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Received: 13 May 2022 | Revised: 14 November 2022 | Accepted: 3 January 2023

DOI: 10.1111/desc.13371

Developmental Science WILEY

RESEARCH ARTICLE

Learning strategy differentially impacts memory connections in children and adults

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Abstract

Even once children can accurately remember their experiences, they nevertheless struggle to use those memories in flexible new ways—as in when drawing inferences. However, it remains an open question as to whether the developmental differences observed during both memory formation and inference itself represent a fundamental limitation on children's learning mechanisms, or rather their deployment of suboptimal strategy. Here, 7–9-year-old children (*N* = 154) and young adults (*N* = 130) first formed strong memories for initial (AB) associations and then engaged in one of three learning strategies as they viewed overlapping (BC) pairs. We found that being told to integrate—combine ABC during learning—both significantly improved children's ability to explicitly relate the indirectly associated A and C items during inference and protected the underlying pair memories from forgetting. However, this finding contrasted with implicit evidence for memory-to-memory connections: Adults and children both formed A-C links prior to any knowledge of an inference test—yet for children, such links were most apparent when they were told to simply encode BC, not integrate. Moreover, the accessibility of such implicit links differed between children and adults, with adults using them to make explicit inferences but children only doing so for well-established direct AB pairs. These results suggest that while a lack of integration strategy may explain a large share of the developmental differences in explicit inference, children and adults nevertheless differ in both the circumstances under which they connect interrelated memories and their ability to later leverage those links to inform flexible behaviours.

KEYWORDS
development, explicit memory, implicit memory, inferential reasoning, memory integration, priming

Research Highlights

- Children and adults view AB and BC pairs related through a shared item, B. This provides an opportunity for learners to connect A–C in memory.
- Being encouraged to integrate ABC during learning boosted performance on an explicit test of A–C connections (children and adults) and protected from forgetting (children).
- Children and adults differed in when implicit A–C connections were formed—occurring primarily when told to separately encode BC (children) versus integrate (adults), respectively.
- Adults used implicit A–C connections to facilitate explicit judgments, while children did not. Our results suggest developmental differences in the learning conditions promoting memory-to-memory connections.

1 | INTRODUCTION

Memories can be used not only to reflect upon the past, but also to guide present and future behaviour (Mack et al., 2018; Schlichting & Preston, 2015; Zeithamova et al., 2012). Indeed, we often draw upon memories of specific episodes to solve unanticipated problems (Carpenter et al., 2021; Giovanello et al., 2009; Zalesak & Heckers, 2009) or imagine never-experienced scenarios (Addis et al., 2011; Schacter et al., 2012). This ability to generate new information by integrating across multiple events is a key function of memory (Sheldon & Levine, 2016; Zeidman & Maguire, 2016)—and yet, one that might emerge relatively late in development (Bauer et al., 2015; Coughlin et al., 2014; DeMaster et al., 2015; Ghetti & Coughlin, 2018; Schlichting et al., 2017, 2022; Shing et al., 2019; Varga & Bauer, 2013). Specifically, past work has shown that children struggle to use their memories flexibly, even despite remembering the underlying experiences (Bauer & San Souci, 2010; Schlichting et al., 2017, 2022). Mechanistically, it has been suggested that such difficulty might lie in *when* memory-to-memory connections are formed: While adults can integrate during learning (i.e., engage in 'integrative encoding'; Schlichting & Preston, 2016; Schlichting et al., 2014, 2015; Shohamy & Wagner, 2008; Varga & Bauer, 2017a; Varga & Manns, 2021; Zeithamova & Preston, 2010; Zeithamova, Dominick & Preston, 2012), children and adolescents might instead wait for an explicit prompt at test (Bauer et al., 2015, 2020a; Varga & Bauer, 2013). These tendencies would yield different memory structures with distinct associated demands for a later test: While adults may already boast the connections needed to support the new decision, children instead would need to make such connections during the judgment itself—taxing young learners with additional operations and ultimately impeding performance.

Despite growing research on this topic, there remain at least two (non-mutually exclusive) possible explanations as to why children do not integrate until prompted. First, it may be the case that integrative encoding—a complex, multi-step process (Bauer & Varga, 2017; Zeithamova, Schlichting et al., 2012), requiring first reactivation of related memories during learning followed by integration upon detecting associative novelty (Schlichting et al., 2014; van Kesteren et al., 2020; Zeithamova & Preston, 2017; Zeithamova, Dominick et al., 2012)—is simply neurocognitively out of reach for children. Children would fail to integrate if the cognitive mechanisms supporting any of these steps were immature—and indeed, past work has shown that children under 10 years of age do not engage in even the first of these steps (reactivation; Miller-Goldwater et al., 2021; Schlichting et al., 2022). However, a second possibility is that adults, but not children, deploy a top-down integration 'strategy,' which could widen the developmental performance gap. Research in adults suggests that although integrative encoding can be engaged in the absence of awareness (Shohamy & Wagner, 2008), both awareness (Varga & Bauer, 2017b) and instruction (Burton et al., 2017) increase its likelihood. Because adults may be better poised to detect the relationships between experiences and/or anticipate a wider array of memory tests than children, they may adopt a more advantageous learning strategy accordingly (Shing et al., 2008, 2010). If lack of an integration strategy is the main source of developmental difference, it would follow that instructing children to integrate during learning would enhance performance. However, if instead children are not yet *able* to integrate, then encouraging them to do so would not help—and might even hurt—performance. We assess these possibilities here.

We additionally reasoned that many explicit tests of memory and inference put children at a disadvantage—due not necessarily to the memory content itself, but rather to demands (e.g., control, interference resolution, selection) related to test format. We aimed to disambiguate these two possible sources of developmental change. As such, we adopted a priming task as an implicit—and relatively purer—measure of memory-to-memory connections (Davis et al., 2021). Past work using similar approaches has shown that priming (i.e., facilitated processing of a target item when preceded by its associate) is sensitive to even arbitrary, experiment-defined pairings (McKoon & Ratcliff, 1979); it is also present even in young children and relatively stable over development (McCauley et al., 1976; McFarland & Kellas, 1975; see also Hasher & Zacks, 1979; Parkin & Streete, 1988). Coupled with typical explicit assessments, we were therefore poised to ask whether development is attributable mainly to a differential tendency to form associative connections (which would be evident in both implicit and explicit tests), or rather differential ability to engage top-down influences at retrieval (only explicit).

We had children and young adults learn overlapping associations (AB, BC) that provided an opportunity for integration (ABC). We tested 7–9-year-old children as we anticipated that while they would be capable of doing the task, they would nevertheless accomplish it differently than adults (Schlichting et al., 2017, 2022; Shing et al., 2019; Wilson & Bauer, 2021). Our key manipulation was in the instructions participants received prior to viewing BC pairs: one third of our participants were told each to retrieve (i.e., recall the related AB pair and ignore BC), encode (focus on the current BC), or integrate (recall A and combine it with BC; an instruction shown to increase integration among adults; Burton et al., 2017; Richter et al., 2015). Integration was indexed as a connection between A and C items, which we quantified first in implicit priming and then explicit inference tests. We hypothesized that in contrast to adults, children would both (1) not exhibit A-C connections in the priming task because it occurred prior to a prompt; and (2) perform best on explicit inference when encouraged to simply encode BC due to their reduced capacity for integrative encoding. We additionally anticipated that children instructed to retrieve might be unable to ignore BC, and therefore have paradoxically better memory for the (irrelevant) BC pairs than adults.

2 | METHOD

Our hypotheses, sample size, and analysis approach were preregistered (https://osf.io/fmv3w/), with deviations as noted.

