb.2016.0054>
- Gómez, R. L., & Edgin, J. O. (2016). The extended trajectory of hippocampal development :

- Implications for early memory development and disorder. *Developmental Cognitive Neuroscience*, 18, 57–69. <https://doi.org/10.1016/j.dcn.2015.08.009>
- Gualtieri, S., & Finn, A. S. (2021). (Accepted) The sweet spot: When children's developing abilities, brains, and knowledge make them better learners Samantha. *Perspectives on Psychological Science*.
- Howard, M. W., & Kahana, M. J. (2002). *A Distributed Representation of Temporal Context*. 299, 269–299. <https://doi.org/10.1006/jmps.2001.1388>
- Hsieh, L.-T., Gruber, M. J., Jenkins, L. J., & Ranganath, C. (2014). Hippocampal Activity Patterns Carry Information about Objects in Temporal Context. *Neuron*, 81(5), 1165–1178. <https://doi.org/10.1016/j.neuron.2014.01.015>.Hippocampal
- Hudson, J. A., Fivush, R., & Kuebli, J. (1992). Scripts and episodes: The development of event memory. *Applied Cognitive Psychology*, 6(6), 483–505. <https://doi.org/10.1002/acp.2350060604>
- Hulme, C., Thomson, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short-term memory span. *Journal of Experimental Child Psychology*, 38(2), 241–253. [https://doi.org/10.1016/0022-0965\(84\)90124-3](https://doi.org/10.1016/0022-0965(84)90124-3)
- Jabès, A., & Nelson, C. A. (2015). 20 years after “the ontogeny of human memory: A cognitive neuroscience perspective,” where are we? *International Journal of Behavioral Development*, 39(4), 293–303. <https://doi.org/10.1177/0165025415575766>
- James, E., Ong, G., Henderson, L. M., & Horner, A. J. (2021). The Formation and Retrieval of Holistic Event Memories Across Development. *Journal of Cognition*, 4(1), 1–9. <https://doi.org/10.5334/joc.149>
- Jung, Y., Walther, D. B., & Finn, A. S. (2020). Children automatically abstract categorical regularities during statistical learning. *Developmental Science*, 24(November), 1–12. <https://doi.org/10.1111/desc.13072>
- Kensinger, E. A., & Schacter, D. L. (1999). When true memories suppress false memories: Effects of ageing. *Cognitive Neuropsychology*, 16(3–5), 399–415. <https://doi.org/10.1080/026432999380852>
- Keresztes, A., Bender, A. R., Bodammer, N. C., Lindenberger, U., Shing, Y. L., & Werkle-Bergner, M. (2017). Hippocampal maturity promotes memory distinctiveness in childhood and adolescence. *Proceedings of the National Academy of Sciences of the United States of America*, 114(34), 9212–9217. <https://doi.org/10.1073/pnas.1710654114>
- Keresztes, A., Ngo, C. T., Lindenberger, U., Werkle-Bergner, M., & Newcombe, N. S. (2018). Hippocampal Maturation Drives Memory from Generalization to Specificity. *Trends in Cognitive Sciences*, 22(8), 676–686. <https://doi.org/10.1016/j.tics.2018.05.004>
- Kikumoto, A., & Mayr, U. (2018). Decoding hierarchical control of sequential behavior in oscillatory EEG activity. *ELife*, 7, 1–36. <https://doi.org/10.7554/eLife.38550>
- Kosie, J. E., & Baldwin, D. (2019). Attention rapidly reorganizes to naturally occurring structure in a novel activity sequence. *Cognition*, 182(September 2018), 31–44. <https://doi.org/10.1016/j.cognition.2018.09.004>
- Kurby, C. A., & Zacks, J. M. (2008). Segmentation in the perception and memory of events. *Trends in Cognitive Sciences*, 12(2), 72–79. <https://doi.org/10.1016/j.tics.2007.11.004>
- Langnes, E., Sneve, M. H., Sederevicius, D., Amlien, I. K., Walhovd, K. B., & Fjell, A. M. (2020). Anterior and posterior hippocampus macro- and microstructure across the lifespan in relation to memory—A longitudinal study. *Hippocampus*, 30(7), 678–692. <https://doi.org/10.1002/hipo.23189>

