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Short- and Long-Delay Consolidation of Memory Accessibility and Precision Across Childhood and Young Adulthood

Iryna Schommartz[1, 2], Angela M. Kaindl[3, 4, 5, 6], Claudia Buss[7, 8], and Yee Lee Shing[1, 2]
[1] Department of Psychology, Goethe University Frankfurt
[2] Center for Individual Development and Adaptive Education of Children at Risk (IDeA), Frankfurt, Germany
[3] Department of Pediatric Neurology, Charité—Universitätsmedizin Berlin
[4] Center for Chronically Sick Children, Charité—Universitätsmedizin Berlin
[5] Institute of Cell and Neurobiology, Charité—Universitätsmedizin Berlin
[6] Department of Pediatric Surgery, Charité—Universitätsmedizin Berlin
[7] Department of Medical Psychology, Charité—Universitätsmedizin Berlin
[8] Development, Health and Disease Research Program, Department of Pediatrics, University of California, Irvine

Childhood is a period when memory consolidation and knowledge base undergo rapid changes. The present study examined short-delay (overnight) and long-delay (after a 2-week period) consolidation of new information either congruent or incongruent with prior knowledge in typically developing 6- to 8-year-old children ($n = 32$), 9- to 11-year-old children ($n = 33$), and 18- to 30-year-old young adults (YA; $n = 39$). Both memory accessibility (cued recall of objects) and precision (precision of object placement) of initially well-learned object–scene pairs were measured. Our results showed that overnight, memory accessibility declined similarly in all age groups; memory precision improved more in younger children (YC) compared to older children (OC) and even declined in YA. After a 2-week period, both memory accessibility and precision became worse. Specifically, while age groups showed similar decline in memory accessibility, precision decline was less in YC than in OC and YA. The accessibility and precision of congruent and incongruent information changed similarly with consolidation in all age groups. Taken together, our results showed that, for initially well-learned information, YC have robust memory consolidation, despite their overall lower mnemonic performance compared to OC and YA, which is potentially crucial for stable and precise knowledge accumulation early on in development.

Public Significance Statement
This study suggests that children can access well-learned information and retain its precision over long delays, indicating robust memory consolidation. It is not guided by congruency bias, suggesting equal weighting of incoming information and flexible schema formation. Because rapid accumulation of knowledge in children is crucial for later academic success, understanding how memories are retained as time passes is important for promoting successful and effective learning across different developmental groups.

Keywords: episodic memory, object–scene pairs, memory consolidation, congruent and incongruent information, prior knowledge

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Iryna Schommartz https://orcid.org/0000-0001-8655-9259
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Correspondence concerning this article should be addressed to Iryna Schommartz, or Yee Lee Shing, Department of Psychology, Goethe University Frankfurt, Theodor-W.-Adorno-Platz, 6, 60323 Frankfurt, Germany. Email: schommartz@psych.uni-frankfurt.de or shing@psych.uni-frankfurt.de

Memory consolidation is a complex mnemonic process that occurs between encoding and retrieval (Moscovitch & Gilboa, 2022). During this process, memories are reorganized and transformed to become long-lasting for days and even decades (Dudai, 2012; Squire et al., 2015). However, it is not well understood how memories stay accessible and precise over different time delays and what factors modulate consolidation-related changes in memories.

Research suggests that detail-rich information may decay faster than gist memory during memory consolidation (Reyna & Brainerd, 1995; Sekeres et al., 2016). On the other hand, Diamond et al. (2020) showed that although memory accessibility for real-world experiences declined with increasing retention interval, the details of accessible memories were highly accurate and retained precision. This suggests that consolidation-related changes in memory accessibility and precision may be modulated by the characteristics of memory representations (Bransford & Johnson, 1972). For instance, prior knowledge may generally benefit congruent memory representations in adults through faster integration of new information into schemas or prior knowledge structures (Gilboa & Marlatte, 2017; van Kesteren et al., 2012). However, it is unclear to what extent these effects hold over longer time intervals and whether they are as robust in children, who have less established and extensive schemas (Brod & Shing, 2022); we aimed to address these knowledge gaps with the current study.

Memory Consolidation Across Development

Successful retrieval of complex memory representations starts to steadily improve around the age of 5 or 6 years (Drummey & Newcombe, 2002; Riggins, 2014; Sluzenski et al., 2006), indicating the kickoff of long-term memory stabilization (Bauer, 2007). Knowledge acquisition and accumulation occur at an exceptionally rapid and intense pace in this age (Bauer, 2021; Bauer et al., 2019), imposing significant demands on cognitive functions, including memory consolidation in children (Brod, Bunge, & Shing, 2017; Nolden et al., 2021). Moreover, childhood is accompanied by ongoing neural maturation, including the brain regions associated with associative binding and strategic control over memory processes (Ghetti & Bunge, 2012; Ofen, 2012; Shing et al., 2008). The structural integrity of these regions was also shown to impact memory consolidation in children (Schommartz et al., 2023).

Studies have shown mixed findings in terms of whether memory consolidation rates over varying time delay differ across age groups. For example, for word–pair associates, Wilhelm et al. (2008) found that short-delay (i.e., overnight) consolidation rates were comparable between 6- to 8-year-old children and young adults (YA). In contrast, Peiffer et al. (2020) found that 7- to 12-year-old children were more efficient than YA in short-delay memory consolidation rates for non-objects and their functions. Similarly, Wang et al. (2018) found that 8- to 12-year-old children had more efficient short-delay memory consolidation rates than YA for "what–where–when" memories. At the same time, research has shown that successful retrieval of events over a longer delay (i.e., over 1 week) increases as children age (Østby et al., 2012), suggesting a continuing development in memory consolidation. Taken together, there is a lack of direct comparison of memory consolidation across short and long delays. Hence it remains unclear how consolidation-related changes in memories evolve over nights and weeks in children compared to adults.

Congruency Effect in Memory

Prior knowledge may be a potential modulator of memory consolidation. Previous research in adults indicates that information that is congruent with prior knowledge is generally better remembered compared to information that is incongruent with prior knowledge (Alba & Hasher, 1983; Bartlett, 1995; Ghosh & Gilboa, 2014). This may be due to resonance of the new information with existing schemas during encoding (Brod & Shing, 2019; Packard et al., 2017; van Kesteren, Beul, et al., 2013), as well as better memory accessibility upon retrieval (Greve et al., 2019). Additionally, congruent information is integrated faster into preexisting schemas during memory consolidation in YA (Hennies et al., 2016; Lewis & Durrant, 2011; van Kesteren et al., 2012). Furthermore, its recognition is enhanced after a consolidation delay (Durrant et al., 2015; van Kesteren, Rijpkema, et al., 2013).