2.1 | Participants

Results are from 130 adults (96 female, 34 male; age range = 25.02–35.95 years [y], mean = 29.17, standard deviation [SD] = 2.99) and 154 children (80 female, 74 male; age range = 7.01–9.93 y, mean = 8.51, SD = 0.85) who met our preregistered inclusion criteria (see Supplementary Information for full sample details). Fifty-one additional participants were tested and excluded for reasons related to their performance: failure to perform the instructed encoding strategy (perhaps due to poor instruction comprehension, described below; 18 children, seven adults); and subthreshold memory for the initial (AB) pairs (defined as <80% correct on the last test round of the initial learning phase; 22 children; four adults). Our reason for requiring near-perfect memory for AB pairs was to ensure that the results are based on our manipulation during the overlapping (BC) exposure and not due to inadequate initial memory. Comparing participants who were ultimately included versus those who were excluded for performance-related reasons revealed no significant differences in working memory in either age group (two-sample t-tests; children: $t(48.72) = 1.66$, $p = 0.102$; adults: $t(11.06) = 1.04$, $p = 0.319$).

Participants were randomly assigned to an instruction condition (retrieve, encode or integrate), and conditions did not differ in terms of age (children: $F(2{,}151) = 0.729$, $p = 0.484$; adults: $F(2{,}127) = 0.162$, $p = 0.850$) or working memory (Supplementary Methods; children: $F(2{,}142) = 2.696$, $p = 0.071$; adults: $F(2{,}125) = 0.326$, $p = 0.723$).

2.2 | Stimuli

Stimuli were pictures of 90 common objects selected as being likely familiar to 7-year-old children (based on age-of-acquisition norms; Kuperman et al., 2012). Objects were organized into 30 ABC 'triads'. Each triad consisted of a fixed set of A, B and C objects of low semantic similarity as determined using WordNet::Similarity (https://wn-similarity.sourceforge.net). Of the 30 triads, six were 'catch' and 24 were 'experimental' triads. Catch triads were included purely to ensure participants were following instructions and were excluded from all analyses. Assignment of stimuli to A, B and C positions within a triad was counterbalanced across participants such that each object occurred equally often in each position.

2.3 | Procedure

Participants provided informed consent (adults) or verbal assent (children); parents/guardians also provided permission for children. Procedures were approved by the ethics committee at our institution, and participants were compensated for their time at a rate of $10/hour.

Sessions were run remotely via video conferencing (Zoom), and the task was presented to participants on their personal computers using Inquisit (programmed in Inquisit 5; https://www.millisecond.com). Each session lasted on average 1.5–2 h. Participants viewed ABC triads as overlapping AB and BC pairs in an associative inference task (Preston et al., 2004) with four phases: Initial (AB) learning, overlapping (BC) exposure, preference (priming) task and final (AC inference and direct) test (Figure 1). Since we manipulated task instructions and experiences were otherwise identical across participants, experimenters were hypothesis-blind and only un-blinded after data collection. Task instructions and practice trials were given to participants immediately before each phase, as described below. For additional procedural details, see Supplementary Methods.

2.3.1 | Initial (AB) learning

During this phase, participants established near-perfect memory for all 30 AB pairs across three study-test cycles. Prior to beginning AB learning, participants were told that they would see two objects on the screen and that they should create a story to help them remember the pair. They were also informed as to how they would be tested on their memory for the AB pairs and encouraged to think back to the stories they made up during learning to help them remember. Participants completed a practice which was identical to the real AB learning,

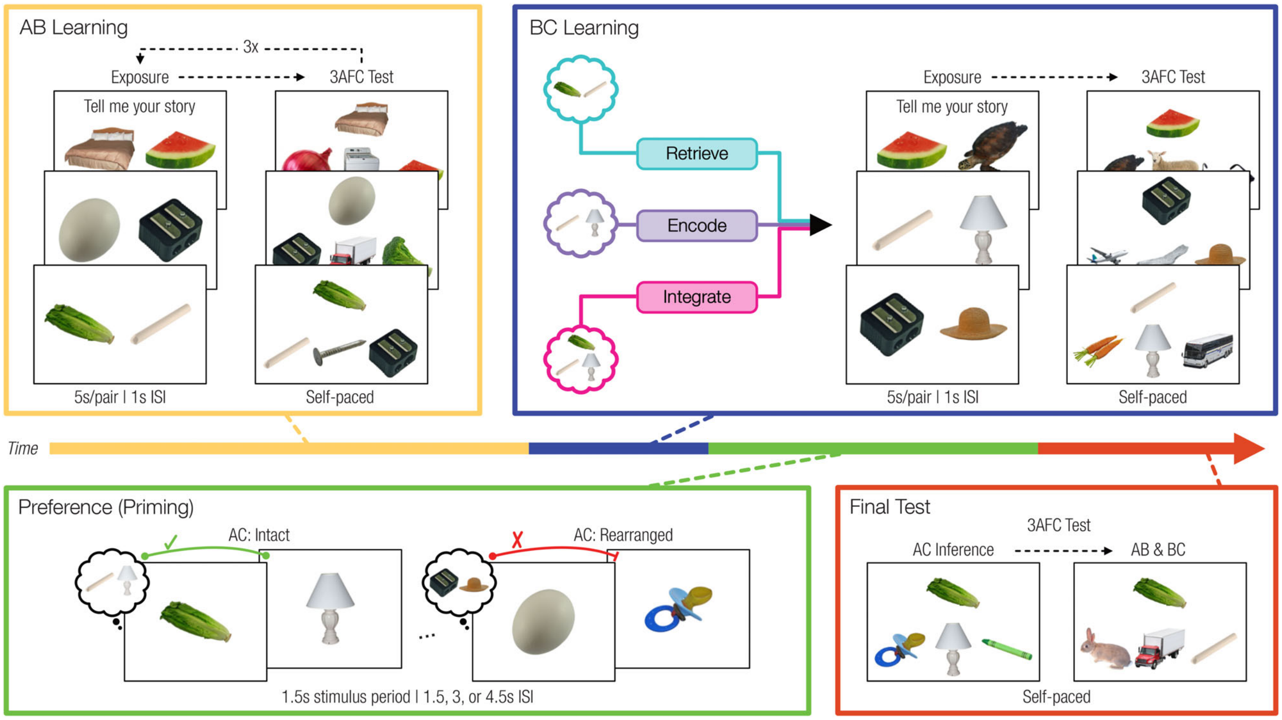

FIGURE 1 Task schematic depicting four experimental phases (coloured boxes; top and bottom) and their order (timeline; middle). During AB learning (top left, yellow), participants studied AB associations (e.g., bed-watermelon) across three study-test cycles. Then, during BC exposure (top right, navy), participants saw a single presentation of overlapping associations (e.g., watermelon-turtle) with which they performed one of three tasks (teal, purple, pink)—retrieve, encode, or integrate—and then took a memory test. Next, participants completed a priming task designed to measure whether connections existed between A and C items in memory (bottom left, green). Predictions are schematized for an intact (left) and rearranged (right) pairing, where presentation of the first object (e.g., lettuce) would facilitate processing of the second (lamp) if the objects were associated in memory (intact; denoted by green connecting line and check mark) and slowed if they were not (egg and pacifier are a rearranged pair; red line and x). Lastly, participants took a final test (bottom right, red) that included both inferential (left) and direct (right) associations.

but with fewer pairs and stimuli that were separate from those used in the main experiment.

During study trials, participants viewed an AB pair (A on the left, B on the right) and were asked to create a story relating the two objects. For most trials (experimental; 5 s stimulus with 1 s inter-stimulus interval [ISI]), participants did not make any overt response but internally rehearsed their story; however, for some trials (catch, first repetition only; 14 s stimulus with 1 s ISI), participants were cued with the text ‘Tell me your story’ appearing on the screen to say their story aloud. Catch trial stories were transcribed by the experimenter and subsequently scored by the first author (ZA) to ensure compliance (Supplementary Methods).

After each study, participants completed a self-paced three alternative-forced-choice (3AFC) test for all 30 AB pairs. Participants were cued with A and were asked to select the associated B. Incorrect options (foils) were familiar B stimuli from other triads. Moreover, experimental triads were never foiled with catch triads or vice versa, such that participants would not be able to use memory for the nature of their response at encoding (i.e., whether the story was produced aloud or rehearsed internally) to influence their selection. Once the participants completed the three study-test blocks, they took a 5-min break during which time they worked on an unrelated puzzle.

