Adolescent-specific memory effects: Evidence from working memory, immediate and 24-hour recognition memory performance in 8- to 30-year-olds

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INTRODUCTION

Many cognitive abilities such as spatial navigation, decision-making and intelligence rely on working memory and long-term memory (Acheson & MacDonald, 2009; Baddeley, 2003; Blacker et al., 2017; Burgess et al., 2002; Collette et al., 2000; Curtis & Lee, 2010; Del Missier et al., 2013; Engle et al., 1999; Fry & Hale, 2000; Moffat et al., 2007; Shadlen & Shohamy, 2016). Working memory enables the maintenance and manipulation of a limited amount of information in consciousness (Baddeley & Hitch, 1974) whereas long-term memory has virtually limitless storage and longevity (Brady et al., 2008). Both forms of memory show changes across the life course (Alibali, 2005; Bauer, 2015; Case, 1992; Conklin et al., 2007; Cowan, 2014; Diamond & Goldman-Rakic, 1989; Fischer, 1980; Ghetti & Lee, 2013; Hasher & Zacks, 1988; Hertzog et al., 2003; Kail & Salthouse, 1994). However, less is known about the interaction between these memory systems, especially during adolescence. The goal of the current study is to examine potential changes in the relationship between working memory and long-term memory from childhood through adolescence and into adulthood.

Developmental studies of working memory show marked improvements throughout childhood (Cowan & Alloway, 2009; Demetriou et al., 2002; Simmering, 2012) and adolescence (Hale et al., 1997; Klingberg, 2006; Luna et al., 2001) that extend into young adulthood (Isbell et al., 2015; Jenkins et al., 1999; H. Kwon et al., 2002; Peverill et al., 2016; Satterthwaite et al., 2013; Zald & Iacono, 1998) and subsequently decline later in adulthood (Weintraub et al., 2013) with aging (Hasher & Zacks, 1988; Hertzog et al., 2003). These changes in working memory have been related to the development of attentional (Buss et al., 2014; Reynolds & Romano, 2016) and inhibitory processes (Bjorklund & Harnishfeger, 1990; Harnishfeger & Bjorklund 1993; Casey et al., 2002; Durston et al., 2002; Diamond & Goldman-Rakic, 1989; Hasher & Zacks, 1988) that involve suppression of task-irrelevant information (i.e., distractors) in favor of relevant information (i.e., targets). As such, developmental changes in working memory performance may vary by the number, salience and complexity of items to be held in mind or forgotten (O'Hare et al., 2008; Satterthwaite et al., 2013; Schleepen & Jonkman, 2009). Moreover, the type of information which different ages attend to may influence working memory and what information is subsequently retained (Blanco & Sloutsky, 2019; Deng & Sloutsky, 2016; Plebanek & Sloutsky, 2017). During adolescence there is evidence of enhanced attention

and memory for reinforced, rewarded and threat-related information during adolescence (Cohen et al., 2019, 2021; Cohen-Gilbert & Thomas, 2013; Davidow et al., 2016; Grose-Fifer et al., 2013; Meyer & Pattwell, 2020; Pattwell et al., 2012) and a preference for novelty (Galvan, 2010; Spear, 2013). Together these findings suggest that developmental patterns in working memory performance and subsequent recognition memory may be influenced by task demands and features of the stimuli (e.g., complexity, relevance, salience, novelty).

Long-term recognition and recall, like working memory, show similar patterns of change with age. Recognition abilities begin to develop in infancy (Nelson, 2001; Nelson, de Haan and Thomas, 2006) and both recognition and recall increase throughout childhood (Bauer & Leventon, 2013; Ghetti & Angelini, 2008; Golarai et al., 2010; Güler & Thomas, 2013; Marshall et al., 2002) and adolescence (Bauer, 2015; DeMaster et al., 2014; Ghetti et al., 2010; Ofen et al., 2007) with evidence of a decline in adulthood (Weintraub et al., 2013). Changes in long-term memory with age have been attributed to a number of possible developmental changes in encoding (e.g., Grady et al., 1995), consolidation (Bauer, 2006; Newcombe et al., 2007) and retrieval (Li et al., 2014; Alberini & Travalia, 2017).

Although both working memory and long-term memory change with age, these processes are often studied separately (Axmacher et al., 2009; Burgess & Hitch, 2005; Cotton & Ricker, 2020; Olivers et al., 2011; Woodman & Chun, 2006). Recent theories suggest that neurocognitive systems for working memory and long-term memory may overlap significantly (Nee et al., 2008). In adults, working memory is thought to be vital to encoding and organizing information for long-term storage (Blumenfeld & Ranganath, 2006; Ranganath et al., 2005) and recall (Fukuda & Woodman, 2017). Associations between working memory and long-term or subsequent recognition memory have been shown in children (Gathercole & Adams, 1994; Lloyd et al., 2009; Rosenberg et al., 2020; Thompson et al., 2019). For example, using Bayesian probabilistic principal components analysis of data from the neurocognitive battery of the Adolescent Brain Cognitive Development^{SM} Study (ABCD Study®) of over 11,000 youth, Thompson et al. (2019) showed that measures of working memory and immediate recognition memory were captured by the same learning and memory component in 9 to 10-year-old children. Rosenberg and colleagues (2020) subsequently showed that performance during both 0- and 2-back conditions of the ABCD Study n-back task were correlated with immediate

recognition memory performance in children. These findings suggest that while sustained attention, as indexed by the 0-back condition, and working memory, as measured by the 2-back condition, may differ in cognitive demands and processes, both impact subsequent recognition in childhood. Yet, neither of these studies investigated long-term memory of information encoded during a working memory task (i.e., following a 24-hour delay) beyond childhood, which could provide important insights into how working memory performance impacts long-term storage and recognition post-consolidation with age, especially during adolescence.

The primary goal of this study was to examine whether working memory differentially influences what information is retained long-term during adolescence relative to childhood and adulthood. We used an identical n-back task and subsequent recognition task to those from the Adolescent Brain Cognitive Development^{SM} Study (ABCD Study®) to assess working memory and recognition memory (Casey et al., 2018), but added a 24-hour delay condition in order to assess long-term recognition memory (Figure 1). Based on evidence of continued changes in working memory and long-term memory into the early twenties (Satterthwaite et al., 2013; Weintraub et al., 2013), and recent neurocognitive evidence supporting the expansion in the definition of adolescence as extending into the early to mid-twenties (Sawyer et al., 2018), we included participants from childhood to adulthood (8 to 30 years) to test for adolescent-specific patterns of developmental change (Somerville, 2013). We also selected this age range to have overlap with the ages to be assessed in the 10- year ABCD longitudinal study of 9 to 10-year-old children. We hypothesized that: 1) both working memory and long-term memory performance would improve into the early twenties (Satterthwaite et al., 2013; Weintraub et al., 2013); and 2) recognition accuracy for novel (i.e., new relative to old items) and salient (i.e., emotional faces relative to neutral faces or places) items from the working memory task would be enhanced during adolescence (Pattwell et al., 2012; Spear, 2010).

Figure 1. Experimental Design. A. The n-back task consisted of 0-back and 2-back conditions. Green outlines represent trials in which a target item was presented in which the correct response is ‘match’. Red outlines represent distractor trials in which the correct response is ‘no-match’. B. A subset of participants completed the recognition memory task immediately after the n-back task C. The remaining participants completed the recognition memory task 24-hours later. Yellow outlines represent trials that were ‘Old’ (i.e., targets or distractors from the n-back task). Blue outlines signify trials that were ‘New’ (i.e., stimuli that the participant had not seen before). Outlines are for visualization purposes and were not included in the task.

RESULTS

Development of working memory

For the working memory task we used the emotional n-back task from the ABCD Study (Casey et al., 2018) with two load conditions (0-back and 2-back). The stimuli consisted of four different types (neutral, fear, happy faces and places). In the 0-back condition, a target stimulus was shown, and participants were asked to respond ‘match’ whenever they saw that target repeat. For the 2-back condition, the target stimulus was any stimulus that repeated with one item intervening between presentations. There were also lures (stimuli that repeated but were not the target item) and non-lures (items that never repeated) to which participants were supposed to respond ‘no-match’ (for further information on this task see Methods and Figure 1A). We first

examined the effects of age, memory load (0-back, 2-back) and stimulus type (neutral, fear, and happy faces and places), on working memory performance (d'). We modeled age with linear, cubic and quadratic polynomial terms of exact age, proposed to represent adolescent nonspecific, adolescent emergent and adolescent specific developmental patterns, respectively (Somerville, 2013). The quadratic age model fit best compared to the null model ($\chi^2(16) = 62.603, p < .0001$) and revealed a main effect of age ($\chi^2(2) = 11.249, p = .0217$) with performance peaking in the late teens and early twenties (Fig. 2A). There was also a significant main effect of memory load ($\chi^2(1) = 12.274, p = .0005$) such that 0-back performance was better than 2-back performance, and a main effect of stimulus type ($\chi^2(3) = 30.389, p < .0001$) with worse performance for places compared to all three categories of faces (Fig. 2B; see Supplemental table 1 for full model). Neither stimulus type nor memory load interacted with age or any other predictors. Finally, there was a main effect of I.Q. ($\chi^2(1) = 5.871, p = .0154$) which was treated as a covariate in analyses for age effects (see Supplemental Table 2 for additional model not including I.Q.). Overall, the results suggest that working memory performance peaks during late adolescence regardless of stimulus type or memory load.

Figure 2. Working memory performance as a function of memory load and stimulus type by age. A. Performance (d') was better on the 0-back than 2-back condition of the n-back task with enhanced performance in the late teens to early twenties relative to younger and older ages for both conditions but no age by load interaction. B. There was no age by stimulus type interaction, but performance (d') varied by stimulus type with poorer performance for places than for faces across all ages.