- Lavenex, P., & Banta Lavenex, P. (2013). Building hippocampal circuits to learn and remember: Insights into the development of human memory. *Behavioural Brain Research*, 254, 8–21. <https://doi.org/10.1016/j.bbr.2013.02.007>
- Lee, A. C. H., Barense, M. D., & Graham, K. S. (2005). The contribution of the human medial temporal lobe to perception: Bridging the gap between animal and human studies. *Quarterly Journal of Experimental Psychology Section B: Comparative and Physiological Psychology*, 58(3–4), 300–325. <https://doi.org/10.1080/02724990444000168>
- Lee, J. K., Fandakova, Y., Johnson, E. G., Cohen, N. J., Bunge, S. A., & Ghetti, S. (2020). Changes in anterior and posterior hippocampus differentially predict item-space, item-time, and item-item memory improvement. *Developmental Cognitive Neuroscience*, 41, 100741. <https://doi.org/10.1016/j.dcn.2019.100741>
- Lee, J. K., Wendelken, C., Bunge, S. A., & Ghetti, S. (2016). A Time and Place for Everything: Developmental Differences in the Building Blocks of Episodic Memory. *Child Development*, 87(1), 194–210. <https://doi.org/10.1111/CDEV.12447>
- Lloyd, M. E., Doydum, A. O., & Newcombe, N. S. (2009). Memory binding in early childhood: Evidence for a retrieval deficit. *Child Development*, 80(5), 1321–1328. <https://doi.org/10.1111/j.1467-8624.2009.01353.x>
- Luo, Y., & Zhao, J. (2018). *Statistical Learning Creates Novel Object Associations via Transitive Relations*. <https://doi.org/10.1177/0956797618762400>
- McClelland, J. L., McNaughton, B. L., & O'Reilly, R. C. (1995). Why there are Complementary Learning Systems in the Hippocampus and Neocortex: Insights from the Successes and Failures of Connectionist Models of Learning and Memory. *Psychological Review*, 102(3), 419–457. <https://doi.org/10.1037/0033-295X.102.3.419>
- Moscovitch, M., Cabeza, R., Winocur, G., & Nadel, L. (2016). Episodic Memory and Beyond: The Hippocampus and Neocortex in Transformation. *Annual Review of Psychology*, 67, 105–. <https://doi.org/10.1146/annurev-psych-113011-143733>
- Newcombe, N. S., Drummey, A. B., Fox, N. A., Lie, E., & Ottinger-Alberts, W. (2000). Remembering early childhood: How much, how, and why (or why not). *Current Directions in Psychological Science*, 9(2), 55–58. <https://doi.org/10.1111/1467-8721.00060>
- Ngo, C. T., Benear, S. L., Popal, H., Olson, I., & Newcombe, N. S. (2021). Contingency of Semantic Generalization on Episodic Specificity: Variations Across Development. *Current Biology*, 31, 1–8. <https://doi.org/10.2139/ssrn.3732375>
- Ngo, C. T., Horner, A. J., Newcombe, N. S., & Olson, I. R. (2019). Development of Holistic Episodic Recollection. *Psychological Science*, 30(12), 1696–1706. <https://doi.org/10.1177/0956797619879441>
- Ngo, C. T., Lin, Y., Newcombe, N. S., & Olson, I. R. (2019). Building up and wearing down episodic memory: Mnemonic discrimination and relational binding. *Journal of Experimental Psychology: General*, 148(9), 1463–1479. <https://doi.org/10.1037/xge0000583>
- Ngo, C. T., Newcombe, N. S., & Olson, I. R. (2017). The ontogeny of relational memory and pattern separation. *Developmental Science*, 21(2), 1–11. <https://doi.org/10.1111/desc.12556>
- Ofen, N., Chai, X. J., Schuil, K. D. I., Whitfield-Gabrieli, S., & Gabrieli, J. D. E. (2012). The development of brain systems associated with successful memory retrieval of scenes. *Journal of Neuroscience*, 32(29), 10012–10020. <https://doi.org/10.1523/JNEUROSCI.1082-11.2012>
- Olson, I. R., & Newcombe, N. S. (2014). Binding together the elements of episodes. In *Wiley*

- Handbook on Child Development* (pp. 285–308).