2.3.2 | Overlapping (BC) exposure

Having formed strong memories for the initial AB pairs, participants were then shown one repetition of each BC pair (i.e., single-shot learning). Prior to beginning this phase, all participants were informed that they would see new pairs but that one of the objects would be old, because it was shown in a pair they saw in the previous learning phase. Participants were also told they would be tested on their memory in the same way as before.

On each trial, participants were presented with a BC pair (B on the left; experimental trials were 5 s stimulus, 1 s ISI) and asked to create a story to help their memory. Participants were given different instructions about the kind of story they should create, which yielded the retrieve, encode and integrate conditions (Richter et al., 2015; in our study, this was an across-participants manipulation). Participants in the retrieve condition were instructed to ignore the current BC pair and think back to their related AB pair story; in the encode condition, to create a story relating the two new BC objects; and in the integrate condition, to recall the associated A object and create a story relating all three (A, B, C) objects. Encode and integrate strategies were meant to mimic separate encoding of AB and BC for later recombination (somewhat akin to what we posited as the naturalistic tendency of children) and ABC integration (tendency of adults), respectively. The retrieve condition was additionally included to assess whether children form associations among to-be-ignored stimuli, yielding the possibility that children might outperform adults in BC memory. We assessed participants' compliance with these instructions through the inclusion of catch trials, in which they spoke their stories aloud (as in AB learning; 14 s stimulus, 1 s ISI). Participants had an opportunity to practice the learning task with separate pairs prior to beginning the real BC learning phase, and were provided with corrective feedback if they incorporated the wrong items into their practice stories.

After BC exposure, participants were tested on their memory for all BC pairs using a self-paced 3AFC test that was similar in format to the AB test. B objects served as prompts, and the correct C objects were presented among foils from other triads of the same type (experimental or catch).

2.3.3 | Preference (priming) task

Next, participants completed a preference task designed as an indirect measure of associative memory. Participants were told that this was a new game where we were interested in knowing what kinds of things they like and dislike; no reference was made to the relation between this task and the other task phases. Experimenters reassured participants that there were no right or wrong answers since everyone has different opinions. Participants were simply asked to try their best to think about each object before answering throughout the game, and to use both like and dislike options. Before beginning the real task, participants completed a short practice task with separate stimuli.

On each trial, participants viewed one A, B, or C stimulus. The stimulus period was 1.5 s, during which time participants viewed a stimulus (0.5 s) and made a preference judgment (i.e., indicate whether they liked or disliked the object; additional 1 s response window). Trials were jittered such that stimulus onsets occurred at inter-trial intervals [ITIs] of 3 s, 4.5 s and 6 s (or 1.5 s, 3 s and 4.5 s ISI) on 40%, 40% and 20% of trials, respectively (timing modelled after Turk-Browne et al., 2012).

Our key question was how participants' response times (RTs) were influenced by the particular object sequencing. Specifically, objects were preceded by other objects from either the same or a different triad (triads were assigned to half each 'intact' and 'rearranged' conditions, respectively). We predicted that processing would be facilitated in the former (and therefore, yield faster RTs) relative to the latter case if participants had memories for the pairs. We embedded in our sequence the indirect AC (first 1/3 of the sequence) as well as direct AB and BC (second 2/3 of the sequences; intermixed) pairs, enabling us to ultimately derive a separate priming measure for each pair type (AC, AB, BC). The task was divided into three blocks, and participants had the opportunity to take a short rest between blocks if they wished.

2.3.4 | Final (inference and direct) test

Next, participants were informed about the overlapping nature of the AB and BC pairs and were instructed that they should infer a relationship between A and C objects that had been associated with the same B object. That is, all participants were cued to integrate. The experimenter walked participants through an example using stimuli from the instructions, but there was no separate practice task. Following these instructions, participants completed the final 3AFC tests over first AC inference (A served as the prompt) and then direct AB and BC (intermixed, tested in the same way as in the initial tests) associations.

2.4 | Comprehension of instructions

Participants stated their stories aloud on catch trials during AB and BC learning, which allowed us to determine their comprehension of and compliance with the task instructions. Specifically, after the session we scored whether participants' stories were correct (i.e., aligned with the instructions) or incorrect, and excluded those who did not get at least 3/6 stories correct for each phase. As noted in Participants, this criterion ultimately led to the exclusion of 18 children (five retrieve; 13 integrate) and seven adults (two retrieve; two encode; three integrate). We assessed whether these exclusions varied significantly by age group, condition, or their interaction using a general linear model with a binomial linking function. We found trend-level evidence for the interaction (age group × condition: $\chi^2(2) = 5.673$, $p = 0.059$), with children being more likely to be excluded than adults in the integrate ($z = 1.960$, $p = 0.050$) but not the other two conditions (both $|z| < 0.936$, both $p > 0.349$). This result suggests that the integrate condition was especially difficult for children. However, we underscore that after these exclusions, all participants ultimately included in our analyses both understood and complied with the task instructions.

2.5 | Statistical analyses

Our statistical analysis approach is described in the Supplementary Methods. Briefly, we analyzed data in R (Team, 2018) using mixed-effects models (Bates et al., 2015). For accuracy and RT on explicit memory and inference tests, we assessed both main effects and the interaction of instruction condition and age group. Predictors for initial AB learning were repetition × age group interaction and main effects, since the instruction manipulation had not yet been introduced. For the implicit measure of memory, we modelled RTs on the priming task within each instruction condition separately as a function of the interaction of age group (child vs. adult) and sequence type (intact vs. rearranged).

3 | RESULTS

3.1 | Robust AB learning in all instruction conditions

AB memory improved across learning (main effect of repetition; $z = 14.22$, $p < 0.001$), becoming near-perfect by the third and final repetition for both age groups (children: mean = 97%, SEM = 0.004; adults: mean = 99%, SEM = 0.002; Figure S1). Children's performance was overall lower than adults' ($z = 7.04$, $p < 0.001$) and showed a statistical trend for steeper learning slopes (marginal condition × repetition interaction; $\chi^2(1) = 3.242$, $p = 0.072$). Importantly, considering performance at the end of AB learning within age revealed no differences as a function of instruction condition (both $\chi^2(2) < 1.79$, $p > 0.408$), underscoring that our groups were matched in overall memory ability before introducing our manipulation. In subsequent analyses, we consider only new learning and integration associated with those AB pairs that were initially learned—that is, correct on the final learning repetition—unless otherwise noted.

3.2 | Explicit memory and inference performance underscores rigidity in children

Next, we assessed whether being instructed to retrieve (AB), encode (BC), or integrate (ABC) during BC exposure differently impacted memory for the single-shot BC pairs and/or later AC inference across age groups.

With respect to BC learning (i.e., performance on the memory test immediately following BC exposure; Figure 2A), the impact of instruction condition on accuracy (Figure 2B) significantly differed between children and adults (instruction condition × age group interaction: $\chi^2(2) = 12.503$, $p = 0.002$). Adults performed significantly better than children under encode and integrate (both $z > 2.569$, $p < 0.011$) instructions. The retrieve condition asked participants to ignore the BC pairs of interest here. In this scenario, adults performed no better than children ($z = 1.575$, $p = 0.115$). Moreover, BC performance was numerically highest following instructions to encode in both age groups: Adults showed a significant advantage of encode over both retrieve ($z = 9.278$, $p < 0.0001$) and integrate ($z = 4.500$, $p < 0.0001$; integrate was also significantly better than retrieve: $z = 5.222$, $p < 0.0001$). For children, the advantage for encode was significant relative only to retrieve ($z = 5.762$, $p < 0.0001$; not different for integrate, $z = 1.263$, $p = 0.207$). A complementary pattern was also observed in RTs, with both children and adults being significantly faster to make accurate BC decisions following encode than integrate instructions (adults: $z = 3.669$, $p = 0.0002$; children: $z = 2.468$, $p = 0.014$; Supplementary Results and Figure 2C). Overall, these results suggest that being encouraged to focus solely on encoding the current BC experience was best for both children and adults, such that the added task of incorporating the held-out A object (as in integrate) impeded BC memory (albeit significant for children in RT but not accuracy).