Development of recognition memory

To assess recognition memory we used the recognition task from the ABCD Study (Casey et al., 2018) that tested memory for old items (targets and lures) from the N-back task as well as new items participants had never seen before. Unlike the ABCD Study however, 97 of the participants were tested immediately following the N-back task and 53 of the participants were tested on an identical recognition task 24-hours later (see S1 for more information on participant demographics). Each participant was shown an image they had either seen before during the N-back task (either an old target or old lure) or an image they had never seen before (a novel neutral, fear, happy face or place) and were asked to respond either ‘Old’ or ‘New’ on each trial (for further information on this task see Methods and Figure 1B and C). We assessed recognition memory performance (d'), by age (linear, cubic and quadratic polynomial terms of exact age), delay (0-hour vs 24-hour), and stimulus type (neutral, fear and happy faces and places) controlling for memory load. The quadratic model was the best fit compared to the null model ($F(16) = 3.078, p < .0001$). The quadratic model revealed a main effect of age ($F(2) = 6.957, p = .0062$) with better recognition memory performance in the late teens and early twenties (Fig. 3A), and a main effect of delay ($F(1) = 6.806, p = .0093$) with better immediate recognition memory compared to long-term (24 hour delay) recognition (Fig. 3A). There was a main effect of stimulus type ($F(3) = 9.904, p < .0001$), that showed better recognition memory for places than for faces (Fig. 3B, See supplemental tables 3 and 4 for full model with and without I.Q.) but stimulus type did not interact with age or other predictors. Overall, the results suggest that recognition memory performance peaks during late adolescence regardless of stimulus type or delay.

Figure 3. Recognition memory performance as a function of delay and stimulus type by age. A. Recognition memory performance (d') was better for the 0-hour than 24-hour delay and varied by age with enhanced performance in mid- to late adolescence relative to younger and older ages. B. This developmental pattern in recognition performance did not differ by stimulus type or delay, but overall performance (d') was better for places than for faces across all ages.

Associations between working memory and recognition memory with age

A primary aim of this study was to examine whether associations between working memory and long-term memory vary with age, especially during adolescence. We first tested for associations between overall working memory performance (d') and subsequent immediate and long-term recognition memory performance (d'). As there were no interactions of memory load, stimulus type or delay with age for either working memory or recognition memory we included these variables as covariates as opposed to primary predictors of interest. The no-age model fit best and revealed a main effect of working memory on recognition memory performance ($F(1) = 24.421, p < .0001$) (Figure 4A). Given better performance on the 0-back vs. 2-back condition during the working memory task, we performed a subsidiary analysis separately examining associations between memory load performance (d') and long-term recognition memory (d') and observed no age effects on recognition memory performance for the 0 back or 2 back conditions

(See Supplemental Figure 5C and 5E). Thus, overall working memory performance predicted immediate and long-term recognition performance regardless of age.

To test for adolescent-specific specific effects in recognition for novel items, we tested whether recognition memory varied by trial type (i.e., old targets and distractors from the n-back task and new items) with age. As there were no effects of stimulus type or memory load by age for either working memory or recognition memory, these variables were not treated as primary variables of interest (see Supplemental Figure 6 testing interactions between stimulus type, trial type and age). The cubic age polynomial model fit best compared to the no-age model ($F(18) = 7.956$, $p < .0001$). There was a main effect of trial type ($F(1) = 189.046$, $p < .0001$) such that recognition accuracy was highest for new items, followed by targets and then distractors (See supplemental table S7); and for delay with higher accuracy for the 0-hour than the 24-hour delay condition ($F(1) = 64.085$, $p < .0001$). There was also a main effect of I.Q. ($F(1) = 6.9743$, $p = .00083$) which was treated as a covariate in analyses for age effects (see Supplemental table 8 for additional model not including I.Q.). Central to our developmental hypotheses, there was a two-way interaction of trial type by age ($F(6) = 4.2490$, $p = .0017$) and a three-way interaction of delay by trial type by age ($F(6) = 5.660$, $p < .0001$, Figure 4B). Visual inspection of the polynomial fits for the two-way interaction showed higher accuracy for new and target items, with peak accuracy emerging by the mid-teens for new items but not until the early twenties for target items.

The three-way interaction revealed that for immediate recognition (0-hour delay), accuracy was higher for targets and new items than distractors with the highest accuracy observed for new items that emerged by the mid-teen years. In contrast, for long-term recognition (24-hour delay), accuracy was highest for new items, especially for adolescents. However, adolescents showed more long-term forgetting of distractors relative to targets than adults, who showed similarly high accuracy for targets and distractors, and children who showed long-term forgetting of both targets and distractors.

To explore whether the developmental patterns in long-term recognition (24-hour delay) by trial type were specifically associated with working memory, we then examined recognition accuracy by trial types for the 0-back and 2-back conditions separately, with the latter condition more

closely aligning with definitions of working memory (Baddeley, 1986, Rosenberg et al., 2020). These analyses revealed a similar pattern for the 2-back condition with the pattern of results above collapsed across load, but not for the 0-back condition (see Supplemental Figure 5D and 5F for analysis by load results). Specifically, adolescents showed better recognition of novel items but more long-term forgetting of distractors relative to targets suggesting that working-memory may influence both long-term memory of relevant information and also subsequent forgetting of irrelevant information.

Given the difference in sample size between the 0- and 24-hour delay subsamples ($n=97$, $n=53$, respectively), a subsidiary analysis with an even-odd split of the larger 0-hour sample ($n=97$) into two smaller samples ($n= 48$ even, $n= 49$ odd) was performed. This analysis showed similar cubic age effects in immediate recognition memory by trial type across the two halves as seen in the originally combined sample (see S2 and figure S3) suggesting that both delay conditions may have been of sufficient size to detect age effects in memory recognition.

Finally, a response bias analysis to test for an overall tendency by adolescents to reject all items during the recognition task as new, revealed no significant effect of, or interactions with age (S7). This result suggests that advantages in detection of novel information by adolescents is not solely due to a response bias.

Figure 4. Relationship between working memory, 0- and 24-hour recognition memory. A. There was a positive association between overall working memory (d') and recognition (d') performance that did not vary by age or delay (0-hour and 24-hour). B. Cubic age model showing predicted accuracy in recognition memory by trial type (new items, targets and distractors) and delay (0-hour and 24-hour). For the 0-hour delay, accuracy was higher for new and target items, with peak accuracy emerging by the mid-teens for new items but not until the early twenties for target items. For the 24-hour delay, adolescents showed better memory for targets than distractors compared to adults, who remembered targets and distractors equally well and children who forgot both targets and distractors. Performance on new items 24-hours later peaked in adolescence.

DISCUSSION

The current study examined whether working memory differentially influences what information is retained long-term during adolescence relative to childhood and adulthood. We first show that working memory, and immediate and long-term recognition memory performance peaks during adolescence from the mid-teens to mid-twenties. Expectedly, overall working memory performance was positively associated with immediate and long-term recognition performance regardless of age. However, recognition of specific items (i.e., old targets and distractors from the n-back task and new items) significantly varied by age and delay. For immediate recognition, accuracy was higher for targets and new items than distractors with the best accuracy observed for new items emerging by the mid-teen years. Increased accuracy for targets emerged later in the early twenties. In contrast, for long-term recognition, accuracy was highest for new items,

especially for adolescents, but they also showed more long-term forgetting of distractors relative to targets than adults, who showed equivalent accuracy for targets and distractors, and children who showed long-term forgetting of both targets and distractors. Together the findings suggest that enhanced discrimination of task-relevant from irrelevant items has subsequent effects on long-term memory of information essential to a goal that may benefit the detection of novel information in adolescents.

Our findings are consistent with the developmental literature showing improvement in both working memory and recognition memory from childhood into the late teens and early twenties (Satterthwaite et al., 2013; Weintraub et al., 2013) and with recent definitions of adolescence extending into the mid-twenties based on neurocognitive development (Sawyer et al., 2018). However, in the current study we also showed a slight decline in working memory, immediate and long-term recognition memory by the late twenties even when controlling for I.Q. in our community-based sample. This result may be related in part to the number of participants and greater variability in performance by adults. Nonetheless, the findings are consistent with prior evidence of enhanced learning during this period when the individual is exploring and negotiating novel environments (Davidow et al., 2016).

Consistent in part with our developmental hypotheses, long-term recognition of specific items from the working memory task varied by age. Specifically, we observed different developmental patterns in immediate and long-term recognition for new versus old items from the n-back task. For immediate recognition, accuracy was higher for targets and new items than distractors with higher accuracy observed for new items which emerged by the mid-teen years. Accuracy for targets peaked slightly later, by the early twenties. This finding may be consistent with changes in inhibitory processes with age with suppression of irrelevant distractors in favor of relevant targets (Bjorklund & Harnishfeger, 1990). In contrast, for long-term recognition, accuracy was highest for new items, especially for adolescents. Thus, adolescents were better in identifying new items relative to old items for both immediate and long-term memory recognition. However, adolescents also showed more long-term forgetting of distractors relative to targets than adults, who showed similarly high accuracy for both targets and distractors. In contrast, children showed long-term forgetting of both. This ability to discriminate goal-relevant from irrelevant

information (targets vs distractors), and to detect novel information (new items) during the extended period of adolescence, is consistent with prior evidence of enhanced learning (Davidow et al., 2016) and novelty seeking during adolescence (Galvan, 2010; Spear, 2013).

A primary goal of the current study was to examine the influence of working memory on long-term memory. To explore whether the developmental patterns in long-term recognition for new versus old items were associated more with working memory processes than attention, we examined recognition accuracy for the low (0-back) and high (2-back) memory load conditions separately given that they each tap different cognitive processes. The 0-back condition taps sustained attention for a single rare target for an entire block of trials. In contrast, the 2-back condition requires attention but also maintenance of several potential targets (i.e., any item that repeats an item presented two trials back) and dropping prior targets from working memory when new ones occur. This latter condition more closely aligns with working memory as characterized in the literature (Baddeley, 2000; Baddeley, 1986). These analyses revealed a similar pattern for the high memory load condition to the overall pattern of results collapsing across load, but not for the no load (0-back) condition. Specifically, the high load condition showed enhanced recognition of new items and more long-term forgetting of distractors relative to targets in adolescents. Adolescents may drop or forget prior irrelevant information (distractor items) in favor of relevant information (targets) given the demands on working memory capacity. Remembering information that was previously essential to a goal and forgetting tangential information may be an important mechanism for rapidly learning about key features of new environments during adolescence.

The sensitivity to novel information by adolescents observed in the current study may reflect enhanced novelty-seeking during this period. Alternatively, this developmental pattern may reflect an overall tendency by adolescents to reject items regardless of whether the information is old or new. As the literature suggests that adolescents are more impulsive than adults (Steinberg et al., 2008) and more vulnerable to false memories (McGuire et al., 2015; Meusel et al., 2012) we completed a supplemental response bias analysis and found no effect of age in response bias. These results suggest that the correct rejection of novel items by adolescents could not solely be attributed to an overall impulsive tendency to reject items more than other ages. As such, our

findings are consistent with prior work suggesting that adolescence is characterized by enhanced novelty seeking (Galvan, 2010; Spear, 2013)

Although recognition memory performance varied by age for specific trial types, we found no overall effect of memory load on overall recognition performance (d') as a function of age (Supplemental Figure 5C and 5E). The lack of memory load effects on overall recognition performance is consistent with previous developmental findings suggesting that while attention (0-back) and working memory (2-back) processes differ, they are both associated with subsequent recognition memory performance in children (Rosenberg et al., 2020; Thompson et al., 2019).