Studies have also shown congruency effects in children, showing improved memory performance for congruent compared to incongruent pairing (Carroll et al., 1979; Heikkilä & Tiippana, 2016). Additionally, in a meta-analytical study, Stangor and McMillan (1992) report that 6- to 10-year-old children better remember congruent information in recall and recognition tests. Similarly, congruency-enhancing effect on memory accessibility was reported by Brod and Shing (2019) in 6- to 7-year-old children and in 8- to 12-year-old children during retrieval of task-induced relevant knowledge (Brod, Lindenberger, & Shing, 2017). Overall, these studies suggest that memory for information that is congruent with prior knowledge is generally enhanced in children, in accordance with observations in YA. However, it remains unclear how this effect evolves over time in children when memories go through consolidation.

Incongruency Effect in Memory

On the other hand, there is also empirical evidence for mnemonic enhancement of information that is incongruent with prior knowledge (Alba & Hasher, 1983). For instance, meta-analyses by Rojahn and Pettigrew (1992) and Stangor and McMillan (1992) showed better memory for incongruent information in adults when recall and recognition tests were controlled for guessing (i.e., including hits and false alarms). Moreover, longer consolidation delays resulted in further bolstering of incongruent information. In another study, adults showed comparable memory for incongruent and congruent information when encoding instructions strategically directed the focus of attention to nonschematic targets (Webb & Dennis, 2020). Furthermore, information that is incongruent may be elaborated more during encoding, leading to a benefit for details of the episode and possibly enhancing memory precision (Cycowicz et al., 2008; Greve et al., 2019; Rojahn & Pettigrew, 1992; van Kesteren et al., 2012). Regarding developmental cohorts, Meng et al. (2019) reported that 5- to 6-year-old children also remembered more faces incongruent with their expectations. Taken together, there are mixed results regarding whether congruent information is consolidated better than incongruent information, or vice versa, and there is a lack of study that investigate the age differences therein.

Current Study

In this study, we examined the consolidation of memory for congruent and incongruent object–scene pairs across a short delay (after one night of sleep) and a long delay (after a 2-week period), comparing 6- to 8-year-old children (referred to as "younger children [YC]"), 9- to 11-year-old children (referred to as "older children [OC]"), and YA. Associative memory accessibility (measured by cued recall of object identity) and memory precision (measured by precision of object placement) were taken as two separate indices of memory consolidation. Memory accessibility indicates the probability of retrieval of a specific object identity associated with a cue (i.e., scene), reflecting the accessibility of the associative connection between the scene and an object–scene memory trace (Harlow & Yonelinas, 2016). Memory precision indicates the spatial precision of the memory trace irrespective of whether an object was accessed or not, reflecting the quality of the memory trace itself (Berens et al., 2020). Particularly, we concentrated on the stabilization of learned memory traces through consolidation, incorporating comparable encoding across age groups through adaptive learning. In general, we hypothesized a decline in memory accessibility and precision across time. We also hypothesized that memory accessibility for congruent information would be higher than for incongruent information. This effect was expected to be comparable across age groups in short delay, but become more pronounced in adults, compared to children, in long delay. Memory precision was expected to be higher for incongruent than congruent information over time, due to encoding-related benefit for details for incongruent information (Cycowicz et al., 2008; Greve & Fischl, 2009; van Kesteren et al., 2012). Furthermore, we hypothesized small or no age group difference in memory accessibility and precision in the short delay; but in the long delay, adults were expected to show a lesser decrease in memory accessibility and precision, followed by OC and then YC.

Method

Participants

In total, 34 YC (6- to 8-year-olds), 33 OC (9- to 11-year-olds), and 39 YA were recruited either from the existing departmental participant database or through word-of-mouth to participate in the study. All participants had normal or corrected-to-normal vision and no history of psychological or neurological disorders. One YA and two YC were identified as extreme outliers based on interquartile range (IQR) for learning and memory recall data (IQR; above $Q3_{\text{upper quartile (75th percentile)}} + 3 \times$ IQR or below $Q1_{\text{lower quartile (25th percentile)}} - 3 \times$ IQR, Hawkins, 1980) and were excluded from analysis. Thus, the final sample size consisted of 32 YC (M_{age}: 7.14 years, age range: 6.0–8.47 years), 33 OC (M_{age}: 9.91 years, age range: 9.0–10.96 years), and 38 YA (M_{age}: 23.43 years; age range: 19.0–30.00; see Table 1 for sample characteristics). We conducted a priori power analysis with WebPower (Zhang & Yuan, 2018) ($f = 0.4$, $\alpha = .05$, $1 - \beta = .95$; effect size based on Schommartz et al., 2023). The analysis revealed a total sample size of 99 participants for between and 98 participants for within effects. Thus, the target sample size was reached as determined.

All participants or their legal guardians provided written informed consent prior to participation. The study was approved by the ethics committee of the Department of Psychology. The participants were compensated with 8 Euros per hour for taking part in the experiment.

Materials and Procedure

Stimuli

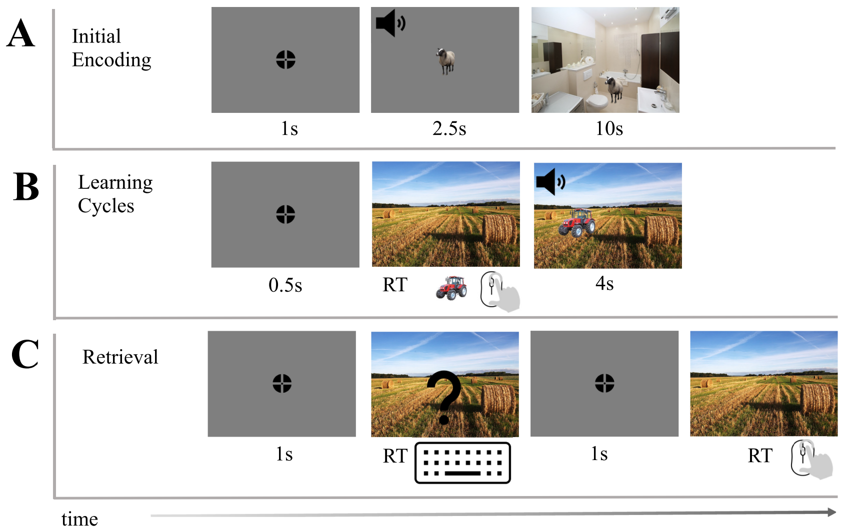
The stimuli for the object–location associations task were chosen based on the curriculum in social studies and science for the first and second grades of German primary school (see a similar procedure in Brod & Shing, 2019). In this way, we controlled for available knowledge by using stimuli that were highly familiar to all age groups (Brod & Shing, 2022). Twenty different themes (e.g., desert, forest, farm animals, etc.) were chosen based on their appearance in the textbooks and teacher ratings. For each theme, a set of four scene pictures and four congruent object pictures was selected, resulting in 80 unique congruent object–scene pairs in total (see Figure 1 for an example). The incongruent condition was created by pairing sets of scenes with incongruent set of objects (i.e., polar bear in a desert), resulting in 80 unique incongruent object–scene pairs. In total, there were 160 unique object–scene pairs. From these, two separate lists of