We next asked how instructions during BC exposure impacted participants' ability to draw novel AC inferences (Figure 3A). Importantly, we restricted to triads for which the corresponding AB and BC pairs were initially learned to control for differences in memory for the direct pairs. Adults were more accurate than children in all conditions (Figure 3B; all $z > 2.405$, $p < 0.017$). There was also a significant interaction of instruction condition and age group ($\chi^2(2) = 18.119$, $p = 0.0001$) that revealed a strikingly different pattern in children and adults. Specifically, children were more accurate following instructions to integrate than either encode or retrieve (integrate vs. encode: $z = 4.443$, $p < 0.0001$; integrate vs. retrieve: $z = 4.858$, $p < 0.0001$), while encode and retrieve were not different from one another ($z = 0.537$, $p = 0.591$). Therefore, despite forming strong BC memories (Figure 2B), children following the encode instructions struggled to make new connections across those memories during explicit AC inference (Figure 3B). In fact, children told to encode BC showed low inference performance that—though significantly above 33.3% chance ($\text{CI}_{95\%} = [0.37, 0.52]$)—was still no better than those children instructed to ignore BC entirely.

Adults, by contrast, were more accurate for both the integrate ($z = 5.433$, $p < 0.0001$) and encode ($z = 5.844$, $p < 0.0001$) relative to retrieve conditions; integrate and encode were not different from one another ($z = 0.498$, $p = 0.618$). In other words, they achieved similar accuracy on AC inferences based upon BC memories formed under either encode (83%) or integrate (82%) instructions. However, adults did show a statistical trend for a difference between these two conditions in terms of speed: They were marginally faster to make correct inferences when told to integrate than encode during learning overall ($t(225) = 1.741$, $p = 0.083$; Supplementary Results and Figure 3C). Inferences were significantly speeded for integrate relative to encode instructions when accounting for differences in direct BC RT (instruction condition × pair type interaction, omitting the low-accuracy retrieve condition: $\chi^2(1) = 37.775$, $p < 0.0001$; the pattern was such that BC memory was significantly slower, $z = -3.596$, $p = 0.0003$, yet inference significantly faster, $z = 2.314$, $p = 0.021$, for integrate versus encode; there was no such interaction for children: $\chi^2(1) = 1.755$, $p = 0.185$).

In summary, considering BC memory and AC inference revealed rigidity in children, in that they performed best on the test that most closely matched their BC instructions: Those told to encode achieved the highest BC accuracy, whereas those in the integrate condition excelled at AC inference. Moreover, despite children in the encode condition learning BC well, they nevertheless struggled to apply those memories flexibly to a new, 'uninstructed' (i.e., not aligning with exposure instructions) test. (This dissociation also underscores the effectiveness of our manipulation: No two instruction conditions were alike in terms of both BC learning and AC inference performance, suggesting that children were modulating their engagement with the material to yield unique retrieve, encode and integrate profiles.) In contrast, adults were more flexible in that they were able to achieve similar inference accuracy with BC memories formed under encode and integrate instructions—though the former did take marginally more time.

Our child age range spanning several years (7–9) allowed us to ask whether there was a transition away from memory rigidity during this period of development, which would provide insight into *when* children become able to use their memories in a flexible manner. Interrogating performance as a function of age (Supplementary Results) revealed a significant age × trial type (BC vs. AC) × instruction condition interaction ($\chi^2(2) = 7.828$, $p = 0.020$) underpinned by significant relationships with accuracy unique to the *uninstructed* test. That is, children in the encode condition showed age-related gains in AC inference

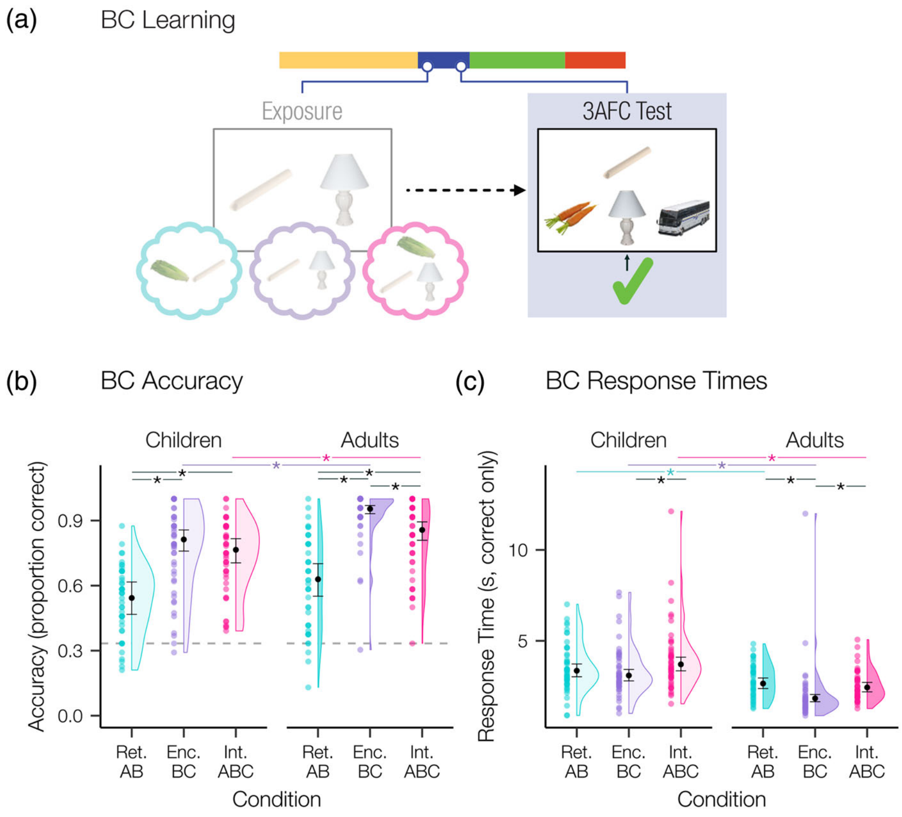

FIGURE 2 BC exposure task performance. (a) Task timeline (top) is depicted as in Figure 1. Participants viewed BC pairs (left) and performed one of three tasks (thought bubbles). They then took a 3AFC BC test (right), the accuracy and RTs on which are depicted in panels B and C. (b) BC accuracy by instruction condition, restricted to pairs for which the corresponding AB was correct during the last learning repetition. (c) RTs on correct BC test trials. For both b and c, points represent participant means. Black circles and confidence intervals represent estimated marginal means and 95% confidence intervals from mixed-effects models. Dashed line represents chance performance. Black significance markers denote pairwise comparisons across instruction conditions within age group; colour-coded markers denote comparisons across age groups, within instruction condition. * $p < 0.05$

(AC: $z = 3.30$, $p < 0.001$; no relationship for BC: $z = 0.63$, $p = 0.529$), whereas those in the integrate group showed improvements only on BC memory (BC: $z = 2.95$, $p = 0.003$; trend in AC: $z = 1.69$, $p = 0.091$; no such relationship for retrieve, both $|z| < 1.10$, both $p > 0.277$; Figure 4A). Moreover, we observed an increasing RT cost unique to the encode group (Figure 4B), with 9-year-olds' RTs mirroring what we observed in adults (Figure 3C). Overall, this finding is consistent with the emergence of memory flexibility during this period in childhood, perhaps at least partially underpinned by a maturing capacity for test-phase memory restructuring.

3.3 | Implicit A-C connections in children and adults prior to explicit inference

We reasoned that above-chance performance on explicit inference might be supported by either (a) separate memories for the individual premise pairs (AB, BC) along with recombination during inference itself; or (b) A–C connections formed during learning. Therefore, we next turned to an indirect assessment that allowed us to ask whether the presence of such connections in memory varied by developmental stage (child, adult) and/or instruction condition (retrieve, encode, integrate). Of note, this assessment occurred prior to participants being informed about the relationship between AB and BC pairs, and before explicit AC inference. Therefore, any evidence for A–C connections at this point in the experiment would indicate their formation in the absence of overt demand.