Finally, we predicted that salient emotional face stimuli (i.e., fearful and happy) might yield adolescent-specific effects on memory given that adolescents have shown sensitivity to emotional and social cues in prior studies (Casey, 2015; Cohen-Gilbert & Thomas, 2013; Dreyfuss et al., 2014; Grose-Fifer et al., 2013; Irwin & Millstein, 1986; Somerville et al., 2011). However, there were no interactions of stimulus type with age for overall working memory, immediate or long-term recognition memory performance. Stimulus type did however differentially impact memory performance. Working memory was better for faces than places, while immediate and long-term recognition memory was better for places. Preferential working memory for faces may be due to faces being more salient stimuli than places especially during development (Caldara et al., 2003; M.-K. Kwon et al., 2016; Pascalis & de Schonen, 1994) and thus easier to hold temporarily in memory within a task block. However, there were three categories of face stimuli (fearful, happy and neutral) and only one category of places. Thus, there were three times as many faces as places to be remembered in the subsequent recognition task. This disproportionate frequency of faces over places could have led to greater interference during subsequent immediate and long-term recognition memory, thus superseding any saliency effects of faces in the working memory task.

Our results should be interpreted in the context of potential limitations. As described above, there were more faces than places in our tasks that might explain our differential effects of stimulus type on working memory and recognition memory. Second, for recognition memory, there were

fewer participants in the 24-hour delay condition than in the immediate memory condition due to difficulty in recruitment and attrition over two days of assessment. Although our immediate and 24-hour samples were similar in average age and variance, the smaller sample size may have led to less reliable results and/or impacted our ability to test for robust long-term memory effects by age. However, our split half analysis of the 0-hour condition revealed strikingly similar developmental results that replicated across both halves of the data ($n=49$ and $n=48$) and were similar to the effects observed with the full 0-hour delay sample ($n=97$) (S3) suggesting sufficient robustness of effects for the two delay conditions. However, replication of the results would further strengthen our findings. Finally, we used a between-subjects design to test immediate and long-term memory similar to prior developmental memory research (Johnson & Casey, 2015; Saragosa-Harris et al., 2021). An alternative design would have been to test each participant on a subset of items from the working memory task, which would have further decreased the number of items that could be tested for different conditions (0-hr versus 24-hr delay). This design may be powerful, but somewhat less feasible given the ABCD task design.

The current study provides evidence of adolescent-specific enhancements in working memory, recognition memory and long-term memory, with evidence of better long-term recognition of task relevant items and better accuracy on novel items during both immediate recognition and long-term memory. Because we used tasks from the ABCD Study that is currently in progress, and included ages that will ultimately be assessed by that study (i.e., 9 to 20 years), our results from this cross-sectional sample provide predictions for future studies with longitudinal ABCD Study data. Moreover, the ABCD Study tests recognition memory immediately after the n-back task, but not 24 hours later. Thus, our results of similarities and differences in immediate versus long-term recognition memory may help to constrain predictions and the interpretations of future studies using ABCD Study data about the development of different memory processes. In sum, our findings of enhanced memory during adolescence may reflect an adaptive mechanism for what we remember and forget during a developmental period that demands rapid learning in novel environments.

METHODS

Participants

A community sample ($n = 175$, 8–30 years) was recruited from the greater New Haven, Connecticut area. Twenty-five participants were excluded due to chance performance on the working memory or recognition tasks, technical difficulties, or not returning for a second session resulting in a final sample of 150 participants (74 males and 76 females; mean age = 19.13; $SD = 6.35$; See Supplemental text for exclusion criteria). Participants were assigned to either a 0-hour delay condition ($n = 97$; 48 males and 49 females; mean age = 18.97; $SD = 6.49$, Figure S1A) or a 24-hour delay condition ($n = 53$; 26 males and 27 females; mean age = 19.41; $SD = 6.13$, Figure S1B). Welch two sample tests of mean age and variance of the 0-hour and 24-hour groups did not significantly differ ($t(150)=0.41$, $p=0.680$, $F(150)=1.12$, $p=0.664$, respectively) and a two-sample Kolmogorov-Smirnov test (Massey, 1951) of the 0-hour and 24-hour participants was not significant ($D(150)=0.093$, $p=0.927$), indicating the two distributions were likely drawn from the same population (S2). All participants provided informed written consent and minors provided written assent approved by the Institutional Review Board

N-back task

The ABCD Study n-back task consisted of high (2-back) and low (0-back) memory load conditions and 4 stimulus categories including happy, fearful and neutral faces and places (Casey et al., 2018, see Figure 1A for design of n-back task). Validity and reliability of the emotional face stimuli have been reported previously and faces were harmonized for luminosity, head size, and head position (Casey et al., 2018; Conley et al., 2018; Tottenham et al., 2009). Place stimuli were from previously published stimulus sets (Casey et al., 2018; Kanwisher, 2001; O’Craven & Kanwisher, 2000; Park & Chun, 2009). The task consisted of two runs. In each run, there were four blocks of each load (0 and 2-back) condition by stimulus type (happy, fearful and neutral faces and places) for a total of 8 blocks, with 10 trials per condition (2.5s each) and 4 fixation blocks (15s each). Each trial consisted of a 2 second stimulus presentation, followed immediately by a 500ms fixation cross. In total, there were 160 trials and 96 unique stimuli. Prior to completing the task, participants completed a brief practice session of four blocks (2 of each n-back memory task; 2 face blocks, 2 place blocks) of four trials each. The stimuli used in the

practice were different from those in the n-back task and subsequent recognition memory tasks. On each trial, participants were instructed to respond “Match” or “No Match” to each stimulus. A “Match” in the 2-back condition was when the current stimulus was the same as two trials back. A “Match” in the 0-back condition was when the current stimulus was the same as a target stimulus shown at the start of the block. In the 0-back condition, there were three different trial types: 1 target repeated 3 times per block, 2 distractors/(lures) repeated 3 times per block and 6 distractors/(non-lures) shown only once each. In the 2-back condition, there were the same trial types: 2 targets repeated twice, 2 distractors/(lures) repeated twice per block and 6 distractors/(non-lures) shown only once each. To control for the number of stimulus repetitions across trial types, only targets and distractors that were lures from both load conditions were subsequently tested in the recognition memory task.

Recognition Memory Task.

The recognition memory task was identical to that of the ABCD Study (Casey et al., 2018), except that it was administered 24-hours later to assess long-term memory in addition to immediate administration following the n-back task (Figure 1B and C). A total of 96 stimuli were presented during the task. These included on average 24 targets ($M = 24.23$, $SD = 0.61$, range = 22-25), 24 distractors/lures ($M = 23.667$, $SD = 0.474$, range = 23-24) and 48 new items ($M = 48.088$, $SD = 0.509$, range = 48-51) during the recognition task (see S4 for more details on distributions of trial types). Each stimulus was presented for 2s followed by a 1s fixation cross. Instructions and a 2-trial practice (one “Old” from the practice and one new stimulus) preceded the recognition memory task. A total of 96 stimuli were presented during the task, including 48 of the 96 “old” stimuli (targets and distractors only) presented during the emotional n-back task and 48 new stimuli, with equal numbers of each stimulus type (12 each of happy, fearful, and neutral facial expressions as well as places). Participants were asked to rate each picture as either “Old” or “New.” Participants were randomly assigned to either a 0- or 24-hour recognition condition to in part control for the frequency in presentation of each trial type when comparing the effects of working memory on subsequent recognition memory (0-delay) and long-term memory (24-hour delay) by stimulus type.

Data analysis

Trial by trial accuracy data from the emotional n-back and recognition memory tasks were extracted using MATLAB R2016a and analyses were conducted using R version 3.6.3 (R Core Team, 2020). We calculated both d' prime (d') and accuracy data for both the working memory and recognition memory tasks. All d' values were adjusted for extreme values (Hautus, 1995) and were calculated using the *psycho* package in R (Makowski, 2018). For the working memory task, d' was calculated by aggregating the number of hits, misses, false alarms and correct rejections for each subject separately for the 0 and 2 back conditions and different stimulus types of the n-back task. For the recognition memory task, d' was calculated for each subject in both the 0-hour and 24-hour conditions separately for each stimulus type. When assessing the relationship between working memory performance and recognition memory performance d' was calculated for working memory separately for each stimulus type and d' for recognition memory was calculated for each delay condition (0-hour and 24-hour) and each stimulus type. When measuring recognition memory performance for individual trial types (targets, distractors and new items) binary accuracy (0 for incorrect, 1 for correct) was calculated for each stimulus type, load type and delay, as you cannot calculate a d' score for each of these items separately. Both accuracy and d' values were then used to assess age effects in working memory and recognition memory performance using polynomial linear regression and mixed effect models using the *lme4* package (Bates et al., 2015).

All within-subject analyses (analyses *not* including an effect of delay) were performed with a linear mixed effect model including a random effect of subject to control for repeated measures. Between-subjects' analyses (i.e., for the 0- and 24-hour conditions) were performed with a simple regression with delay as a predictor. Z-scored, age-corrected I.Q. (Wechsler Abbreviated Scale of Intelligence WASI-II; Wechsler, 2011) and sex were included in all models in the main text as covariates. I.Q. scores were collected for all but seven participants. These participants were included in the analyses given that linear models can account for missing data, and the key results hold regardless of whether I.Q. was included in the models or not (See supplemental tables 2, 4, 6 and 8). All reported age-effects and statistics in all tables were corrected for multiple comparisons using Bonferroni correction.

To test for age-related changes in working memory, 0- and 24-hour recognition memory, we modeled age with linear, quadratic, and cubic polynomial terms of exact age. Next, we tested each model against the others and a null model without age using either a log-likelihood ratio test for mixed effect models, or an analysis of variance (ANOVA) for simple linear models. All nested models were tested for goodness of fit relative to a null model with the same fixed effects using either a log-likelihood ratio test for the mixed effect models, or an analysis of variance (ANOVA) for linear models. A p -value < 0.05 in either case was taken to indicate a better fit of one model over the other. Following the identification of the best fitting age model, covariates were then added to each model and compared directly to the simpler model using a log-likelihood ratio test or ANOVA. A p -value < 0.05 on either test was taken to indicate that the covariate explained a significant amount of variance. Otherwise, the simpler model was preferred. Full descriptions of the best fitting models are reported in the main text and in Supplemental Tables 1-8.