Table 1
Sample Characteristics by Age Group (Children, YA)

	YC ($N = 32$)	OC ($N = 33$)	YA ($N = 39$)	Group differences		
				YC versus OC	YC versus YA	OC versus YA
Measures	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)		*p*	
Demographic measures						
Age	7.14 (0.68)	9.91 (0.58)	23.43 (2.68)	***	***	***
$\text{Sex}_{\text{(male/female)}}$	15/17	20/13	17/22			
General IQ score	109.23 (19.67)	106.88 (10.75)	104.16 (7.13)	n.s.	n.s.	n.s.
Verbal IQ score	108.19 (11.78)	109.41 (10.32)	106.81 (9.29)	n.s.	n.s.	n.s.
Socioeconomic status						
ISCED—family	5.8 (1.12)	5.27 (1.34)	—	n.s.	***	***
$\text{Sleep duration}_{\text{(hours)}}$						
First night	10.29 (0.83)	9.74 (1.31)	6.68 (1.69)	n.s.	***	***
Average	9.35 (1.52)	9.21 (1.10)	7.19 (1.02)	n.s.	***	***

Note. Age was measured in years. IQ scores were based on Reynolds Intellectual Assessment Scales and Intellectual Screening test (Reynolds & Kamphaus, 2003). Sleep was measured with self-report diary assessing night sleep in hours. YA = young adults; YC = younger children; OC = older children; n.s. = nonsignificant difference; ISCED = International Standard Classification of Education 2011 (Division of Statistics on Education, Office of Statistics, 1975).
*** $p < .001$.

Figure 1
Object–Location Associations Task



Note. (A) Initial encoding: in the initial encoding phase, participants were instructed to remember object–location pairs, memorizing the exact location of each object within the scene. (B) Learning cycles: in the learning phase, participants placed the object to the learned location by dragging it with the computer mouse. After that, the correct object–location association was displayed again. (C) Retrieval: in the retrieval phase, participants recalled and named the object associated with the scene and placed the object at the learned location by dragging it with the computer mouse. RT = reaction time; s = second. See the online article for the color version of this figure.

stimuli were created (i.e., 80 stimuli pairs in each list, 40 congruent and 40 incongruent pairs), which were randomly assigned to participants. Notably, each of the 20 semantic themes shared congruent and incongruent pairs. For instance, within the iceberg theme, a polar bear, a penguin, a clown, and a palm tree were presented, each with a unique iceberg scene (Figure 2). Objects were placed within scenes in plausible locations.

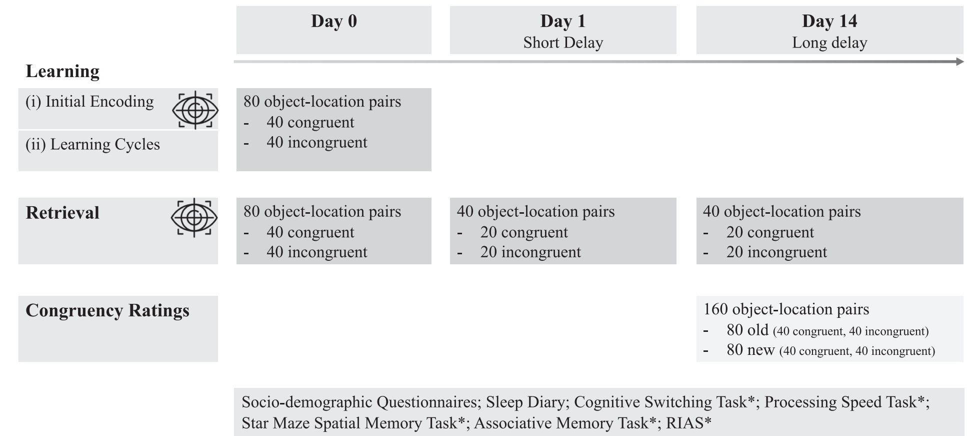
Object–Location Associations Task

The object–location associations task consisted of three phases as follows (see Figure 1):

Learning phase$_{(Day\ 0)}$:

1. Initial encoding phase (Figure 1A). The initial encoding phase was divided into two parts. In each part, participants had to encode a set of 40 object–location pairs (i.e., 20 congruent and 20 incongruent). In each trial, participants saw an object for 2.5 s and heard its name. Afterward, the same object was presented superimposed on a scene at a particular location for 10 s. Participants were instructed to memorize the exact location of the object within the scene using elaboration (e.g., by creating a story). Such elaborative encoding strategies have been shown to aid memory performance in both children and adults (Craik & Tulving, 1975). Participants had to rate the quality of their stories (“1”—*excellent*, “2”—*good*, “3”—*poor*, “4”—*no story*).
2. Learning phase (Figure 1B). The learning immediately followed encoding and was divided into two parts, each following a corresponding encoding part. It was set up in a quasi-adaptive manner, with at least one learning cycle for all participants and up to four learning cycles based on individual performance. In each trial, participants were presented with a scene and an object placed below it, and they were required to drag the object to the correct location on the scene using a computer mouse. There was no time limit for the response. Once the object was placed, it was named again and displayed for 4 s. The placement was considered correct if the deviation from the correct position was not more than 90 pixels, corresponding to half of the object’s size. If the overall accuracy of the object did not reach 85% across all trials in a learning cycle, the next learning cycle was initiated. This procedure aimed to minimize variances attributed to encoding, so that the comparison of subsequent memory consolidation could be made with starting points as similar as possible across individuals and age groups.
3. Retrieval phase (Figure 1C). On Day 0, all 80 learned pairs were retrieved. On Day 1, half of the 80 pairs underwent retrieval, followed by the other half on Day 14. In each trial, participants first saw the scene and were asked to recall the object associated with it. The answer was typed in by the experimenter. After that, the corresponding object was presented below the scene and participants had to drag the object with the computer mouse to the learned location. No time limits were placed on the response. Day 0 pairs were pseudorandomly distributed among Days 1 and 14, maintaining a balance between congruent and incongruent object–location pairs (i.e., 20 congruent and 20 incongruent pairs).