Our approach was to assess whether participants were speeded in making decisions about C objects that were preceded or 'primed' by their indirectly associated A object ('intact' pairings) as compared with an unrelated A ('rearranged'). (We focus on the A-C portion of the priming task which occurred first, as we saw evidence for memory disruption—primarily in adults—that might explain the lack of priming we observed for direct associations tested later in the task; see Influence of Preference Task on Memory in Supplementary Results.) Our logic was that, if and only if A and C were connected in memory, processing of A would facilitate processing of the associated C—even on an unrelated preference judgment. We therefore compared priming task RTs between intact and rearranged targets to investigate whether evidence for such facilitation existed among children and adults who had received retrieve, encode and integrate instructions during BC exposure. Of note, here we deviated slightly from our preregistration

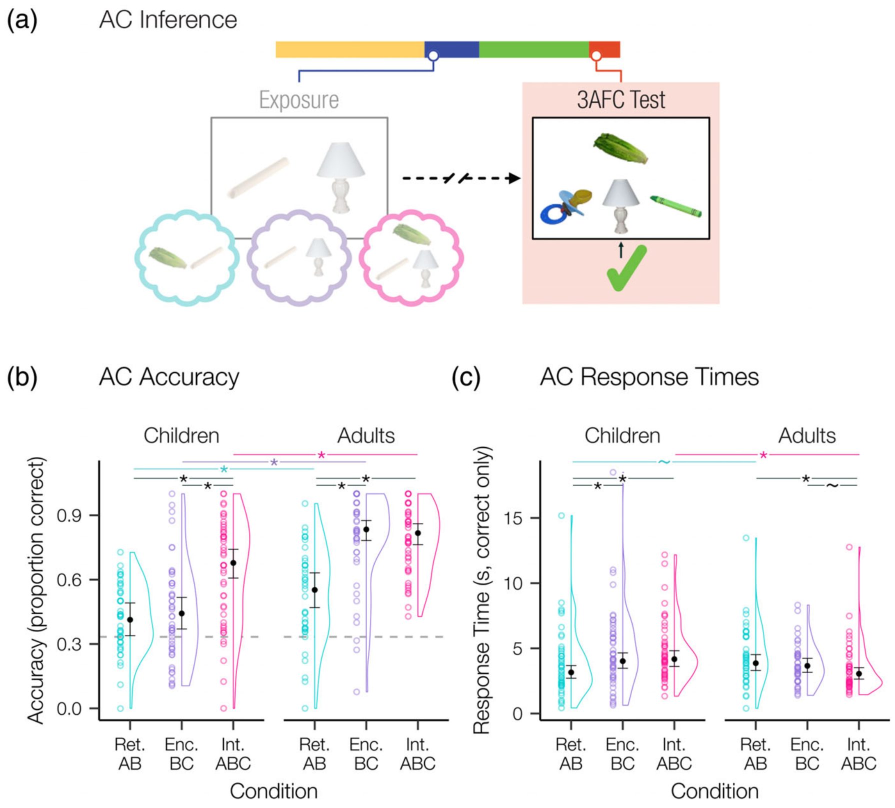

FIGURE 3 Inference performance (explicit measure). (a) After BC exposure (blue in top timeline; with instruction manipulation, left) and the priming task (green in timeline), participants completed an explicit inference test (red in timeline; right). (b) Accuracy on AC inference decisions, considering only AC trials for which the associated AB and BC were both correct during learning (final repetition for AB pairs). (c) RTs on correct trials, also restricted to correct direct pair memory as in panel b. Data are depicted as in Figure 2. * $p < 0.05$; ~ $p < 0.10$

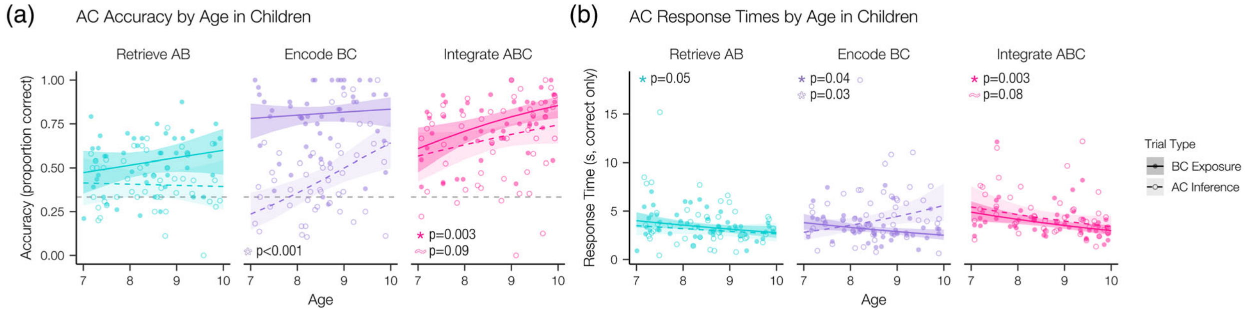

FIGURE 4 Performance (y-axes) on BC pairs (solid lines) and AC inferences (dashed lines) as a function of age in years (x-axes) among children. (a) Accuracy and (b) RT. Data are the same as in Figures 2 and 3, but re-plotted by age. For all plots, coloured points represent individual participant means for BC memory (filled circles) and AC inference (open circles). Lines and 95% confidence bands are derived from mixed-effects models. Full statistics are provided in the Supplementary Results. * $p < 0.05$; ~ $p < 0.10$

by including trials irrespective of subsequent AC inference success, as we found developmental differences in the correspondence between these two tasks (see below). Our initial hypothesis was that adults but not children would spontaneously connect A-C items in memory, with developmental differences being significant only in integrate. Moreover, we predicted that adults would show sensitivity to instructions, with A-C connections being most evident in integrate.

Results were partly consistent with these predictions (Figure 5). Specifically, we found that on average, adults in only the integrate condition ($z = 2.262$, $p = 0.024$; and not the other two, both $|z| < 0.989$, both $p > 0.322$) exhibited significant priming. However, contrary to our hypothesis, this effect was not unique to adults: Children in the encode ($z = 2.375$, $p = 0.018$; but not in integrate, $z = 1.320$, $p = 0.187$; or retrieve, $z = 0.939$, $p = 0.348$) condition also stored A-C connections in memory. Moreover, we did not observe a significant age group × sequence type (intact vs. rearranged) interaction in any instruction condition (all $\chi^2(1) < 1.140$, $p > 0.285$), suggesting children and adults do not differ from one another in the degree of priming. Together, these results suggest that while children and adults alike connect indirectly related memories during new learning

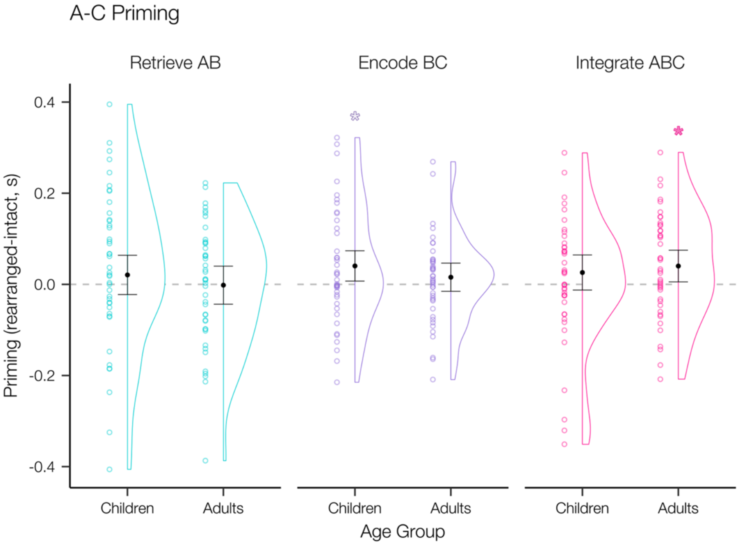

FIGURE 5 A–C priming task (implicit measure). Overall priming effects for A–C pairs by age group (children, left and adults, right violin in each pair) and instruction condition (colour). Coloured points are individual participant means; black points represent estimated marginal means and 95% confidence intervals from mixed-effects models. $^{*}p < 0.05$ versus zero

experiences, they might be most apt to do so under different learning strategies.