To assess the impact of working memory on recognition memory across age, we used overall n-back task performance (d') as a continuous predictor of recognition memory performance for the 0- and 24-hour delay conditions. We then examined binary accuracy (0 for incorrect, 1 for correct) for each of the three trial types (old targets, old distractors, and new items) in the immediate and long-term recognition memory conditions controlling for stimulus type and memory load (see S6 examining interactions with stimulus type). We also tested accuracy for each of the three trial types for 0-back and 2-back items separately in a follow-up exploratory analysis (see S5). Binomial models were used to predict accuracy by trial type, delay (0-hour and 24-hour), and age polynomials compared to a model without age as a factor.

Given the difference in sample size between the 0- and 24-hour delay subsamples, a subsidiary analysis with an even-odd split of the larger 0-hour sample ($n = 97$) into two smaller samples ($n = 48$ even, $n = 49$ odd) was performed to test for robustness of developmental patterns in recognition memory for the two delay conditions (see S3). Finally, we calculated non-parametric response bias ($B''D$) for recognition memory to test for any age effects to determine if there was an increased tendency in adolescents to reject recognition items as new regardless of whether they were old or new items (see S7).

REFERENCES

- Acheson, D. J., & MacDonald, M. C. (2009). Verbal Working Memory and Language Production: Common Approaches to the Serial Ordering of Verbal Information. *Psychological Bulletin*, 135(1), 50–68. <https://doi.org/10.1037/a0014411>
- Alberini, CM & Travlia, A (2017) *Infantile Amnesia: A Critical Period of Learning to Learn and Remember*. *Journal of Neuroscience* 14 37 (24) 5783-5795
- Alibali, M. W. (2005). Gesture in Spatial Cognition: Expressing, Communicating, and Thinking About Spatial Information. *Spatial Cognition & Computation*, 5(4), 307–331. https://doi.org/10.1207/s15427633scc0504_2
- Axmacher, N., Haupt, S., Cohen, M. X., Elger, C. E., & Fell, J. (2009). Interference of working memory load with long-term memory formation. *European Journal of Neuroscience*, 29(7), 1501–1513. <https://doi.org/10.1111/j.1460-9568.2009.06676.x>
- Baddeley, A. (1986). *Working memory*. Clarendon Press/Oxford University Press.
- Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, 4(11), 417–423. [https://doi.org/10.1016/S1364-6613\(00\)01538-2](https://doi.org/10.1016/S1364-6613(00)01538-2)
- Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders*, 36(3), 189–208. [https://doi.org/10.1016/S0021-9924\(03\)00019-4](https://doi.org/10.1016/S0021-9924(03)00019-4)
- Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47–89). Academic Press. [https://doi.org/10.1016/S0079-7421\(08\)60452-1](https://doi.org/10.1016/S0079-7421(08)60452-1)

- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1–48.
<https://doi.org/10.18637/jss.v067.i01>
- Bauer P. J. (2006) Constructing a past in infancy: a neuro-developmental account. *Trends Cogn Sci* 10:175–181. 10.1016/j.tics.2006.02.009
- Bauer, P. J. (2015). Development of episodic and autobiographical memory: The importance of remembering forgetting. *Developmental Review*, 38, 146–166.
<https://doi.org/10.1016/j.dr.2015.07.011>
- Bauer, P. J., & Leventon, J. S. (2013). Memory for One-Time Experiences in the Second Year of Life: Implications for the Status of Episodic Memory. *Infancy*, 18(5), 755–781.
<https://doi.org/10.1111/infa.12005>
- Bjorklund, D. F., & Harnishfeger, K. K. (1990). The resources construct in cognitive development: Diverse sources of evidence and a theory of inefficient inhibition. *Developmental Review*, 10(1), 48–71. [https://doi.org/10.1016/0273-2297\(90\)90004-N](https://doi.org/10.1016/0273-2297(90)90004-N)
- Blacker, K. J., Weisberg, S. M., Newcombe, N. S., & Courtney, S. M. (2017). Keeping Track of Where We Are: Spatial Working Memory in Navigation. *Visual Cognition*, 25(7–8), 691–702. <https://doi.org/10.1080/13506285.2017.1322652>
- Blanco, N. J., & Sloutsky, V. M. (2019). Adaptive Flexibility in Category Learning? Young Children Exhibit Smaller Costs of Selective Attention than Adults. *Developmental Psychology*, 55(10), 2060–2076. <https://doi.org/10.1037/dev0000777>
- Blumenfeld, R. S., & Ranganath, C. (2006). Dorsolateral Prefrontal Cortex Promotes Long-Term Memory Formation through Its Role in Working Memory Organization. *Journal of Neuroscience*, 26(3), 916–925. <https://doi.org/10.1523/JNEUROSCI.2353-05.2006>

- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences*, 105(38), 14325–14329. <https://doi.org/10.1073/pnas.0803390105>
- Burgess, N., & Hitch, G. (2005). Computational models of working memory: Putting long-term memory into context. *Trends in Cognitive Sciences*, 9(11), 535–541. <https://doi.org/10.1016/j.tics.2005.09.011>
- Burgess, N., Maguire, E. A., & O’Keefe, J. (2002). The Human Hippocampus and Spatial and Episodic Memory. *Neuron*, 35(4), 625–641. [https://doi.org/10.1016/S0896-6273\(02\)00830-9](https://doi.org/10.1016/S0896-6273(02)00830-9)
- Buss, A. T., Fox, N., Boas, D. A., & Spencer, J. P. (2014). Probing the early development of visual working memory capacity with functional near-infrared spectroscopy. *NeuroImage*, 85, 314–325. <https://doi.org/10.1016/j.neuroimage.2013.05.034>
- Caldara, R., Thut, G., Servoir, P., Michel, C. M., Bovet, P., & Renault, B. (2003). Face versus non-face object perception and the “other-race” effect: A spatio-temporal event-related potential study. *Clinical Neurophysiology*, 114(3), 515–528. [https://doi.org/10.1016/S1388-2457\(02\)00407-8](https://doi.org/10.1016/S1388-2457(02)00407-8)
- Case, R., & And Others. (1992). *The Mind’s Staircase: Exploring the Conceptual Underpinnings of Children’s Thought and Knowledge*. Lawrence Erlbaum Associates, Inc.
- Casey, B. J. (2015). Beyond Simple Models of Self-Control to Circuit-Based Accounts of Adolescent Behavior. *Annual Review of Psychology*, 66(1), 295–319. <https://doi.org/10.1146/annurev-psych-010814-015156>

- Casey, B. J., Tottenham, N., & Fossella, J. (2002). Clinical, imaging, lesion, and genetic approaches toward a model of cognitive control. *Developmental Psychobiology*, 40(3), 237–254. <https://doi.org/10.1002/DEV.10030>
- Casey, B. J., Cannonier, T., Conley, M. I., Cohen, A. O., Barch, D. M., Heitzeg, M. M., Soules, M. E., Teslovich, T., Dellarco, D. V., Garavan, H., Orr, C. A., Wager, T. D., Banich, M. T., Speer, N. K., Sutherland, M. T., Riedel, M. C., Dick, A. S., Bjork, J. M., Thomas, K. M., ... Dale, A. M. (2018). The Adolescent Brain Cognitive Development (ABCD) study: Imaging acquisition across 21 sites. *Developmental Cognitive Neuroscience*, 32, 43–54. <https://doi.org/10.1016/j.dcn.2018.03.001>
- Cohen, A. O., Glover, M. M., Shen, X., Phaneuf, C. V., Avallone, K. N., Davachi, L., & Hartley, C. A. (2021). *Reward enhances memory via age-varying online and offline neural mechanisms across development* (p. 2021.09.14.460286). <https://doi.org/10.1101/2021.09.14.460286>
- Cohen, A. O., Matese, N. G., Filimontseva, A., Shen, X., Shi, T. C., Livne, E., & Hartley, C. A. (2019). Aversive learning strengthens episodic memory in both adolescents and adults. *Learning & Memory*, 26(7), 272–279. <https://doi.org/10.1101/lm.048413.118>
- Cohen-Gilbert, J. E., & Thomas, K. M. (2013). Inhibitory control during emotional distraction across adolescence and early adulthood. *Child Development*, 84(6), 1954–1966. <https://doi.org/10.1111/cdev.12085>
- Collette, F., Van der Linden, M., & Poncelet, M. (2000). Working Memory, Long-Term Memory, and Language Processing: Issues and Future Directions. *Brain and Language*, 71(1), 46–51. <https://doi.org/10.1006/brln.1999.2209>

- Conklin, H. M., Luciana, M., Hooper, C. J., & Yarger, R. S. (2007). Working Memory Performance in Typically Developing Children and Adolescents: Behavioral Evidence of Protracted Frontal Lobe Development. *Developmental Neuropsychology*, 31(1), 103–128. <https://doi.org/10.1080/87565640709336889>
- Conley, M. I., Dellarco, D. V., Rubien-Thomas, E., Cohen, A. O., Cervera, A., Tottenham, N., & Casey, B. (2018). The racially diverse affective expression (RADIATE) face stimulus set. *Psychiatry Research*, 270, 1059–1067. <https://doi.org/10.1016/j.psychres.2018.04.066>
- Cotton, K., & Ricker, T. J. (2020). Working memory consolidation improves long-term memory recognition. *Journal of Experimental Psychology. Learning, Memory, and Cognition*. <https://doi.org/10.1037/xlm0000954>
- Cowan, N. (2014). Working Memory Underpins Cognitive Development, Learning, and Education. *Educational Psychology Review*, 26(2), 197–223. <https://doi.org/10.1007/s10648-013-9246-y>
- Cowan, N., & Alloway, T. (2009). Development of working memory in childhood. In *The development of memory in infancy and childhood, 2nd ed* (pp. 303–342). Psychology Press.
- Curtis, C. E., & Lee, D. (2010). Beyond working memory: The role of persistent activity in decision making. *Trends in Cognitive Sciences*, 14(5), 216–222. <https://doi.org/10.1016/j.tics.2010.03.006>
- Davidow, J. Y., Foerde, K., Galván, A., & Shohamy, D. (2016). An Upside to Reward Sensitivity: The Hippocampus Supports Enhanced Reinforcement Learning in Adolescence. *Neuron*, 92(1), 93–99. <https://doi.org/10.1016/j.neuron.2016.08.031>