Figure 2
Experimental Procedure



Note. The testing took place across 3 days. (i) On Day 0, participants had to learn and retrieve 80 object–location associations (40 congruent and 40 incongruent). (ii) On Day 1, for retrieval (short delay), 40 pairs (20 congruent and 20 incongruent) learned on Day 0 were retrieved. (iii) On Day 14, for retrieval (long delay), 40 other pairs (20 congruent and 20 incongruent) learned on Day 0 were retrieved. Across all testing days, participants also performed sociodemographic questionnaires and other psychometric tests which were distributed across sessions. During the initial encoding and retrieval, eye-tracking measurements were taken, which are beyond the scope of this article. An asterisk indicates that further details about these measurements, which are beyond the scope of this article, are in the online supplemental materials. RIAS = Reynolds Intellectual Assessment Scales and Intellectual Screening test.

4. Congruency ratings phase (Figure S1 in the online supplemental materials). On Day 14, to check whether participants classified object–scene image pairs in accordance with our congruency classification, participants executed two parts of a congruency rating task. The first part of this task contained 80 old, learned images of object–scene pairs. The image of an object was always presented on the left beside the image of a scene. The second part of this task contained 80 new, not-learned pairs. Participants had to rate how well the objects fit or matched the scene on a scale from 1 to 4, providing subjective congruency rating ("1"—*do not fit at all*, "2"—*do not fit*, "3"—*rather fit*, "4"—*fit very well*).

Assessment of Demographic and Cognitive Covariates

Intelligence quotient (IQ) scores were assessed using the Reynolds Intellectual Assessment Scales and Intellectual Screening test (Reynolds & Kamphaus, 2003) for all age groups. General sociodemographic questionnaires to assess sociodemographic characteristics of the participants were administered as well. Sleep was measured with self-report diary assessing night sleep in hours. These measures were collected to ensure the comparability of the age groups regarding general intelligence score, sleep quality, and socioeconomic status.

Experimental Procedure

Testing took place across 3 days (see Figure 2). On Day 0, the experimental procedure began with a short interactive training with four object–location associations using a PowerPoint presentation to familiarize participants with the object–location associations task and to teach them the elaborative encoding strategy to assess the quality of their stories. This was done using a standardized procedure across all participants. After that a brief practice task started with five object–location pairs. The experimental task started with the initial encoding of unique sets of object–location associations. During encoding, eye-tracking measurements were taken. Encoding of each set was followed by a brief distraction task in which participants listened to a string of numbers and then recalled them. This was followed by the learning phase with retrieval-encoding cycles.

On Day 0, participants had to retrieve 80 object–location associations learned previously. On each of Days 1 and 14, participants retrieved half of the object–location associations learned on Day 0. The duration of retrieval depended on reaction time and lasted between 8 and 15 min. During retrieval, eye-tracking measurements were also taken. Across all testing days, participants filled out sociodemographic questionnaires and performed other psychometric tests after completing the main task.

Behavioral Data Acquisition

The task paradigm during all phases was presented using Psychtoolbox (Kleiner et al., 2007) software in Matlab 9.5, R2018b (MATLAB, 2018). During the encoding, learning, and retrieval phases, stimuli were presented on a computer screen with a resolution of 1,920 × 1,080 pixels. Participants used a computer mouse to drag and drop objects to locations and a response box to deliver their responses.

Transparency and Openness

We report the power analysis to determine our sample size, all data exclusions, all manipulations, and all measures in the study, and we follow Journal Article Reporting Standards (Kazak, 2018). The data, analysis code, and study material are available at (Schommartz, Kaindl, et al., 2023). The analyses of all behavioral measures were performed with R packages (R Core Team, 2022) in RStudio 1.4.1106 (RStudio). We conducted linear mixed-effects (LME) models using the lmer function from the lme4 package in R (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017). Throughout the analyses, significance levels were set to $\alpha < .05$. The study's design and its analysis were not preregistered.

Data Analysis: Learning

To capture the learning pattern, we conducted an LME model to analyze deviations during object placement (in pixel) with random intercepts of subject and item, a between-subject fixed factor of group (YC, OC, and YA), and within-subjects fixed factors of item type (congruent, incongruent) and learning cycle (1–4).

Data Analysis: Memory Accessibility

Memory accessibility on Days 0, 1, and 14 was measured via a cued recall test of learned object–scene pairs. Correct answers were coded as 1 and incorrect as 0. We conducted a generalized LME model to capture memory accessibility at the item level with random intercepts of subject and item, binominal distribution, a between-subject factor of group (YC, OC, and YA), and within-subjects factors of item type (congruent, incongruent) and session (Days 0, 1, and 14).

To characterize the change in memory accessibility over short versus long delays, we first calculated differences in memory accessibility for short delay (Day 0–Day 1) and for long delay (Day 0–Day 14) only for the items that were correctly recalled and thus successfully learned on Day 0. Second, we aggregated these values to obtain a single value for change in memory accessibility per subject, item type, and delay. We conducted LME model for these differences' measures with random intercepts of subject, a between-subject factor of group (YC, OC, and YA), and within-subjects factors of item type (congruent, incongruent) and delay (short delay, long delay).

Data Analysis: Memory Precision

Memory precision was calculated as a normalized measure ranging between 0 and 1 for all items, using the following formula: [precision = 1 − (deviation − minimal (deviation))/range of deviation)]. The range of deviation was based on aggregated data (see further details in Figure S0 in the online supplemental materials). A higher precision value indicates less deviation and thus higher precision of object placement. The LME model for memory precision at the item level was calculated with random intercepts of subject and item, a between-subject factor of group (YC, OC, and YA), and within-subjects factors of item type (congruent, incongruent) and session (Days 0, 1, and 14).

To characterize the change in memory precision over short versus long delays, we calculated differences in memory precision for short delay (Day 0–Day 1) and for long delay (Day 0–Day 14) irrespective whether the items were accessed or not. We conducted the LME model to capture these difference measures with random intercepts of subject and item, a between-subject factor of group (YC, OC, and YA), and within-subjects factors of item type (congruent, incongruent) and delay (short delay, long delay).