3.4 | Results of follow-up analyses hint at emergence of integration among children told to integrate

The findings in the integrate condition are on their surface somewhat consistent with our original predictions: That even despite being instructed to integrate, children would not form A-C connections. However, we believe it would be premature to conclude an absence of integration in this group on the basis of the present data. (Relatedly, it is again worth underscoring that we did not find significant evidence for the hypothesized interaction in the integrate condition or any other instruction condition, and as such we cannot conclude that integration is stronger in adults than children.)

We performed two follow-up analyses to further interrogate evidence for integration among children told to integrate. The results of these analyses provide some indication that integration may exist, albeit weakly, in this group; and this may in part be because it is emerging over the sampled developmental period. First, given the lack of correspondence between implicit and explicit memory measures in children for the novel A-C connections (described below), we reasoned that it may be most appropriate to interrogate evidence for such priming in children across *all* trials—that is, irrespective of not only subsequent explicit AC inference performance but also irrespective of initial AB and BC direct pair learning success. This also serves to increase the number of trials contributing to the analysis among children, thereby affording more statistical power. Under this more lenient restriction, children now showed a statistical trend toward priming in the integrate condition ($z = 1.819$, $p = 0.069$; the effect also remained significant in adults, $z = 2.014$, $p = 0.044$). Therefore, it may be that restricting according to explicit memory exhibited in the 3AFC tests led us to underestimate these connections in children. Second, we asked whether priming varied across age (continuously) among children. The age × sequence type interaction was not significant ($\chi^2(1) = 2.335$, $p = 0.126$); however, we did find trend-level evidence for priming at the older ($z = 1.887$, $p = 0.059$) end of our age range that was not present at the younger ($z = -0.813$, $p = 0.416$). Together, these results are broadly consistent with the notion that some children in the integrate group—perhaps particularly those approaching age 10—may form A-C connections when told to engage an integration strategy. However, given these findings provide only trend-level evidence for these ideas, future studies will be needed to replicate and extend upon the present data.

3.5 | Developmental differences in implicit-explicit correspondence

We next set out to assess the behavioural significance of the implicit connections exhibited during the priming task. Specifically, we reasoned that greater facilitative priming for an association might translate to more accurate or faster decisions on the corresponding explicit inference or memory test trial. Of note, we anticipated substantial person-to-person and even memory-to-memory variability in the tendency to connect interrelated memories (Pajkert et al., 2017; Schlichting & Preston, 2014, 2016; Schlichting et al., 2014, 2015; Zeithamova, Dominick et al., 2012), instruction manipulation aside. Moreover, we reasoned the instruction manipulation would impact *what* is eligible for associative binding, not *whether* such binding occurs (Davis et al., 2021). Therefore, here we consider participants from all instruction conditions, reasoning that any strong item-item link exhibited during the priming task—perhaps regardless of when or how it was formed—could support performance on a subsequent explicit 3AFC test. Importantly given prior work (Bauer, Cronin-Golomb, Porter, Jaganjac & Miller, 2020), we also anticipated that the nature of the implicit-explicit relationship might be stronger in adults than children.

To assess the trial-by-trial link between the degree of priming and subsequent test performance, we needed experience-specific values representing the degree to which a response is particularly speeded

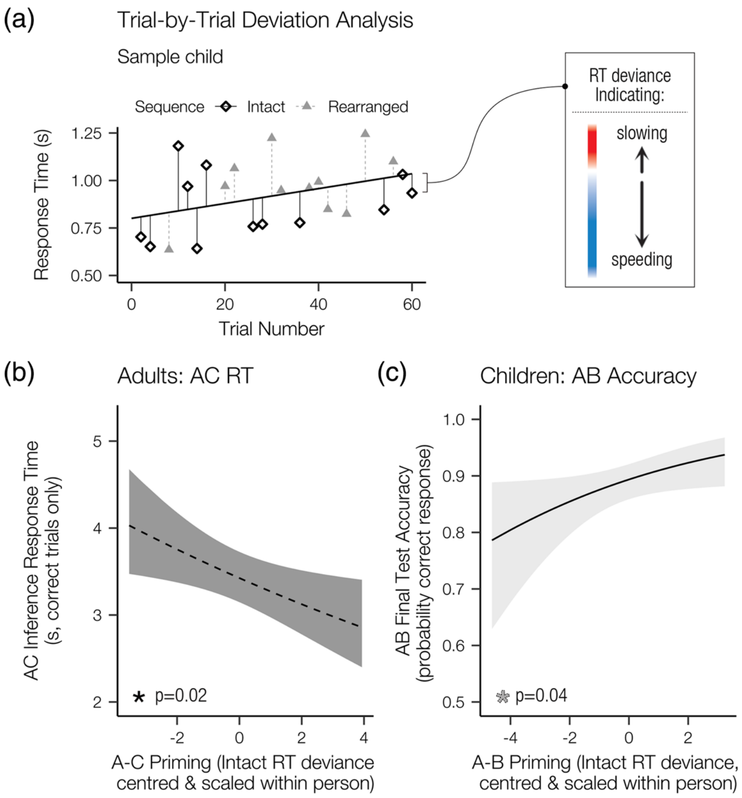

FIGURE 6 Trial-by-trial correspondence between implicit (priming) and explicit (3AFC test) measures. (a) Analysis approach depicted for one sample participant (child). We fit a linear model to each participant's RTs, and the computed the residuals (i.e., predicted—observed, such that observations below the solid line yield positive 'RT deviance' scores; lines) to yield an estimate of the degree to which a particular response was speeded (bottom of graph below fitted line; blue zone on colour bar) or slowed (top of graph; red zone on colour bar) removing overall change across the task block. We then related this trial-to-trial variability in RT to explicit test performance. (b) Negative association between a and c priming and RT on the explicit AC inference test (dashed line) in adults (darker colour). Priming was associated with faster subsequent inference. (c) Positive association between A-B priming and AB accuracy (solid line) in children (lighter colour). In all panels, lines and 95% confidence bands are derived from mixed-effects models. * $p < 0.05$

or slowed for a given target object. However, we found that RTs significantly changed across the task (slopes in intact and rearranged, for children and adults; all $z > 7.21$, $p < 0.001$), such that participants became on average slower as the task went along. Therefore, rather than considering raw RTs, we instead developed an analysis approach to remove these overall trends (Figure 6A). Briefly, we regressed RTs to target objects on trial number for each participant. We then computed, for each target object, the degree to which the observed RT differed from the participants' predicted average RT at that same trial number (i.e., residuals; predicted—observed). This approach allowed us to remove the effect of trial number, such that values for any particular object were not contaminated with *when* (i.e., at what trial number) it had been presented during the preference task. Positive values indicated a faster-than-average response, whereas negative values indicated a slower-than-average response. We then centered and scaled these values within-participant, thereby removing differences across individuals in the overall level and variability of priming to isolate the within-person relationship between implicit and explicit measures of associative memory.

Both children and adults showed some evidence for a correspondence between implicit and explicit measures, yet it occurred for different types of associations: Adults showed an implicit-explicit relationship that was specific to the indirect A-C links, while children showed such correspondence only for direct AB pairs. Specifically in adults, the degree of A-C priming predicted the speed of the corresponding subsequent correct inference ($t(76.41) = -2.40$, $p = 0.019$; Figure 6B; no relationship for AC accuracy: $z = 1.13$, $p = 0.259$). Adults also did not show any significant trialwise relationships between these implicit and explicit assessments of memory for either AB or BC direct pairs in either accuracy or RT (all $|z| < 0.72$, $p > 0.476$). In contrast, children did not show any significant associations between A-C priming and inference in terms of either accuracy or speed (both $p > 0.115$). However, they did show significant correspondence between A-B priming and accuracy on the final explicit AB test ($z = 2.07$, $p = 0.038$; Figure 6C; no relationship with RT: $t(93.23) = -0.61$, $p = 0.543$). There were no significant relationships observed in children for BC associations (both $i > 0.319$).