- Del Missier, F., Mäntylä, T., Hansson, P., Bruine de Bruin, W., Parker, A. M., & Nilsson, L.-G. (2013). The Multifold Relationship Between Memory and Decision Making: An Individual-differences Study. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, 39(5), 1344–1364. <https://doi.org/10.1037/a0032379>
- DeMaster, D., Pathman, T., Lee, J. K., & Ghetti, S. (2014). Structural Development of the Hippocampus and Episodic Memory: Developmental Differences Along the Anterior/Posterior Axis. *Cerebral Cortex*, 24(11), 3036–3045. <https://doi.org/10.1093/cercor/bht160>
- Demetriou, A., Christou, C., Spanoudis, G., & Platsidou, M. (2002). The development of mental processing: Efficiency, working memory, and thinking. *Monographs of the Society for Research in Child Development*, 67(1), vii–154. <https://doi.org/10.1111/1540-5834.671173>
- Deng, W. S., & Sloutsky, V. M. (2016). Selective attention, diffused attention, and the development of categorization. *Cognitive Psychology*, 91, 24–62. <https://doi.org/10.1016/j.cogpsych.2016.09.002>
- Diamond, A., & Goldman-Rakic, P. (1989). Comparison of human infants and rhesus monkeys on Piaget's AB task: Evidence for dependence on dorsolateral prefrontal cortex. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, 74, 24–40. <https://doi.org/10.1007/BF00248277>
- Dreyfuss, M., Caudle, K., Drysdale, A. T., Johnston, N. E., Cohen, A. O., Somerville, L. H., Galván, A., Tottenham, N., Hare, T. A., & Casey, B. J. (2014). Teens impulsively react rather than retreat from threat. *Developmental Neuroscience*, 36(3–4), 220–227. <https://doi.org/10.1159/000357755>

Durston, S., Thomas, K. M., Yang, Y., Uluğ, A. M., Zimmerman, R. D., & Casey, B. J. (2002).

A neural basis for the development of inhibitory control. *Developmental Science*, 5(4),

F9–F16. <https://doi.org/10.1111/1467-7687.00235>

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory,

short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of*

Experimental Psychology: General, 128(3), 309–331. [https://doi.org/10.1037/0096-](https://doi.org/10.1037/0096-3445.128.3.309)

3445.128.3.309

Fischer, K. W. (1980). A theory of cognitive development: The control and construction of

hierarchies of skills. *Psychological Review*, 87(6), 477–531.

<https://doi.org/10.1037/0033-295X.87.6.477>

Fry, A. F., & Hale, S. (2000). Relationships among processing speed, working memory, and

fluid intelligence in children. *Biological Psychology*, 54(1), 1–34.

[https://doi.org/10.1016/S0301-0511\(00\)00051-X](https://doi.org/10.1016/S0301-0511(00)00051-X)

Fukuda, K., & Woodman, G. F. (2017). Visual working memory buffers information retrieved

from visual long-term memory. *Proceedings of the National Academy of Sciences*,

114(20), 5306–5311. <https://doi.org/10.1073/pnas.1617874114>

Galvan, A. (2010). Adolescent development of the reward system. *Frontiers in Human*

Neuroscience, 4, 6. <https://doi.org/10.3389/neuro.09.006.2010>

Gathercole, S. E., & Adams, A. M. (1994). Children's Phonological Working Memory:

Contributions of Long-Term Knowledge and Rehearsal. *Journal of Memory and*

Language, 33(5), 672–688. <https://doi.org/10.1006/jmla.1994.1032>

- Ghetti, S., & Angelini, L. (2008). The Development of Recollection and Familiarity in Childhood and Adolescence: Evidence From the Dual-Process Signal Detection Model. *Child Development*, 79(2), 339–358. <https://doi.org/10.1111/j.1467-8624.2007.01129.x>
- Ghetti, S., DeMaster, D. M., Yonelinas, A. P., & Bunge, S. A. (2010). Developmental Differences in Medial Temporal Lobe Function during Memory Encoding. *Journal of Neuroscience*, 30(28), 9548–9556. <https://doi.org/10.1523/JNEUROSCI.3500-09.2010>
- Ghetti, S., & Lee, J. K. (2013). The Development of Recollection and Familiarity During Childhood: Insight from Studies of Behavior and Brain. In *The Wiley Handbook on the Development of Children's Memory* (pp. 309–335). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781118597705.ch14>
- Golarai, G., Liberman, A., Yoon, J. M. D., & Grill-Spector, K. (2010). Differential development of the ventral visual cortex extends through adolescence. *Frontiers in Human Neuroscience*, 3. <https://doi.org/10.3389/neuro.09.080.2009>
- Grady CL, McIntosh AR, Horwitz B, Maisog JM, Ungerleider LG, Mentis MJ, Pietrini P, Schapiro MB, Haxby JV. Age-related reductions in human recognition memory due to impaired encoding. *Science*. 1995 Jul 14;269(5221):218-21. doi: 10.1126/science.7618082. PMID: 7618082.
- Grose-Fifer, J., Rodrigues, A., Hoover, S., & Zottoli, T. (2013). Attentional capture by emotional faces in adolescence. *Advances in Cognitive Psychology*, 9(2), 81–91. <https://doi.org/10.2478/v10053-008-0134-9>
- Güler, O. E., & Thomas, K. M. (2013). Developmental differences in the neural correlates of relational encoding and recall in children: An event-related fMRI study. *Developmental Cognitive Neuroscience*, 3, 106–116. <https://doi.org/10.1016/j.dcn.2012.07.001>

- Hale, S., Bronik, M. D., & Fry, A. F. (1997). Verbal and spatial working memory in school-age children: Developmental differences in susceptibility to interference. *Developmental Psychology*, 33(2), 364–371. <https://doi.org/10.1037/0012-1649.33.2.364>
- Hasher, L., & Zacks, R. T. (1988). Working Memory, Comprehension, and Aging: A Review and a New View. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 22, pp. 193–225). Academic Press. [https://doi.org/10.1016/S0079-7421\(08\)60041-9](https://doi.org/10.1016/S0079-7421(08)60041-9)
- Harnishfeger K.K., Bjorklund D.F. (1993) The Ontogeny of Inhibition Mechanisms: A Renewed Approach to Cognitive Development. In: Howe M.L., Pasnak R. (eds) *Emerging Themes in Cognitive Development*. Springer, New York, NY. https://doi.org/10.1007/978-1-4613-9220-0_2
- Hautus, M. J. (1995). Corrections for extreme proportions and their biasing effects on estimated values of d' . *Behavior Research Methods, Instruments, & Computers*, 27(1), 46–51. <https://doi.org/10.3758/BF03203619>
- Hertzog, C., Dixon, R. A., Hultsch, D. F., & MacDonald, S. W. S. (2003). Latent Change Models of Adult Cognition: Are Changes in Processing Speed and Working Memory Associated With Changes in Episodic Memory? *Psychology and Aging*, 18(4), 755–769. <https://doi.org/10.1037/0882-7974.18.4.755>
- Irwin, C. E., & Millstein, S. G. (1986). Biopsychosocial correlates of risk-taking behaviors during adolescence: Can the physician intervene? *Journal of Adolescent Health Care*, 7(6, Suppl), 82–96.
- Isbell, E., Fukuda, K., Neville, H. J., & Vogel, E. K. (2015). Visual working memory continues to develop through adolescence. *Frontiers in Psychology*, 6. <https://doi.org/10.3389/fpsyg.2015.00696>

- Jenkins, L., Myerson, J., Hale, S., & Fry, A. F. (1999). Individual and developmental differences in working memory across the life span. *Psychonomic Bulletin & Review*, 6(1), 28–40.
<https://doi.org/10.3758/bf03210810>
- Johnson, D. C., & Casey, B. J. (2015). Extinction during memory reconsolidation blocks recovery of fear in adolescents. *Scientific Reports*, 5, 8863.
<https://doi.org/10.1038/srep08863>
- Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychologica*, 86(2), 199–225. [https://doi.org/10.1016/0001-6918\(94\)90003-5](https://doi.org/10.1016/0001-6918(94)90003-5)
- Kanwisher, N. (2001). Faces and places: Of central (and peripheral) interest. *Nature Neuroscience*, 4(5), 455–456. <https://doi.org/10.1038/87399>
- Klingberg, T. (2006). Development of a superior frontal–intraparietal network for visuo-spatial working memory. *Neuropsychologia*, 44(11), 2171–2177.
<https://doi.org/10.1016/j.neuropsychologia.2005.11.019>
- Kwon, H., Reiss, A. L., & Menon, V. (2002). Neural basis of protracted developmental changes in visuo-spatial working memory. *Proceedings of the National Academy of Sciences of the United States of America*, 99(20), 13336–13341.
<https://doi.org/10.1073/pnas.162486399>
- Kwon, M.-K., Setoodehnia, M., Baek, J., Luck, S. J., & Oakes, L. M. (2016). The development of visual search in infancy: Attention to faces versus salience. *Developmental Psychology*, 52(4), 537–555. <https://doi.org/10.1037/dev0000080>
- Li, S, Callaghan BL, Richardson R (2014) Infantile amnesia: forgotten but not gone. *Learn Mem* 21:135–139. 10.1101/lm.031096.113

- Lloyd, M. E., Doydum, A. O., & Newcombe, N. S. (2009). Memory Binding in Early Childhood: Evidence for a Retrieval Deficit. *Child Development*, 80(5), 1321–1328.
<https://doi.org/10.1111/j.1467-8624.2009.01353.x>
- Luna, B., Thulborn, K. R., Munoz, D. P., Merriam, E. P., Garver, K. E., Minshew, N. J., Keshavan, M. S., Genovese, C. R., Eddy, W. F., & Sweeney, J. A. (2001). Maturation of widely distributed brain function subserves cognitive development. *NeuroImage*, 13(5), 786–793. <https://doi.org/10.1006/nimg.2000.0743>
- Makowski, D. (2018). The psycho Package: An Efficient and Publishing-Oriented Workflow for Psychological Science. *Journal of Open Source Software*, 3(22), 470.
<https://doi.org/10.21105/joss.00470>
- Marshall, D. H., Drummey, A. B., Fox, N. A., & Newcombe, N. S. (2002). An Event-Related Potential Study of Item Recognition Memory in Children and Adults. *Journal of Cognition and Development*, 3(2), 201–224.
https://doi.org/10.1207/S15327647JCD0302_4
- Massey, F. J. (1951). The Kolmogorov-Smirnov Test for Goodness of Fit. *Journal of the American Statistical Association*, 46(253), 68–78.
<https://doi.org/10.1080/01621459.1951.10500769>
- Meyer H.C., Pattwell S.S. (2020) Memory across Development, with Insights from Emotional Learning: A Nonlinear Process. *The Cognitive Neurosciences*:243.
- McGuire, K., London, K., & Wright, D. B. (2015). Developmental Trends in False Memory Across Adolescence and Young Adulthood: A Comparison of DRM and Memory Conformity Paradigms: DRM and memory conformity. *Applied Cognitive Psychology*, 29(3), 334–344. <https://doi.org/10.1002/acp.3114>