Sex (female, male) was added as a covariate in all models. Significant effects were followed up with the Sidak post hoc multiple comparisons test. Directionality of delay-related changes in memory accessibility and precision were assessed with model-based Bonferroni-corrected tests. For other group differences in age, IQ scores, and sociodemographic status, in case of violated assumptions of homogeneity of variances, a Games–Howell test was performed (Lee & Lee, 2018). The effect size estimation was performed with omega squared (ω^2) as a less biased estimate for reporting practical significance of observed effects (Okada, 2013). To determine the amount of variance explained by the model, we used partR2 package in R (Stoffel et al., 2021) with bootstrapping to calculate confidence intervals and report package to report the results (Makowski et al., 2023). The code of this analysis has been made publicly available at Open Science Framework and can be accessed at Schommartz, Kaindl, et al. (2023). Finally, we also analyzed story quality ratings as an indication of encoding elaboration and post hoc congruency ratings as a manipulation check for congruency (full overview of the results in the online supplemental materials).

Results

Learning on Day 0

In the following, we characterize the learning of object–location associations on Day 0. On average, to reach the set criterion of 85% correctly placed objects, YC needed 2.29 learning cycles ($SD = 1.05$, range: 1–4), OC needed 2.09 learning cycles ($SD = 0.98$, range: 1–4), and YA needed 1.58 learning cycles ($SD = 0.61$, range: 1–4). The LME model (Table S1 for full statistical report and Figure S1 in the online supplemental materials) revealed that deviation from the target location was higher in YC compared to OC, $b = 32.7$, $z = 4.89$, $p_{\text{Sidak-adjusted}} < .001$, and YA, $b = 77.5$, $z = 11.9$, $p_{\text{Sidak-adjusted}} < .001$, and in OC compared to YA, $b = 44.8$, $z = 6.9$, $p_{\text{Sidak-adjusted}} < .001$. While the overall learning precision improved with each new learning cycle, $b = -17.16$, $t(22981) = -13.45$, $p < .001$, OC's location memory improved significantly more compared to YC, $b = -7.75$, $t(22981) = -4.01$, $p_{\text{Sidak-adjusted}} < .001$. Hence, despite our training-to-criterion procedure, YA showed overall better learning precision than both child groups, while OC outperformed YC. We did not observe any significant difference in learning between congruent and incongruent items.

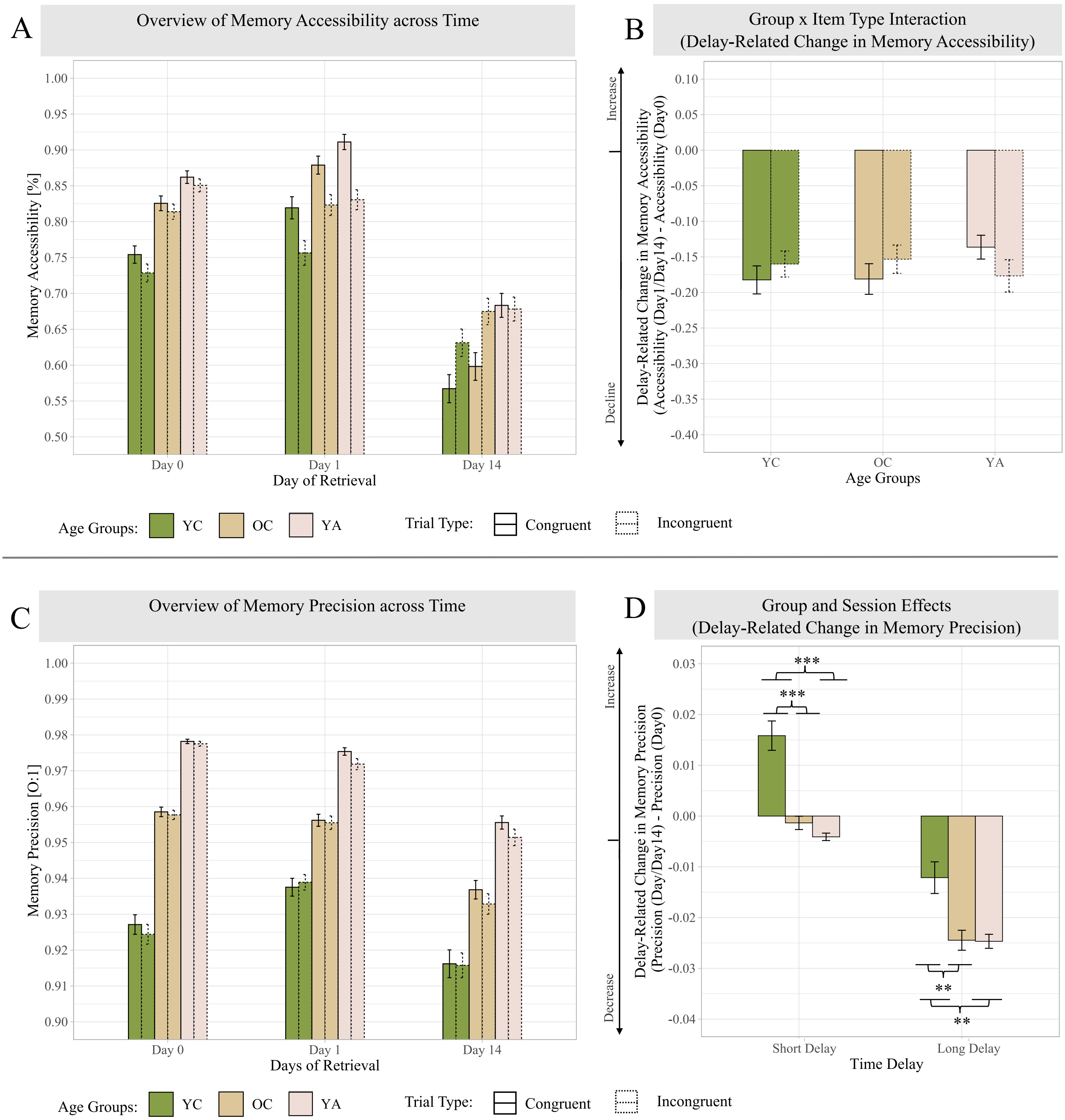
Memory Accessibility

Overall Memory Accessibility

First, we characterized memory accessibility at each session (see Figure 3A). The LME model (Table S2A for full statistical report in the online supplemental materials) revealed lower odds of overall accessibility in YC compared to YA, $b = -0.77$, $z = -4.27$, $p_{\text{Sidak-adjusted}} < .001$, and OC, $b = -0.48$, $z = -2.55$, $p_{\text{Sidak-adjusted}} = .032$, but not in OC compared to YA ($p_{\text{Sidak-adjusted}} = .28$). Furthermore, the model revealed lower odds of accessibility on Day 0 compared to Day 1, $b = -0.32$, $z = -4.63$, $p_{\text{Sidak-adjusted}} < .001$; but higher odds of accessibility on Day 0 compared to Day 14, $b = 1.18$, $z = 19.62$, $p_{\text{Sidak-adjusted}} < .001$. Additionally, we analyzed, controlling for retrieval day, whether overall memory accessibility improved with age in children. Our results revealed that overall memory accessibility improves with age in YC, $b = 0.005$, $t = 3.91$, $p_{\text{FDR-adjusted}} < .001$, and in OC,