These results highlight that in adults—perhaps because their memories were disrupted over the course of the priming task (see Supplementary Results)—only A-C connections (measured early in the priming task) mirrored later explicit inference decisions. Children also showed a correspondence between implicit and explicit memory behaviours. Yet, in contrast to adults, this relationship was only present for direct AB pairs. This finding is consistent with the idea that only the most established AB associations may give rise to implicitly detectable connections that are also accessible during the explicit test in children. By contrast, A-C links may be more tenuous, remaining unavailable to children during an explicit inference decision.

3.6 | Integration offers protection from forgetting in children

Children exhibited substantial forgetting between initial and final direct pair tests (see Supplementary Results). Inspired by past work in adults showing that integration can offer protection from forgetting

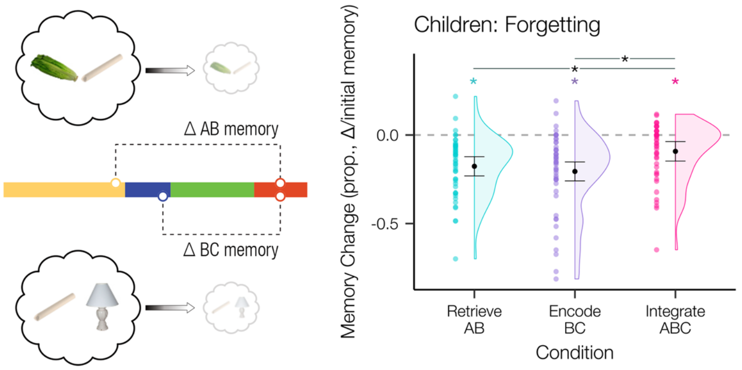

FIGURE 7 Forgetting in children. Left, here we quantified the drop in memory performance from the initial (top AB, from the final repetition during learning in yellow; bottom BC, from the BC exposure test in blue to the final direct pair test in red). Difference scores were divided by initial memory (proportion correct) to correct for differences in memory at baseline. Right, direct pair (AB, BC combined) forgetting in children as a function of instruction condition (colour). All conditions showed significant forgetting (here, values significantly below zero; colour-coded asterisks), but this decline was attenuated in the integrate group (black asterisks denote pairwise comparisons). * $p < 0.05$

(Anderson & McCulloch, 1999; Radvansky, 2005), here we ask whether the same is true in children by comparing performance decrements across instruction conditions (Bauer, Esposito et al., 2020; Varga & Bauer, 2013). We performed this analysis for children only, as the ceiling levels of performance in adults, we reasoned, would lead us to necessarily mis- (under-) estimate the size of their performance decrement.

Directly comparing children's performance between initial exposure and final test revealed an overall decrease ($z = 9.354$, $p < 0.0001$) that nevertheless differed significantly by instruction condition ($\chi^2(2) = 14.524$, $p = 0.0007$). To compare forgetting across conditions, we divided the change in memory accuracy from the learning-phase to final test by the initial learning-phase memory ((final test—learning) / learning; Figure 7). Forgetting differed significantly across conditions ($F(2,138) = 4.592$, $p = 0.011$): Children instructed to integrate forgot proportionally fewer direct pairs (AB, BC combined) than did children instructed to either encode ($t(138) = 2.926$, $p = 0.004$) or retrieve ($t(138) = 2.166$, $p = 0.032$). Integration also offered more protection for AB memories relative to AB retrieval on its own (condition × task phase interaction on AB memory for retrieve vs. integrate: $\chi^2(1) = 4.377$, $p = 0.036$); and likewise, integrating A into the BC memory yielded more robust memories than encoding BC in isolation (condition × task phase interaction on BC direct pair memory for encode vs. integrate: $\chi^2(1) = 8.210$, $p = 0.004$). In sum, while children exhibited forgetting in all conditions, this decline was the smallest when they were encouraged to integrate during BC exposure. Therefore, in addition to offering the greatest flexibility by maximizing performance on the explicit inference test, attempting to combine the three memory elements into a single, coherent story during learning (as in the integrate condition) was also beneficial to children's retention of the underlying direct associations.

4 | DISCUSSION

We manipulated learning strategy as children and young adults were presented with new (BC) information that could be related to prior (AB) knowledge. Children's performance on explicit tests mirrored their focus during exposure, consistent with prior reports of mnemonic rigidity in development (DeMaster et al., 2015; Ghetti & Fandakova, 2020). Integration was overall the optimal strategy for children in terms of yielding the most robust (i.e., least likely to be forgotten) direct pair memories and best inference. Implicit signatures also revealed that children formed indirect A-C connections prior to the inference test in the encode condition (and perhaps to a lesser extent in the integrate condition). As expected, adults also formed such links when told to integrate, and yet showed signs that these links were eroded when the associative structure was disrupted in the priming task (Supplementary Results). We also found a relationship between implicit indirect A-C connections and explicit inference in adults but not children—despite the latter group showing a tight correspondence for well-learned direct AB pairs. Together, these results indicate that differential access to an advantageous learning strategy may indeed explain the bulk of developmental difference in explicit inference. However, developmental differences nevertheless remain in terms of the learning circumstances that best promote implicit memory-to-memory connections, as well as the accessibility of those connections for later explicit choice.

Both adults and children performed optimally on the explicit assessment that most closely matched their exposure instructions: BC memory was best for the encode condition (though notably, integration also did not 'cost' children much in terms of BC learning; Bauer, Esposito et al., 2020), and AC inference was best (in terms of accuracy for children, and RT for adults) for integrate. This difference in inference performance across conditions was especially pronounced in children—there was a whopping 24% accuracy difference in children (AC inference, encode versus integrate), yet a difference only in speed for adults. There are multiple mechanisms by which adopting different strategies during overlapping BC learning might result in different levels of AC inference. For instance, it might be the case that the similarity between the experience of BC exposure and AC test (taking into account e.g., cognitive context) is especially low in the encode condition, thereby disadvantaging children in particular as they rely more heavily on these sorts of cues (Ackerman, 1985; Levy-Gigi & Vakil, 2010). On the other hand, it might be that an integration strategy actively facilitates performance by directing participants' attention to both similarities and differences between experiences (Wahlheim & Jacoby, 2013). We found that integration benefitted not only flexible inference, but also protected direct pair memories from forgetting in children. This finding aligns with past work in adults showing that the engagement of such a strategy protects from varied sorts of memory failure (e.g., interference, retrieval-induced forgetting; Anderson & McCulloch, 1999; Radvansky, 2005); and work in children that integration does not blur underlying memories (Bauer, Esposito et al., 2020), but instead might even promote their retention over longer delays (Varga & Bauer, 2013). Overall, our findings suggest that giving children access to an integration strategy during learning may largely close the performance gap between children and adults in explicit inference.

In adults, explicit performance differences between encode and integrate conditions were subtle, appearing in inference RT but not accuracy. These similar levels of accuracy, however, were supported by different underlying structures: Explicit inferences in the encode but not integrate condition were made from separately stored initial AB and overlapping BC memories, therefore requiring additional test-phase processing. Specifically, we found that inferences in the encode condition took relatively more time than did those in the integrate condition; and moreover, saw no overall evidence of A-C linkage in the priming measure. These findings are generally consistent with past reports, which have also shown that encode and integrate instructions yield minimal differences in accuracy despite robust effects in more sensitive metrics like brain response (Richter et al., 2015) and recall dependency (i.e., integration increases the likelihood of recalling A and C together given B; Burton et al., 2017). We also found that children may become increasingly better equipped to accomplish the more time-consuming test-phase processing associated with the encode condition between ages 7–9.

Comparing encode and integrate to retrieve also provided clear evidence that reactivation—despite being a necessary first step—is not sufficient for integrative encoding to occur. Even among children, reactivation of AB coupled with the intention of ignoring BC appeared to prevent memory linkage on average: Not only was explicit inference poor, but neither children nor adults showed implicit evidence of connecting A and C items. Given that some (Burton et al., 2017; Howard et al., 2009; but not all, Richter et al., 2015; Zeithamova & Preston, 2017) past perspectives have suggested that co-activation of AB and BC traces might be all that is necessary for integration, this finding provides an interesting data point to the contrary. Our observation that even children—despite their relatively poorer attentional control (Plebanek & Sloutsky, 2019; Wendelken et al., 2011)—are able to follow instructions to ignore BC and prevent its inclusion in the memory trace is especially noteworthy. We anticipated that children, much in the way of 'hyperbinding' in older adults (Campbell et al., 2010; Davis et al., 2021), might fail to ignore the present BC information and store the ABC relationship—including irrelevant C—in memory. However, there was no evidence for this phenomenon among either children or adult retrieve participants. It remains an open question as to whether slightly different instructions (e.g., to retrieve AB but make no mention of ignoring BC) would yield different effects.