- Park, S. H., Rogers, L. L., & Vickery, T. J. (2018). The roles of order, distance, and interstitial items in temporal visual statistical learning. *Attention, Perception, and Psychophysics*, 80(6), 1409–1419. <https://doi.org/10.3758/s13414-018-1556-1>
- Pathman, T., Doydum, A., & Bauer, P. J. (2013). Bringing order to life events: Memory for the temporal order of autobiographical events over an extended period in school-aged children and adults. *Journal of Experimental Child Psychology*, 115(2), 309–325. <https://doi.org/10.1016/j.jecp.2013.01.011>
- Pathman, T., & Gheetti, S. (2014). The Eyes Know Time: A Novel Paradigm to Reveal the Development of Temporal Memory. *Child Development*, 85(2), 792–807. <https://doi.org/10.1111/cdev.12152>
- Pathman, T., & Gheetti, S. (2015). Eye movements provide an index of veridical memory for temporal order. *PLoS ONE*, 10(5), 1–17. <https://doi.org/10.1371/journal.pone.0125648>
- Paz-Alonso, P. M., Gheetti, S., Donohue, S. E., Goodman, G. S., & Bunge, S. A. (2008). Neurodevelopmental correlates of true and false recognition. *Cerebral Cortex*, 18(9), 2208–2216. <https://doi.org/10.1093/cercor/bhm246>
- Pearce, J. W. (2009). *Generating stimuli for neuroscience using PsychoPy*. 2(January), 1–8. <https://doi.org/10.3389/neuro.11.010.2008>
- Picard, L., Cousin, S., Guillery-Girard, B., Eustache, F., & Piolino, P. (2012). How Do the Different Components of Episodic Memory Develop? Role of Executive Functions and Short-Term Feature-Binding Abilities. *Child Development*, 83(3), 1037–1050. <https://doi.org/10.1111/j.1467-8624.2012.01736.x>
- Piolino, P., Hisland, M., Ruffeveille, I., Matuszewski, V., Jambaqué, I., & Eustache, F. (2007). Do school-age children remember or know the personal past? *Consciousness and Cognition*, 16(1), 84–101. <https://doi.org/10.1016/j.concog.2005.09.010>
- Poole, D. A., & White, L. T. (1991). Effects of Question Repetition on the Eyewitness Testimony of Children and Adults. *Developmental Psychology*, 27(6), 975–986. <https://doi.org/10.1037/0012-1649.27.6.975>
- Pudhiyidath, A., Roome, H. E., Coughlin, C., Nguyen, K. V., & Preston, A. R. (2020). Developmental differences in temporal schema acquisition impact reasoning decisions. *Cognitive Neuropsychology*, 3294(0), 1–21. <https://doi.org/10.1080/02643294.2019.1667316>
- Raj, V., & Bell, M. A. (2010). Cognitive processes supporting episodic memory formation in childhood: The role of source memory, binding, and executive functioning. *Developmental Review*, 30(4), 384–402. <https://doi.org/10.1016/j.dr.2011.02.001>
- Ramsaran, A. I., Schlichting, M. L., & Frankland, P. W. (2019). The ontogeny of memory persistence and specificity. *Developmental Cognitive Neuroscience*, 36(September 2018), 100591. <https://doi.org/10.1016/j.dcn.2018.09.002>
- Raviv, L., & Arnon, I. (2018). The developmental trajectory of children's auditory and visual statistical learning abilities: modality-based differences in the effect of age. *Developmental Science*, 21(4), 1–13. <https://doi.org/10.1111/desc.12593>
- Ribordy, F., Jabès, A., Banta Lavenex, P., & Lavenex, P. (2013). Development of allocentric spatial memory abilities in children from 18 months to 5 years of age. *Cognitive Psychology*, 66(1), 1–29. <https://doi.org/10.1016/j.cogpsych.2012.08.001>
- Richards, B. A., Xia, F., Santoro, A., Husse, J., Woodin, M. A., Josselyn, S. A., & Frankland, P. W. (2014). Patterns across multiple memories are identified over time. *Nature*