Figure 3

Memory Accessibility and Precision Over Time



Note. (A) Overview of memory accessibility. Memory accessibility was operationalized as percentage of correctly recalled objects associated with scenes during retrieval on Day 0 (immediately after learning), Day 1 (overnight after learning), and Day 14 (2 weeks after learning). (B) Delay-related differences in memory accessibility. Delay-related differences were calculated as item-level differences in memory accessibility for short delay (Day 1–Day 0) and long delay (Day 14–Day 0). Higher positive values of delay-related change indicate higher increase in memory associability. Higher negative values of delay-related change indicate higher decrease in memory accessibility. (C) Overview of memory precision. Memory precision was operationalized as normalized deviation during object placement on Day 0 (immediately after learning), Day 1 (overnight after learning), and Day 14 (2 weeks after learning). (D) Delay-related differences in memory precision. Delay-related differences were calculated as item-level differences in memory precision for short delay (Day 1–Day 0) and long delay (Day 14–Day 0). Higher positive values of delay-related change indicate higher increase in memory precision. Higher negative values of delay-related change indicate higher decrease in memory precision. YC = 6- to 8-year-old children; OC = 9- to 11-year-old children; YA = young adults. n.s. = nonsignificant difference. See the online article for the color version of this figure.

** $p < .01$. *** $p < .001$.

$b = 0.003$, $t = 2.23$, $p_{\text{FDR-adjusted}} = .036$, indicating at age-related improvement in memory accessibility earlier in childhood.

Delay-Related Change in Memory Accessibility

Second, we examined aggregated changes in memory accessibility for correctly recalled items on Day 0 across time; particularly testing for group and item type differences in short- and long-delay accessibility (see Figure 3B). The LME model for changes in memory accessibility for initially strong accessible memories (see Table 2 for full statistical report) revealed a significant main effect of delay, showing a decrease in accessibility over time, $b = -0.21$, $t(322) = -18.10$, $p_{\text{Sidak-adjusted}} < .001$. Importantly, the interaction between group and item type was significant, $F(2302) = 3.43$, $p = .033$. However, model-based post hoc tests revealed no difference in accessibility between congruent and incongruent items within age groups (all $p_{\text{Sidak-adjusted}} > .106$) and between age groups (all $p_{\text{Sidak-adjusted}} > .081$), indicating similarly robust consolidation of memory accessibility for congruent and incongruent items within and across age groups. No other main or interaction effect was significant (all $ps > .135$).

In addition, to account for higher odds of accessibility overnight after learning on Day 1, we explored changes in memory accessibility for items not accessed on Day 0 (see Table S4 and Figure S4 for full detailed statistical report in the online supplemental materials). The results showed higher accessibility for incongruent compared to congruent items after short delay; but higher accessibility for congruent items compared to incongruent items after long delay. These effects were similar across age groups.

In summary, although YC showed overall lower memory accessibility compared to the other age groups, we observed a similar decrease in accessibility in all age groups over time for initially successfully accessed items. Congruent and incongruent information was consolidated with similar accessibility across time and age groups.

Memory Precision

Overall Memory Precision

First, we examined memory precision at each session for each item, irrespective of whether the items were successfully accessed or not (see Figure 3C). The LME model (Table S1B for detailed statistical report in the online supplemental materials) revealed overall lower precision in YC compared to OC, $b = -0.023$, $z = -5.17$, $p_{\text{Sidak-adjusted}} < .001$, and YA, $b = -0.042$, $z = -9.92$, $p_{\text{Sidak-adjusted}} < .001$, and lower precision in OC compared to YA, $b = -0.020$, $z = -4.59$, $p_{\text{Sidak-adjusted}} < .001$. Furthermore, we observed significantly lower precision on Day 0 compared to Day 1, $b = -0.003$, $z = -2.58$, $p_{\text{Sidak-adjusted}} = .02$; and significantly higher precision on Day 0 compared to Day 14, $b = 0.020$, $z = 15.97$, $p_{\text{Sidak-adjusted}} < .001$, indicting an increase in precision overnight and a decrease after a 2-week period. Additionally, we analyzed, controlling for retrieval day, whether overall memory precision improved with age in children. Our results revealed that overall memory precision did not improve with age in YC, $b = -0.00006$, $t = 0.20$, $p_{\text{FDR-adjusted}} = .841$, but significantly improved with age in OC, $b = 0.0008$, $t = 3.54$, $p_{\text{FDR-adjusted}} < .001$, indicating that age-related improvement in memory precision only in late childhood.

Delay-Related Change in Memory Precision

Second, we examined changes in memory precision over time, particularly testing for group and item type differences in short- and long-delay precision on item level for all items (see Figure 3D). The LME model for changes in memory precision (see Table 3 for a full detailed statistical report) revealed a significant delay effect, showing overall higher precision loss in long compared to short delay, $b = -0.024$, $z = -10.72$, $p_{\text{Sidak-adjusted}} < .001$. Furthermore, there was a significant age group effect, namely overall precision declined less in YC compared to OC, $b = -0.015$, $z = -3.43$, $p_{\text{Sidak-adjusted}} = .002$, and YA, $b = -0.016$, $z = -3.83$, $p_{\text{Sidak-adjusted}} < .001$, but not in OC compared to YA, $b = -0.001$, $z = -0.27$, $p_{\text{Sidak-adjusted}} = .962$. Instead of a decline in precision observed in YA in short delay, $t(1438) = 5.61$, $p_{\text{Bonferroni-adjusted}} < .001$, YC showed an improvement in precision $t(1230) = -5.47$, $p_{\text{Bonferroni-adjusted}} < .001$, while OC maintained their precision, $t(1318) = 1.02$, $p_{\text{Bonferroni-adjusted}} = .31$. Overall, in short delay YC showed higher increase in precision compared to OC, $b = -0.017$, $z = -3.58$, $p_{\text{Sidak-adjusted}} = .001$, and YA, $b = -0.019$, $z = -4.15$, $p_{\text{Sidak-adjusted}} < .001$, while there was no difference between OC and YA, $b = -0.002$, $z = -0.47$,

Table 2

Statistical Overview of the Main and Interaction Effects of the LME Models for Delay-Related Difference in Memory Accessibility ($R^2 = .52$)

Fixed effect	*F* (*df*)	*p*	ω^2
Item type	0.01 (1302)	.911	.00
Delay	**336.15 (1308)**	**<.001*** **	**.52**
Group	0.77 (2104)	.467	.00
Sex	1.96 (1104)	.164	.009
Group × Item Type	**3.43 (2302)**	**.033***	**.02**
Delay × Item Type	0.92 (1305)	.339	.00
Group × Delay	0.73 (2308)	.479	.00
Group × Item Type × Delay	2.02 (2305)	.135	.006

Note. Statistically significant results are highlighted by bold formatting. The following reference levels were used: for item type—congruent; for group—YC; for session—Day 0; for delay—short delay. LME = linear mixed effects; R^2 = amount of variance explained by the model; ω^2 = effect size; YC = younger children. Type III analysis of variance with Satterthwaite's method was used for delay-related differences model.
* $p < .05$. *** $p < .001$.