With respect to implicit A-C connections, adults exhibited such priming only in integrate—consistent with past findings that this strategy can enhance connections between indirectly related items (Burton et al., 2017). Children by contrast connected A and C in the encode condition (and perhaps marginally so in integrate). While these results were not what we predicted, they might nevertheless be sensible in the context of other work on spreading activation showing connections can be formed between related memories under certain learning conditions as early as infancy (Barr et al., 2001, 2014; Hayne & Gross, 2017). Here, why might it be the case that children form such indirect connections when instructed to simply encode BC—particularly given that adults do not? One set of possibilities is related to the fact that the encode condition is the only one that does not have a strategy change between initial AB and overlapping BC exposure, and as such the cognitive contexts may be most similar in this condition (i.e., the task is identical between AB and BC learning phases, with only the materials themselves being different; Sahakyan & Delaney, 2003, 2005). Such similarity of mental state during AB and BC learning could yield source confusion (Cycowicz et al., 2001; Riggins, 2014) in children, such that A and C become linked because their associated memory traces are not easily distinguishable. Alternatively, it could be that this similarity in cognitive context provides additional cues that are enough to trigger spontaneous retrieval of AB—again, given children's demonstrated sensitivity to the similarity between study and test (Ackerman, 1985; Levy-Gigi & Vakil, 2010)—despite no overt instruction to do so. It might be the case that then, having not been explicitly told to ignore either AB or BC in this condition, children engage in something akin to hyperbinding such that A, B and C connections are nevertheless formed (Davis et al., 2021); which is interestingly thought to be a purely implicit phenomenon in older adults (Campbell & Hasher, 2018). One paradigm-related reason why such (spontaneous) memory reactivation might be plausible here when it has not been reported in prior work using related paradigms (Bauer, Cronin-Golomb et al., 2020; Schlichting et al., 2022) is that here, we purposely provided learners with ample AB experience to enable effortful retrieval (needed for both the retrieve and integrate conditions) during BC exposure. Therefore, spontaneous retrieval might have occurred given the well-learned nature of the AB pairs to support integration (Hayes-Roth, 1977; Schlichting et al., 2015); given past work (Krøjgaard et al., 2017), such spontaneous retrieval may be even more likely successful than strategic retrieval required in the integration condition. Future work will be needed to tease apart these two possibilities. Regardless of the reason for their emergence, it is worth underscoring that we observed links in the encode condition that were (1) triad-specific, rather than between A and C item types more generally; and (2) did not support explicit inference in children. Additional research will be required to develop a fuller picture of how an overt integration strategy might differentially impact implicit and explicit aspects of memory in childhood, given we saw only trend-level evidence for A-C connections in this condition.

Relating implicit to explicit assessments of A-C connections revealed an intuitive correspondence in adults: Across all learning conditions, inference problems associated with more priming in the preceding preference task were solved faster than those exhibiting less priming. However, this same pattern was not found in children. These findings are highly consistent with prior work: Specifically, one past study (Bauer, Cronin-Golomb et al., 2020) also showed that children's implicit connections across related experiences (stem facts) did not relate to their explicit performance—in that study, children's ability to combine related facts on an open-ended test. Consistent with the idea that more tentative links may exist, however, the researchers did find evidence of a correspondence when explicit links were assessed using an alternative-forced-choice test (Bauer, Cronin-Golomb et al., 2020). Here, we extend this work by showing that children's apparent difficulty accessing such implicit connections might be specific to those that are weaker and/or span memories: We found that children *did* show an implicit-explicit relationship in the expected direction for the well-established and directly experienced AB pairs. Therefore, future work will be needed to better understand children's difficulty leveraging such existing implicit links during an explicit test. Particularly for emergent or weak links (such as indirect A-C connections), it may be the case that providing further support at test or using a different sort of memory assessment could increase children's ability to access their memories on demand.

There are several limitations to the present study. One is that participants—and perhaps children especially—may have experienced fatigue since the task was relatively long and completed online. This issue might have been exacerbated given our data collection was completed during the COVID-19 pandemic, and as such most participants were also using their devices for work or school. This fatigue might have yielded suboptimal performance in, for example, the fast-paced priming task. Such factors may have reduced our ability to detect implicit A-C connections that truly exist (e.g., perhaps in the integrate condition among children). However, given that we would not expect such effects to differ between instruction conditions within each age group, nor to create artifactual evidence for connections, we suggest that this concern would not have greatly influenced our conclusions. A second limitation is that due to the online nature of our study, participation was limited to individuals who had access to a computer and internet connection in their homes. Our participants were therefore likely of relatively high socioeconomic status given they had these resources readily available. Finally, our task was quite challenging, which led to the exclusion of 51 participants for failure to meet our performance-based criteria. Integration appeared especially challenging for children, with exclusion rates due to low catch trial performance being higher for children than adults only in this instruction condition. While we can be confident that those participants we retained did understand and were able to perform the task as intended, it is nevertheless important to keep in mind that our results reflect this high-performing sample. Given this study required much of participants in terms of both resource access and performance, it is possible that the results we observed would not generalize to the broader population—a limitation that might be particularly salient in the integration condition.

Together, our results suggest that children's lack of knowledge of an integration strategy during learning may explain a large share of the developmental differences reported on explicit tests of memory-based inference. This finding has strong significance: Contrary to our predictions, children aged 7–9 years are not fundamentally incapable of integration; and it may be that the demands of explicit memory and inference tests exaggerate behavioural differences between children and adults. Children do form memory-to-memory connections—though they might be more tenuous, less accessible and therefore less influential for explicit behaviours. This finding presents a notable challenge as many key behaviours require the ability to reference one's memories in a self-guided, controlled way—even for children, such as when writing a test in school. Future work is needed to determine whether interventions during explicit test might be more effective than the learning-phase manipulation we deploy here, and perhaps support children in their ability to access and use their stored knowledge to its fullest extent.

AUTHOR CONTRIBUTIONS

Zahra Abolghasem and Margaret L. Schlichting designed research; Zahra Abolghasem, Tiffany H.-T. Teng, Elida Nexha, Cherrie Zhu, Cindy S. Jean, Mariana Castrillon, Eric Che, Eva V. Di Nallo performed research; Zahra Abolghasem and Margaret L. Schlichting analyzed data; Zahra Abolghasem and Margaret L. Schlichting wrote the paper; all authors provided comments and approved final paper.

ACKNOWLEDGMENTS

We thank Huiqin Chen, Alyssa Ho Jia Mei, Eden Prosser, Amy Pan, Daniel Wurgaft, CéAnn Marks and Sabrina Zhu for assistance with recruitment, stimulus development and data collection; and Michael Mack, Nicole Varga, Tess Forest and members of the Budding Minds Lab for helpful discussions. Thanks to Nicole Varga and Michael Mack for reading and providing helpful comments on an earlier version of this manuscript. This work was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant (RGPIN-04933-2018), Canadian Institutes of Health Research (CIHR) Project Grants (PJT-178337 and PJT-159492), Canada Foundation for Innovation JELF, Ontario Research Fund (36876) and University of Toronto startup funds to MLS; and a NSERC Undergraduate Student Research Award (USRA) to ZA.

ETHICS STATEMENT

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

CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Data are available on the Open Science Framework (OSF) at https://osf.io/fmv3w/.

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How to cite this article: Abolghasem, Z., Teng, T. H.-T., Nexha, E., Zhu, C., Jean, C. S., Castrillon, M., Che, E., Nallo, E. V. D., & Schlichting, M. L. (2023). Learning strategy differentially impacts memory connections in children and adults. *Developmental Science*, *26*, e13371. https://doi.org/10.1111/desc.13371