- Meusel, L.-A. C., MacQueen, G. M., Jaswal, G., & McKinnon, M. C. (2012). *Youth are more Vulnerable to False Memories than Middle- Aged Adults due to Liberal Response Bias*. 7.
- Moffat, S. D., Kennedy, K. M., Rodrigue, K. M., & Raz, N. (2007). Extrahippocampal Contributions to Age Differences in Human Spatial Navigation. *Cerebral Cortex*, 17(6), 1274–1282. <https://doi.org/10.1093/cercor/bhl036>
- Nee, D. E., Berman, M. G., Moore, K. S., & Jonides, J. (2008). Neuroscientific Evidence About the Distinction Between Short- and Long-Term Memory. *Current Directions in Psychological Science*, 17(2), 102–106. <https://doi.org/10.1111/j.1467-8721.2008.00557.x>
- Nelson, C. A. (2001). The development and neural bases of face recognition. *Infant and Child Development*, 10(1–2), 3–18. <https://doi.org/10.1002/icd.239>
- Nelson, C. A., de Haan, M., & Thomas, K. M. (2006). *Neuroscience of cognitive development: The role of experience and the developing brain*. John Wiley & Sons Inc.
- Newcombe NS, Lloyd ME, Ratliff KR (2007) Development of episodic and autobiographical memory: a cognitive neuroscience perspective. *Adv Child Dev Behav* 35:37–85. 10.1016/B978-0-12-009735-7.50007-4
- O’Craven, K. M., & Kanwisher, N. (2000). Mental imagery of faces and places activates corresponding stimulus-specific brain regions. *Journal of Cognitive Neuroscience*, 12(6), 1013–1023. <https://doi.org/10.1162/08989290051137549>
- Ofen, N., Kao, Y.-C., Sokol-Hessner, P., Kim, H., Whitfield-Gabrieli, S., & Gabrieli, J. D. E. (2007). Development of the declarative memory system in the human brain. *Nature Neuroscience*, 10(9), 1198–1205. <https://doi.org/10.1038/nn1950>

- O'Hare, E. D., Lu, L. H., Houston, S. M., Bookheimer, S. Y., & Sowell, E. R. (2008). Neurodevelopmental changes in verbal working memory load-dependency: An fMRI investigation. *NeuroImage*, 42(4), 1678–1685.
<https://doi.org/10.1016/j.neuroimage.2008.05.057>
- Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, 15(7), 327–334. <https://doi.org/10.1016/j.tics.2011.05.004>
- Pallier G, Wilkinson R, Danthiir V, Kleitman S, Knezevic G, Stankov L, Roberts RD. The role of individual differences in the accuracy of confidence judgments. *J Gen Psychol*. 2002 Jul;129(3):257-99. doi: 10.1080/00221300209602099. PMID: 12224810.
- Park, S., & Chun, M. M. (2009). Different roles of the parahippocampal place area (PPA) and retrosplenial cortex (RSC) in panoramic scene perception. *NeuroImage*, 47(4), 1747–1756. <https://doi.org/10.1016/j.neuroimage.2009.04.058>
- Pascalis, O., & de Schonen, S. (1994). Recognition memory in 3- to 4-day-old human neonates. *Neuroreport*, 5(14), 1721–1724.
- Pattwell, S. S., Duhoux, S., Hartley, C. A., Johnson, D. C., Jing, D., Elliott, M. D., Ruberry, E. J., Powers, A., Mehta, N., Yang, R. R., Soliman, F., Glatt, C. E., Casey, B. J., Ninan, I., & Lee, F. S. (2012). Altered fear learning across development in both mouse and human. *Proceedings of the National Academy of Sciences*, 109(40), 16318–16323.
<https://doi.org/10.1073/pnas.1206834109>
- Peverill, M., McLaughlin, K. A., Finn, A. S., & Sheridan, M. A. (2016). Working memory filtering continues to develop into late adolescence. *Developmental Cognitive Neuroscience*, 18, 78–88. <https://doi.org/10.1016/j.dcn.2016.02.004>

- Plebanek, D. J., & Sloutsky, V. M. (2017). Costs of Selective Attention: When Children Notice What Adults Miss. *Psychological Science*, 28(6), 723–732.
<https://doi.org/10.1177/0956797617693005>
- Ranganath, C., Cohen, M. X., & Brozinsky, C. J. (2005). Working Memory Maintenance Contributes to Long-term Memory Formation: Neural and Behavioral Evidence. *Journal of Cognitive Neuroscience*, 17(7), 994–1010. <https://doi.org/10.1162/0898929054475118>
- Reynolds, G. D., & Romano, A. C. (2016). The Development of Attention Systems and Working Memory in Infancy. *Frontiers in Systems Neuroscience*, 10.
<https://doi.org/10.3389/fnsys.2016.00015>
- Rosenberg, M. D., Martinez, S. A., Rapuano, K. M., Conley, M. I., Cohen, A. O., Cornejo, M. D., Hagler, D. J., Meredith, W. J., Anderson, K. M., Wager, T. D., Feczko, E., Earl, E., Fair, D. A., Barch, D. M., Watts, R., & Casey, B. J. (2020). Behavioral and Neural Signatures of Working Memory in Childhood. *Journal of Neuroscience*, 40(26), 5090–5104. <https://doi.org/10.1523/JNEUROSCI.2841-19.2020>
- Saragosa-Harris, N. M., Cohen, A. O., Shen, X., Sardar, H., Alberini, C. M., & Hartley, C. A. (2021). Associative memory persistence in 3- to 5-year-olds. *Developmental Science*, 24(5), e13105. <https://doi.org/10.1111/desc.13105>
- Satterthwaite, T. D., Wolf, D. H., Erus, G., Ruparel, K., Elliott, M. A., Gennatas, E. D., Hopson, R., Jackson, C., Prabhakaran, K., Bilker, W. B., Calkins, M. E., Loughead, J., Smith, A., Roalf, D. R., Hakonarson, H., Verma, R., Davatzikos, C., Gur, R. C., & Gur, R. E. (2013). Functional Maturation of the Executive System during Adolescence. *Journal of Neuroscience*, 33(41), 16249–16261. <https://doi.org/10.1523/JNEUROSCI.2345-13.2013>

- Sawyer, S. M., Azzopardi, P. S., Wickremarathne, D., & Patton, G. C. (2018). The age of adolescence. *The Lancet Child & Adolescent Health*, 2(3), 223–228.
[https://doi.org/10.1016/S2352-4642\(18\)30022-1](https://doi.org/10.1016/S2352-4642(18)30022-1)
- Schleeper, T. M. J., & Jonkman, L. M. (2009). The Development of Non-Spatial Working Memory Capacity During Childhood and Adolescence and the Role of Interference Control: An N-Back Task Study. *Developmental Neuropsychology*, 35(1), 37–56.
<https://doi.org/10.1080/87565640903325733>
- Shadlen, M. N., & Shohamy, D. (2016). Decision Making and Sequential Sampling from Memory. *Neuron*, 90(5), 927–939. <https://doi.org/10.1016/j.neuron.2016.04.036>
- Simmering, V. R. (2012). The development of visual working memory capacity during early childhood. *Journal of Experimental Child Psychology*, 111(4), 695–707.
<https://doi.org/10.1016/j.jecp.2011.10.007>
- Somerville, L. H. (2013). The Teenage Brain: Sensitivity to Social Evaluation. *Current Directions in Psychological Science*, 22(2), 121–127.
<https://doi.org/10.1177/0963721413476512>
- Somerville, L. H., Hare, T., & Casey, B. (2011). Frontostriatal maturation predicts cognitive control failure to appetitive cues in adolescents. *Journal of Cognitive Neuroscience*, 23(9), 2123–2134. <https://doi.org/10.1162/jocn.2010.21572>
- Spear, L. P. (2010). *The behavioral neuroscience of adolescence*. W. W. Norton & Company.
- Spear, L. P. (2013). Adolescent Neurodevelopment. *Journal of Adolescent Health*, 52(2, Supplement 2), S7–S13. <https://doi.org/10.1016/j.jadohealth.2012.05.006>

- Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments & Computers*, 31(1), 137–149. <https://doi.org/10.3758/BF03207704>
- Steinberg, L., Albert, D., Cauffman, E., Banich, M., Graham, S., & Woolard, J. (2008). Age differences in sensation seeking and impulsivity as indexed by behavior and self-report: Evidence for a dual systems model. *Developmental Psychology*, 44(6), 1764–1778. <https://doi.org/10.1037/a0012955>
- Thompson, W. K., Barch, D. M., Bjork, J. M., Gonzalez, R., Nagel, B. J., Nixon, S. J., & Luciana, M. (2019). The structure of cognition in 9 and 10 year-old children and associations with problem behaviors: Findings from the ABCD study's baseline neurocognitive battery. *Developmental Cognitive Neuroscience*, 36, 100606. <https://doi.org/10.1016/j.dcn.2018.12.004>
- Tottenham, N., Tanaka, J. W., Leon, A. C., McCarry, T., Nurse, M., Hare, T. A., Marcus, D. J., Westerlund, A., Casey, B. J., & Nelson, C. (2009). The NimStim set of facial expressions: Judgments from untrained research participants. *Psychiatry Research*, 168(3), 242–249. <https://doi.org/10.1016/j.psychres.2008.05.006>
- Weintraub, S., Dikmen, S. S., Heaton, R. K., Tulsky, D. S., Zelazo, P. D., Bauer, P. J., Carlozzi, N. E., Slotkin, J., Blitz, D., Wallner-Allen, K., Fox, N. A., Beaumont, J. L., Mungas, D., Nowinski, C. J., Richler, J., Deocampo, J. A., Anderson, J. E., Manly, J. J., Borosh, B., ... Gershon, R. C. (2013). Cognition assessment using the NIH Toolbox. *Neurology*, 80(11 Suppl 3), S54-64. <https://doi.org/10.1212/WNL.0b013e3182872ded>

Woodman, G. F., & Chun, M. M. (2006). The role of working memory and long-term memory in visual search. *Visual Cognition*, 14(4–8), 808–830.