Table 3

Statistical Overview of the Main and Interaction Effects of the Linear Mixed Models for Delay-Related Difference in Memory Precision ($R^2 = .16$)

Fixed effect	*F* (*df*)	*p*	ω^2
Item type	0.05 (1161)	.821	.00
Delay	**114.99 (1164)**	**<.001*** **	.41
Group	**8.75 (2104)**	**<.001*** **	.13
Sex	0.01 (1105)	.934	.00
Group × Item Type	1.46 (27834)	.233	.0001
Delay × Item Type	1.21 (1162)	.273	.001
Group × Delay	1.43 (27913)	.237	.0001
Group × Item Type × Delay	0.086 (27874)	.918	.00

Note. Statistically significant results are highlighted by bold formatting. The following reference levels were used: for item type—congruent; for group—YC; for session—Day 0; for delay—short delay. YC = younger children; R^2 = amount of variance explained by the model; ω^2 = effect size. Type III analysis of variance table with Satterthwaite's method.
*** $p < .001$.

$p_{\text{Sidak-adjusted}} = .952$. In long delay, YC showed lesser decrease in precision compared to OC, $b = -0.013$, $z = -2.67$, $p_{\text{Sidak-adjusted}} = .023$, and YA, $b = -0.013$, $z = -2.81$, $p_{\text{Sidak-adjusted}} = .015$, while there was no difference between OC and YA, $b = -0.00005$, $z = -0.011$, $p_{\text{Sidak-adjusted}} = 1.0$.

In summary, we observed that although YC showed overall lower precision than the other two age groups, they uniquely showed improvements in memory precision in short delay and lesser decline in precision in long delay with consolidation, compared to other age groups. OC and YA showed decline in precision with consolidation. Congruent and incongruent spatial information was consolidated with similar precision across time and age groups.

In addition, to control for accessibility impact on precision, we conducted an additional analysis of consolidation-related changes in precision for only successfully accessed items on Day 0. The results showed very similar pattern of memory precision change (see Table S3 and Figure S3 for a full detailed statistical report in the online supplemental materials).

Discussion

In the present study, we investigated memory consolidation of accessibility and precision for well-learned object–scene pairs (through intentional elaborative strategy and repeated learning cycles) that were either congruent or incongruent with prior knowledge. A retrieval test was conducted immediately after learning (Day 0), after one night of sleep (Day 1), and after a 2-week period (Day 14) in 6- to 8-year-old YC, 9- to 11-year-old OC, and YA. We were most interested in delay-related change in memory accessibility and precision for short delay (Day 0–Day 1) and long delay (Day 0–Day 14).

We found that overnight memory accessibility for initially successfully accessed items declined similarly in all age groups. However, while YC showed an increase in memory precision, OC and YA showed a decrease in precision. After 2 weeks, both memory accessibility and precision declined. All age groups showed a similar decline in memory accessibility. However, precision was maintained by YC better than by OC and YA. There was no difference in the consolidation of memory accessibility and precision of congruent or incongruent information over time and across age groups. Taken together, while YC showed overall worse memory accessibility and precision than OC and YA, they maintained similarly to other age groups accessibility of information with consolidation and maintained better the precision of spatial information compared to other age groups over time. Additionally, well-learned congruent and incongruent information is similarly accessible and precise across age groups over time with consolidation.

Similar Short- and Long-Delay Decrease in Accessibility Across Age Groups

We found that all age groups showed similar short- and long-delay decrease in memory accessibility, although YC exhibited lower initial accessibility after learning compared to other age groups. Overall memory accessibility also increased with age in both age groups. Regarding the latter, the emerging and malleable knowledge base of YC may limit their general memory accessibility (Brod & Shing, 2022; Shing et al., 2010). Related to this, Robertson and Köhler (2007) showed that in early and middle childhood, semantic competence predicted mnemonic performance even in tests that did not require direct access to semantic information. Furthermore, YC may benefit less from using embedded context through stories to aid recall due to immature strategy utilization compared to OC and YA (Bransford & Johnson, 1972; Murnikov & Kask, 2021; Shing et al., 2008).

At the same time, we show that while memory accessibility deficits are pronounced during and after learning in YC, they are not translated to retention of memory accessibility over time. Consistent with our findings, some previous studies show that children have comparable or even better consolidation of learned information than adults. For example, Wilhelm et al. (2008) reported comparable overnight memory retention between 6- to 8-year-old children and YA for visuospatial and word–pair associations, while Peiffer et al. (2020) and Wang et al. (2018) reported higher short-delay memory consolidation for associative information in children. In addition, the beneficial effects of sleep for memory consolidation in children may be especially pronounced for recollection memory (Ellenbogen et al., 2006; Gaudreau et al., 2001; Urbain et al., 2016; Wilhelm et al., 2012). For instance, Urbain et al. (2016) found that nap consolidation in 8- to 12-year-old children was like that of YA but occurred at a much faster rate, indicating a rapid neural reorganization of memory traces in childhood. This process may contribute to the rapid accumulation of new knowledge and skills in mid and late childhood. To summarize, our study suggests that the amount of learned information differs between age groups, but all age groups can access well-learned information equally well overnight and after a 2-week period; indicating that neurodevelopmental differences play a less important role in memory access over time. Overall, our findings suggest that well-learned information retained after learning is consolidated in YC as robustly as in OC and YA over time.

Improvement in Memory Precision With Consolidation in YC

Our study found that after short delay, YC showed improvement in memory precision, while OC retained their precision, and YA showed a decrease in precision. After long delay, precision in YC decreased less compared to OC and YA. Overall memory precision increased with age only in OC, indicating that main age-related improvement in memory precision was observed in late childhood. Our results suggest that although YC were generally less precise after learning, they improved in their precision overnight and showed less decrease after a 2-week delay compared to OC and YA.