- Neuroscience*, 17(7), 981–986. <https://doi.org/10.1038/nn.3736>
- Richmond, J., & Nelson, C. A. (2009). Relational memory during infancy: evidence from eye tracking. *Developmental Science*, 12(4), 549–556. <https://doi.org/10.1111/J.1467-7687.2009.00795.X>
- Riggins, T. (2014). Longitudinal investigation of source memory reveals different developmental trajectories for item memory and binding. *Developmental Psychology*, 50(2), 449–459. <https://doi.org/10.1037/a0033622>
- Riggins, T., Canada, K. L., & Botdorf, M. (2020). Empirical Evidence Supporting Neural Contributions to Episodic Memory Development in Early Childhood: Implications for Childhood Amnesia. *Child Development Perspectives*, 14(1), 41–48. <https://doi.org/10.1111/cdep.12353>
- Riggins, T., Geng, F., Botdorf, M., Canada, K., Cox, L., & Hancock, G. R. (2018). Protracted hippocampal development is associated with age-related improvements in memory during early childhood. *NeuroImage*, 174(February), 127–137. <https://doi.org/10.1016/j.neuroimage.2018.03.009>
- Rollins, L., & Cloude, E. B. (2018). Development of mnemonic discrimination during childhood. *Learning and Memory*, 25(6), 294–297. <https://doi.org/10.1101/lm.047142.117>
- Saffran, J. R. (2020). Statistical Language Learning in Infancy. *Child Development Perspectives*, 14(1), 49–54. <https://doi.org/10.1111/cdep.12355>
- Saffran, J. R., Newport, E. L., Aslin, R. N., Tunick, R. A., & Barrueco, S. (1997). Incidental Language Learning: Listening (and Learning) out of the Corner of Your Ear. *Psychological Science*, 8(2), 101–105. <https://doi.org/10.1111/j.1467-9280.1997.tb00690.x>
- Saragosa-Harris, N. M., Cohen, A. O., Shen, X., Sardar, H., Alberini, C. M., & Hartley, C. A. (2021). Associative memory persistence in 3- to 5-year-olds. *Developmental Science*, January, 1–9. <https://doi.org/10.1111/desc.13105>
- Schapiro, A. C., Gregory, E., Landau, B., McCloskey, M., & Turk-Browne, N. B. (2014). The Necessity of the Medial Temporal Lobe for Statistical Learning. *Journal of Cognitive Neuroscience*, 26(8), 1736–1747. <https://doi.org/10.1162/jocn>
- Schapiro, A. C., Kustner, L. V., & Turk-Browne, N. B. (2012). Shaping of object representations in the human medial temporal lobe based on temporal regularities. *Current Biology*, 22(17), 1622–1627. <https://doi.org/10.1016/j.cub.2012.06.056>
- Schapiro, A. C., Turk-Browne, N. B., Botvinick, M. M., & Norman, K. A. (2017). Complementary learning systems within the hippocampus: a neural network modelling approach to reconciling episodic memory with statistical learning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1711), 20160049. <https://doi.org/10.1098/rstb.2016.0049>
- Schapiro, A. C., Turk-Browne, N. B., Norman, K. A., & Botvinick, M. M. (2016). Statistical learning of temporal community structure in the hippocampus. *Hippocampus*, 26(1), 3–8. <https://doi.org/10.1002/hipo.22523>
- Schlichting, M. L., Guarino, K. F. K. F., Schapiro, A. C., Turk-browne, N. B., & Preston, A. R. (2016). Hippocampal Structure Predicts Statistical Learning and Associative Inference Abilities during Development. *Journal of Cognitive Neuroscience*, 29(1), 37–51. <https://doi.org/10.1162/jocn>
- Schlichting, M. L., Guarino, K. F., Roome, H. E., & Preston, A. R. (2021). Developmental differences in memory reactivation relate to encoding and inference in the human brain. *Nature Human Behaviour*.