<https://doi.org/10.1080/13506280500197397>

Zald, D. H., & Iacono, W. G. (1998). The development of spatial working memory abilities. *Developmental Neuropsychology*, 14(4), 563–578.

<https://doi.org/10.1080/87565649809540729>

SUPPLEMENTAL MATERIALS

Supplemental Text and Figures.

S1. Sample demographics. Exclusion criteria included estimated I.Q. as measured by the Wechsler Abbreviated Scale of Intelligence (WASI-II; Weschler, 2011) of less than 70. Ten of the 175 recruited participants were excluded from analyses due to a full-scale I.Q. of less than 70. Of the remaining 165 participants, four were excluded for chance performance on the working memory task ($< 60\%$ accuracy at $p < .05$). Eight additional subjects were excluded because of experimenter error in administering the recognition memory task, and three more were excluded for not returning for their second appointment 24 hours later. Thus, behavioral data from 150 of the 175 recruited participants (74 males and 76 females; mean age = 19.13; $SD = 6.35$) are reported in the final analyses. The sample consisted of diverse racial/ethnic backgrounds: (39% White, 13% Black, 7% Hispanic, 9% Hispanic/Latinx, 3% Non-Hispanic Latinx, 12% Asian, 2% American Indian, 6% Other/Mixed-race, 9% Not reported). Figure S1 shows the distribution of these 150 participants by age and sex for the n-back task and recognition memory task performed immediately or 24 hours later.

Supplemental Figure 1. Demographics of sample A. Distribution of age and sex for sample tested on n-back task ($n = 150$). B. Distribution of age and sex for subsamples tested either 0 ($n = 97$), or 24 hours ($n = 53$) after the n-back task or tested on n-back task by age and sex. Ages ranged from 8-30 and the overall sample was roughly equated for gender ($M = 74$, $F = 76$). Sex was controlled for in all analyses and no main effects of sex were found in any models.

S2. Demographic Comparisons. Of the 150 total participants, 97 were administered a recognition memory task immediately following the n-back task ($n = 97$; 48 males and 49 females; mean age = 18.97; $SD = 6.49$) and 53 participants ($n = 53$; 26 males and 27 females; mean age = 19.41; $SD = 6.13$) were tested on the same recognition memory test 24-hours later to test both immediate and long-term memory. To address concerns about the discrepancy between the number of participants in these two conditions and the ages of these participants given that our primary questions were developmental in nature, we analyzed the demographic makeups of both groups (See supplemental Figure 2A and B for distributions). There were fewer participants in the 24-hour condition due to attrition ($n = 53$), but a Welch two sample test of the means revealed the mean age of the two groups did not differ ($t(150) = 0.41$, $p = 0.680$) and the variance of the two samples was not significantly different ($F(150) = 1.12$, $p = 0.664$). Furthermore, a two-sample Kolmogorov-Smirnov test of the 0-hour and 24-hour participants was not significant ($D(150) = 0.093$, $p = 0.927$), indicating that the two distributions were likely drawn from the same population. Visual inspection of density plots of the ages of the two samples shows similar distributions between 0-hour and 24-hour groups (S2 A and B).

Supplemental Figure 2. Demographics comparisons of 0-hour and 24-hour plots. A. Density plots of the age distribution in the 0-hour condition red lines show density function. B. Density plots of the age distribution in the 24-hour condition red lines show density function C. Box plot of the average age of the 0-hour sample D. Box plot of the average age of the 24-hour sample

S3. Split-Half analysis for the 0-hour subjects to assess power of results.

To address whether the number of participants in the 24-hour delay condition was sufficient, we conducted a split-half analysis of the 0-hour delay participants. We took every other participant (even-odd split) and put them into one group (first half) and then took all the remaining participants and put them into a second group (second half). This was done to roughly equate the ages of the two groups and indeed, these two groups did not differ by mean age ($t(94)=0.22$, $p=0.830$) when conducting a Welch-two sample t-test, and the sex distribution of half 1 (M=24, F=25) and half 2 (M=25, F=23) was roughly equivalent. This left us with a first half 0-hour delay group with 49 participants (mean age = 19.11, $SD = 6.56$) and a second half 0-hour delay group with 48 participants (mean age = 18.83, $SD = 6.48$), which was fewer participants than in the 24-hour delay group ($n=53$).

We then re-ran our trial type by age by delay models as a test case to see if the same general developmental performance patterns emerged in the first half and second half as when all 97 participants were included in the original analysis. All statistics were Bonferroni corrected for multiple comparisons. Indeed, a model with a cubic age term was the best fitting model for both the first half ($F(18) = 6.47$, $p<.0001$) and second half ($F(18) = 6.792$, $p<.0001$) analyses consistent with the original analysis (see Supplemental Figure 3 for comparisons). Both the first half ($F(3) = 20.070$, $p<.0001$) and second half ($F(3) = 17.851$, $p<.0001$) analyses had a main effect of age, as well as a trial type by delay by age interaction for the first ($F(6) = 3.460$, $p=.0122$) and second half ($F(6) = 5.563$, $p<.0001$). Likewise, visual inspection shows that the trial type effects remain similar to the original collapsed data regardless of either half of the data used. Performance new items is higher than target items in adolescence, and target performance continues to improve into the mid-twenties, whereas the performance on distractor items is relatively flat across development and significantly worse across age than performance on targets and new items. The similarity of these results to the original 0-hour delay results with only half of the participants may indicate that the 24-hour delay data, which had slightly more subjects than the split-halves of the 0-hour delay, was sufficiently robust to show developmental trends even at the level of individual trial types.

Supplemental Figure 3. Split half comparisons of 0-hour data for the trial type interactions. A. The original trial type, by age interaction from the main text using all participants for the 0-hour data best fit from a cubic age model. B. One half (odd numbered split) of the 0-hour participants showing a similar age by trial type interaction as the original data with all participants included. A cubic model of age was still the best fitting model with half the participants. C. The second half (even numbered split) of the 0-hour participants showing a similar age by trial type interaction as the original data with all participants included. A cubic model of age was still the best fitting model with half the participants.

S4. Supplemental Methods Information

Distribution of target, distractor and new items across participants. Most participants (105 of 150) were tested on exactly 24 targets, 24 distractors/lures and 48 new items during the recognition task while 45 participants (26 in the 0-hour delay condition and 19 in the 24-hour delay condition) were tested on varying numbers of items with a mean average frequency in targets of 24.15 ($SD = 0.628$, range = 22-25), in distractors/lures of 23.72 ($SD = 0.454$, range = 23-24) and in new items of 48.12 ($SD = 0.59$, range = 48-51). These participants included 26 of 97 (27%) in the 0-hour condition and 19 of 53 (36%) in the 24-hour condition. The mean age of all participants with varying items did not significantly differ between the 0- and 24-hour delay conditions (0-hour: $M = 17.95$, $SD = 7.25$; 24-hour: $M = 18.81$, $SD = 5.79$; $t(42) = 0.444$, $p = 0.6951$). As reported in the main text, across the entire sample the average number of targets was 24.23 ($SD = 0.61$, range = 22-25), of distractors was 23.667 ($SD = 0.474$, range = 23-24) and of new items was 48.088 ($SD = 0.509$, range = 48-51).

S5. Relationship between working memory and recognition memory by load

To determine whether working memory-load had an impact on subsequent recognition memory performance, we investigated the effect of load (0-back and 2-back) on d' in the recognition memory task (0 and 24-hour). We re-calculated working memory d' for each subject using only items that were tested in the 0-back and 2-back load conditions. We then calculated hit rate for 0-back and 2-back items separately in the recognition memory task. Thus, for each subject, this yielded two separate working memory d' values and two separate recognition hit rate values for 0-back items and for 2-back items. We then fit linear models predicting recognition memory (hit rate) by working memory (d'), delay condition (0- vs 24-hour), and stimulus type (neutral, fear and happy faces and places) for the 0-back and 2-back items respectively with age polynomials (no-age, linear, quadratic and cubic polynomials). In both cases, as when collapsed, we still found that the no-age model fit best with a significant effect of working memory d' on recognition memory hit rate for 0-back ($F(1) = 328.682, p < .0001$) and 2-back ($F(1) = 208.780, p < .0001$) items respectively (Supplemental Figure 5C and 5E).

We likewise assessed recognition memory binary accuracy (0 for incorrect, 1 for correct) by trial type (target, distractor and new items), by age (no-age, linear, quadratic and cubic polynomials), delay condition (0- vs 24-hour), and stimulus type (neutral, fear and happy faces and places) for items tested in the 0-back and 2-back conditions of the n-back task separately. We found that a quadratic age polynomial for age was the best fitting model for the 0-back items compared to the no-age model ($F(12) = 9.494, p < .0001$), with significant two-way interactions between age and trial type ($F(4) = 4.204, p = .0127$) and delay and age ($F(2) = 5.772, p = .0187$). We also found a significant three-way interaction between trial type, delay and age ($F(4) = 3.516, p = .0428$). Visual inspection suggests that for 0-back items there was an adolescent advantage for new items and targets in both the 0-hour and 24-hour delays (S5D). Distractor item performance was flat across age in the immediate condition and peaked by the early twenties in the 24-hour condition. These results may indicate that attention to relevant items (new and targets) peaks during adolescence, whereas there is still significant long-term forgetting of distractors until the early twenties.

For the 2-back items, we found that a cubic age polynomial was the best fitting model compared to the no-age model ($F(18) = 7.137, p < .0001$) consistent with the developmental pattern when collapsing across memory load reported in the main text. In this model we found a main effect of age ($F(3) = 21.146, p < .0001$), as well as a trial type by age interaction ($F(6) = 4.764, p = .0004$) and a trial type by delay by age interaction ($F(6) = 5.312, p = .0001$). Visual inspection of the three-way interaction suggests that recognition accuracy for new items was best for all ages but peaked and plateaued by the mid-teens in the immediate delay and 24-hour delay (S5F). Performance on targets and distractors was roughly equivalent across age for the 0-hour delay, but for the 24-hour delay, adolescents showed long-term forgetting of distractors relative to targets, whereas adults showed similarly high accuracy for targets and distractors and children showed long-term forgetting of both targets and distractors. These results are similar to the pattern reported in the main text (Figure 4B) when the data were collapsed by load and provide some support that our collapsed results showing long-term forgetting of distractors relative targets and better performance on new items by adolescents are driven by the 2-back condition. The 2-back condition is thought to be a measure of working memory rather than the 0-back condition. These results suggest that working memory may influence long-term memory of relevant items and forgetting of irrelevant information during adolescence.