Regarding general lower memory precision in children after learning, these findings are consistent with Guillery-Girard et al. (2013), who demonstrated that spatial associative memory continues to improve into adulthood. Also Sarigiannidis et al. (2016) reported continuous increase in memory precision for 7- to 12-year-old children. Moreover, the precision–recall task may have placed higher demands on memory reconstruction, resulting in more pronounced age differences (Brainerd et al., 2009; Craik & McDowd, 1987; Rhodes et al., 2019). However, the ability to better retain detail-rich memories with increasing age may be mostly pronounced during immediate recall and dissipate across more prolonged consolidation periods, as shown by robust memory precision in YC over time.

On one hand, these findings are consistent with previous studies that reported comparable or even more efficient short-delay memory retention rates for associative memories in primary school children than in YA (Peiffer et al., 2020; Wang et al., 2018). On the other hand, our findings provide a novel evidence based on continuously sampled memory precision, that over longer delays YC retain memory precision relatively more robustly than OC and YA. Of note is that during learning, YC conducted more learning cycles and received repeated feedback about the correct location. Therefore, the continual improvement and updating of their performance may have led to more stabilized and resistant to decay memory precision (MacLeod et al., 2018), despite lower levels of retained details (McDermott & Zerr, 2019; Yu et al., 2022). On the other hand, higher number of initially retained details reflected in higher initial memory precision in YA could provide more opportunities for the information's quality decay. Moreover, our findings are convergent with the postulation that detail-rich memory tend to fade faster than gist-like memories in YA (Reyna & Brainerd, 1998; Sekeres et al., 2016).

However, reduced consolidation in location memory in children was also observed. For example, Schommartz et al. (2023) reported reduced retention rates in 6- to 7-year-old children in comparison to YA, employing a three-alternative forced-choice task for location recognition. This divergence in findings regarding the robustness of consolidation may be attributed to the differences in involved memory recollection processes. Recall employed in the current study and recognition employed in Schommartz et al. (2023) may impose distinct demands on memory retrieval and storage processes, which may increase with passing time (Craik & McDowd, 1987; Eagle & Leiter, 1964; Freund et al., 1969). For example, during the three-alternative forced-choice task, adults may benefit more from the reactivation of perceptual details (Davis et al., 2010) and from guessing (Freund et al., 1969) compared to children. Employing a more demanding recall procedure, these age-related benefits for YA become obsolete.

Taken together, our findings indicate that YC show precise accumulation of well-learned information over time to a higher degree than OC and YA. In the context of rapid knowledge accumulation, it would suggest that even if the overall quality of information precision is lower in children compared to YA, it is retained more robustly over longer delays, which is beneficial for successful schema formation.

Similar Delay-Related Change in Memory Accessibility and Precision for Congruent and Incongruent Items Over Time Across Age Groups

We observed that overall memory accessibility and precision as well as delay-related changes in memory accessibility and precision for congruent and incongruent information were similar in all age groups over time. Previous studies with primarily incidental learning have generally shown consolidation-related mnemonic enhancement for information congruent with prior schemas, applying a two-choice recognition task after learning (Hennies et al., 2016), a visual item recognition task (van Kesteren, Rijpkema, et al., 2013), and an associative object–scene recognition task (Brod & Shing, 2019). Similarly robust consolidation of congruent and incongruent information in all age groups in our study may be due to elaborative/semantic encoding with strategic story creating. It may have facilitated the creation of new schemas for incongruent information and schema-related mnemonic enhancement for congruent information, both through further repeated adaptive learning procedure (van Kesteren et al., 2012; van Kesteren, Rijpkema, et al., 2013). Furthermore, particularly in children, a nonfitting items could have required more effort during encoding (as seen in worse rating of incongruent stories), it may have resulted in more enhanced reactivation of incongruent memories during learning, equalizing their accessibility and precision over time for children (Greve et al., 2019; van Kesteren et al., 2012; van Kesteren, Beul, et al., 2013). All these factors could have beneficially impact memory accessibility and precision over time irrespective of congruency. Concerning child groups, our results suggest that during the general phase of knowledge accumulation, children tend to retain information equally well irrespective whether it fits into prior knowledge or not. This may generally be beneficial for schema formation and updating for children, who may weight incoming information without congruency bias.

Taken together, our findings provide new evidence that well-learned imbedded-in-context information is accessed and precisely retrieved by children and adults irrespective of whether it fits prior knowledge or not. From an educational perspective, it may imply that children weigh incoming congruent and incongruent information similarly during knowledge acquisition and schema formation. It may allow fast and effective updating and robust long-time storage of new knowledge.

Limitations and Future Directions

Several limitations of the current study should be noted. First, despite the adaptive learning procedure to maximize comparability of final preconsolidation performance, we observed group differences in final learning and overall memory performance. Future studies may adapt learning individually, for example, by excluding correctly positioned items from further learning cycles to facilitate learning and reduce overall task workload (Karpicke & Roediger, 2008; McDermott & Zerr, 2019). Alternatively, future studies may adjust the number of items necessary for different age groups to reach the predefined criteria, equalizing their final performance. Second, with the cross-sectional extreme-group design, we could not draw conclusions about potential longitudinal changes in memory accessibly and precision over time with increasing age and knowledge schema. Future studies could include other age groups to ensure lifespan comparison and ideally investigate potential age- and knowledge-related changes longitudinally. Finally, during memory retrieval on Day 0, all to-be-recalled objects were presented again during the location recall task for participants to drag the objects to the correct location. It may have enhanced reactivation and consolidation of object information, affecting the accessibility measure on Days 1 and 14 retrieval. Future studies may show, for instance, an empty square for the precision task to avoid further relearning.

Conclusions

In this study, we provide novel empirical evidence that 6- to 8-year-old children, despite overall lower mnemonic performance, showed robust consolidation of memory accessibility and stronger consolidation of memory precision over time compared to 9- to 11-year-old children and YA. These findings suggest that if YC successfully acquire new information, they could access it and retain precision over longer delays. Moreover, our study extends previous findings based on immediate retrieval and shows that in late childhood, well-learned memories may be robustly accessed over time. Additionally, we showed that for well-learned information both children and adults tend to retain congruent and incongruent well-learned information similarly. This may suggest consolidation enhancement of newly acquired information that updates existing knowledge schemas or creates new schemas, weighting equally incoming information. Together, these findings indicate the power of consolidation that helps children to retain complex associative information robustly and precisely.

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