- Schlichting, M. L., Mumford, J. A., & Preston, A. R. (2015). Learning-related representational changes reveal dissociable integration and separation signatures in the hippocampus and prefrontal cortex. *Nature Communications*, 6, 1–10. <https://doi.org/10.1038/ncomms9151>
- Schlichting, M. L., & Preston, A. R. (2015). Memory integration: Neural mechanisms and implications for behavior. *Current Opinion in Behavioral Sciences*, 1, 1–8. <https://doi.org/10.1016/j.cobeha.2014.07.005>
- Scoville, W. B., & Milner, B. (1957). Loss of recent memory after bilateral hippocampal lesions. *The Journal of Neuropsychiatry and Clinical Neurosciences*, 20(11), 11–21. <https://doi.org/10.1176/jnp.12.1.103-a>
- Shing, Y. L., Finke, C., Hoffmann, M., Pajkert, A., Heekeren, H. R., & Ploner, C. J. (2019). Integrating across memory episodes: Developmental trends. *PLoS ONE*, 14(4), 1–11. <https://doi.org/10.1371/journal.pone.0215848>
- Shing, Y. L., Werkle-Bergner, M., Brehmer, Y., Müller, V., Li, S. C., & Lindenberger, U. (2010). Episodic memory across the lifespan: The contributions of associative and strategic components. *Neuroscience and Biobehavioral Reviews*, 34(7), 1080–1091. <https://doi.org/10.1016/j.neubiorev.2009.11.002>
- Shohamy, D., & Turk-Browne, N. B. (2013). Mechanisms for widespread hippocampal involvement in cognition. *Journal of Experimental Psychology: General*, 142(4), 1159–1170. <https://doi.org/10.1037/a0034461>
- Shufaniya, A., & Arnon, I. (2018). Statistical Learning Is Not Age-Invariant During Childhood: Performance Improves With Age Across Modality. *Cognitive Science*, 42(8), 3100–3115. <https://doi.org/10.1111/cogs.12692>
- Slone, L. K., & Johnson, S. P. (2018). When learning goes beyond statistics: Infants represent visual sequences in terms of chunks. *Cognition*, 178(May), 92–102. <https://doi.org/10.1016/j.cognition.2018.05.016>
- Sloutsky, V. M., & Fisher, A. V. (2004). When development and learning decrease memory: Evidence against category-based induction in children. *Psychological Science*, 15(8), 553–558. <https://doi.org/10.1111/j.0956-7976.2004.00718.x>
- Sluzenski, J., Newcombe, N. S., & Kovacs, S. L. (2006). Binding, relational memory, and recall of naturalistic events: A developmental perspective. *Journal of Experimental Psychology: Learning Memory and Cognition*, 32(1), 89–100. <https://doi.org/10.1037/0278-7393.32.1.89>
- Smith, L. B., Jayaraman, S., Clerkin, E., & Yu, C. (2018). The Developing Infant Creates a Curriculum for Statistical Learning. *Trends in Cognitive Sciences*, 1–12. <https://doi.org/10.1016/j.tics.2018.02.004>
- Tompary, A., Zhou, W. X., & Davachi, L. (2020). Schematic memories develop quickly, but are not expressed unless necessary. *Scientific Reports*, 10(1), 1–17. <https://doi.org/10.1038/s41598-020-73952-x>
- Turk-Browne, N. B., Jungé, J., & Scholl, B. J. (2005). The automaticity of visual statistical learning. *Journal of Experimental Psychology: General*, 134(4), 552–564. <https://doi.org/10.1037/0096-3445.134.4.552>
- Vlach, H. A. (2014). The Spacing Effect in Children’s Generalization of Knowledge: Allowing Children Time to Forget Promotes Their Ability to Learn. *Child Development Perspectives*, 8(3), 163–168. <https://doi.org/10.1111/CDEP.12079>
- Zeithamova, D., & Bowman, C. R. (2020). Generalization and the hippocampus: More than one story? *Neurobiology of Learning and Memory*, 175(July). <https://doi.org/10.1016/j.nlm.2020.107317>