Supplemental Figure 5. A. Relationship between working memory (d') and overall recognition memory performance collapsed across all loads (d') again shows a general positive association between working memory and recognition memory that did not vary by age. B. Mean accuracy in recognition memory by trial type (new items, old targets, old distractors), delay (0 and 24 hour) and age collapsed across load. C. Relationship between working memory (d') and recognition accuracy on 0-back items shows a general positive association between working memory and recognition memory that did not vary by age. D. Mean accuracy in recognition memory by trial type for items from 0-back blocks of the working memory task by delay condition by age. Participants showed better performance regardless of delay, for targets and new items relative to distractors that peaked in late adolescence. E. Relationship between working memory (d') and recognition accuracy on 2-back items shows a general positive association between working memory and recognition memory that did not vary by age. F. Mean accuracy in recognition memory by trial type for items from 2-back blocks of the working memory task for the 0- and 24-hour delay conditions. Recognition performance was better for new items than for targets and distractors from the working memory. Adults however showed similar long-term memory (24-hour delay) for all three trial types than either children or adolescents. Adolescents in their mid-teens showed a slight advantage in long-term memory for targets over distractors.

S6. Supplemental analyses including stimulus type as a factor to examine interactions with trial type and age.

To further interrogate the main effect of stimulus type we saw when analyzing overall recognition memory performance (d') (see Figure 3B in the main text), we ran a model including stimulus type (place, neutral face, fear face and happy face), trial type (new, target and distractor) and age (no-age, linear, quadratic and cubic polynomials) as factors in predicting binary recognition memory accuracy, while controlling for load, delay, I.Q. and sex. All age effects were Bonferroni corrected for multiple comparisons. Performance was best fit by a quadratic model compared to the no-age model ($F(24) = 5.376$, $p < .0001$) (see Supplemental table 13 for full model). The quadratic model had a main effect of trial type ($F(1) = 188.667$, $p < .0001$), stimulus type ($F(3) = 18.039$, $p < .0001$) and age ($F(2) = 35.950$, $p < .0001$), as well as an interaction between age and trial type ($F(4) = 4.068$, $p = .0161$). These main effects and interactions mirrored the results from Figure 3 in the main text when stimulus type was included as a covariate. In addition, there was an interaction between age, stimulus type and trial type ($F(12) = 2.924$, $p = .0028$). Visual inspection indicated that overall, there was an adolescent advantage in performance on recognition of new items across all the stimulus types (S6). For places, performance on targets and distractors peaked in adolescence. For both happy face and fear faces, performance on targets and distractors across age was relatively flat, as was performance on neutral face targets. Performance on neutral face distractors peaked in late adulthood and performance on targets was relatively flat. Overall, this provides additional evidence for adolescent sensitivity to novel items in the recognition memory task, as well as an indication that places might be treated differently from faces in the recognition memory task.

Supplemental Figure 6. Recognition memory performance by stimulus type, trial type and age. Recognition memory performance including stimulus type as an interaction term along with trial type and age revealed an overall quadratic fit. Across all the conditions, there was a general adolescent advantage in recognition of new items regardless of stimulus type. For places specifically, there was also an adolescent advantage for targets and distractor items not seen in the other stimulus types.

S7. Supplemental analyses examining possible response bias effects. To constrain our interpretation of the enhanced rejection of new items in the recognition memory task by adolescents, we examined response bias across age. Response bias was calculated using $B''D$ from the *psycho* package in R (Makowski, 2018) given that some participants were near ceiling performance and $B''D$ is more robust to extreme hit rates and false alarm rates (say 0 or 1.00) and non-normal response distributions than other measures of response bias like beta (Pallier, 2002; Stanislaw & Todorov, 1999). $B''D$ is a non-parametric measure of bias, with values around 0 indicating no bias. In the context of our recognition memory task, positive values would indicate a tendency to say ‘New’ and negative values would indicate a tendency to say ‘Old’. $B''D$ was used to assess age effects in response bias for recognition memory performance using a polynomial linear regression model using the *lme4* package (Bates et al., 2015). We examined the interaction of age polynomials (linear, cubic, quadratic) with the fixed effect of delay (immediate or 24 hours) while controlling for both sex and I.Q. for the overall recognition memory models (Main text, Figure 3A). All age-effects were corrected for multiple comparisons using Bonferroni correction. We found no significant effect of age for response bias. The next best fitting quadratic age model was not a better fit than the no-age model ($F(4) = 3.323$, $p = .0746$) and the quadratic model did not yield a main effect of age ($F(2) = 0.1194$). The no-age model did not yield any main effects of delay, sex or I.Q. There was an overall tendency across subjects to respond ‘New’ more frequently ($M = 0.357$, $SD = 0.322$), with $B''D$ scores above 0 for both the 0-hour ($M = 0.366$, $SD = 0.3122$) and 24-hour samples ($M = 0.339$, $SD = 0.3418$). This perhaps indicates a general tendency in this task to guess ‘New’ by default, but as this did not vary with age, it does not indicate that the developmental findings reported in the main text were simply due to certain ages (i.e., adolescents) responding ‘New’ more frequently than other ages.

Tables

Tables showing main effects and interactions of significant models from the main text.

Below are all the main effects and interactions of each of the models referred to in the main text including working memory (Fig. 2), recognition memory (Fig. 3), trial type recognition memory (Fig. 4B) and interactions between working memory and recognition memory analyses (Fig. 4A). All these models were also run and reported below without I.Q. (Supplemental tables 2, 4, 6 and 8). All significant p-values for age-effect and their interactions were corrected for using Bonferroni correction as they were in the main text.

Supplemental Table 1. Working Memory stimulus type model. Working memory age squared model main effects and interactions reported in Figure 2 in the main text

<i>Conditions</i>	<i>Chisq</i>	<i>Df</i>	<i>Pr(>Chisq)</i>
(Intercept)	1186.6181	1	0.0000
StimulusType	30.3890	3	0.0000
Load	12.2736	1	0.0005
poly(ExactAge, degree = 2)	11.2486	2	0.0217
SEX	0.2620	1	0.6087
IQ_Z	5.8714	1	0.0154
StimulusType:Load	7.0882	3	0.0691
StimulusType:poly(ExactAge, degree = 2)	3.4457	6	0.7512
Load:poly(ExactAge, degree = 2)	1.2507	2	0.5351
StimulusType:Load:poly(ExactAge, degree = 2)	3.3789	6	0.7600

Supplemental Table 2. Working Memory stimulus type models not including I.Q. Working memory age squared model main effects and interactions reported in Figure 2 in the main text not including I.Q. as a covariate in the model. Results are qualitatively similar.

<i>Conditions</i>	<i>Chisq</i>	<i>Df</i>	<i>Pr(>Chisq)</i>
(Intercept)	1217.6816	1	0.0000
StimulusType	33.2052	3	0.0000
Load	14.9897	1	0.0001
poly(ExactAge, degree = 2)	11.1347	2	0.0228
SEX	0.3279	1	0.5669
StimulusType:Load	6.5873	3	0.0863
StimulusType:poly(ExactAge, degree = 2)	2.7349	6	0.8413
Load:poly(ExactAge, degree = 2)	0.7216	2	0.6971
StimulusType:Load:poly(ExactAge, degree = 2)	2.4177	6	0.8776

Supplemental Table 3. Recognition memory stimulus models. Recognition memory quadratic model main effects and interactions reported in Figure 3 in the main text.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
(Intercept)	156.6119	1	321.9190	0.0000
StimulusType	14.4540	3	9.9035	0.0000
Delay	3.3112	1	6.8063	0.0093
poly(ExactAge, degree = 2)	6.7686	2	6.9565	0.0062
SEX	0.7901	1	1.6241	0.2031
IQ_Z	1.3564	1	2.7882	0.0955
StimulusType:Delay	0.1913	3	0.1311	0.9416
StimulusType:poly(ExactAge, degree = 2)	1.5647	6	0.5360	0.7810
Delay:poly(ExactAge, degree = 2)	0.2093	2	0.2151	0.8065
StimulusType:Delay:poly(ExactAge, degree = 2)	0.9929	6	0.3402	0.9155
Residuals	267.5721	550	NA	NA

Supplemental Table 4. Recognition memory stimulus models not including I.Q. A. Recognition memory age squared model main effects and interactions reported in Figure 3 in the main text not including I.Q. as a covariate. Results are qualitatively similar.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
(Intercept)	153.8773	1	310.4310	0.0000
StimulusType	15.0668	3	10.1319	0.0000
Delay	2.7771	1	5.6025	0.0183
poly(ExactAge, degree = 2)	7.2886	2	7.3519	0.0042
SEX	0.7186	1	1.4497	0.2291
StimulusType:Delay	0.1062	3	0.0714	0.9752
StimulusType:poly(ExactAge, degree = 2)	1.3196	6	0.4437	0.8495
Delay:poly(ExactAge, degree = 2)	0.9489	2	0.9572	0.3846
StimulusType:Delay:poly(ExactAge, degree = 2)	1.3464	6	0.4527	0.8432
Residuals	285.0213	575	NA	NA

Supplemental Table 5. Recognition memory models testing for interactions with working memory. No-age effect model showing effect of working memory d' on recognition memory d' , and other main effects and interactions from Figure 4A in the main text.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
(Intercept)	4.6067	1	14.8021	0.0002
dprime	7.6004	1	24.4211	0.0000
Delay	0.5824	1	1.8712	0.1736
IQ_Z	0.0178	1	0.0571	0.8114
SEX	0.9117	1	2.9293	0.0892
WM_dprime:Delay	0.0376	1	0.1210	0.7285
Residuals	42.9485	138	NA	NA

Supplemental Table 6. Recognition memory models testing for interactions with working memory not including I.Q. No-age effect model showing effect of working memory d' on recognition memory d' , and other main effects and interactions from Figure 4A in the main text not including I.Q. as a covariate. Results are qualitatively similar.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
(Intercept)	4.4661	1	14.3472	0.0002
dprime	7.7649	1	24.9443	0.0000
Delay	0.5923	1	1.9028	0.1699
SEX	0.8200	1	2.6341	0.1068
dprime:Delay	0.0408	1	0.1310	0.7179
Residuals	45.1367	145	NA	NA

Supplemental Table 7. Recognition memory models testing for impact of working memory. Recognition memory cubic trial type by delay model controlling for stimulus type and load main effects and interactions reported in Figure 4B in the main text.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
TrialType	33.2134	1	189.0464	0.0000
Delay	11.2590	1	64.0850	0.0000
poly(ExactAge, degree = 3)	13.1135	3	24.8801	0.0000
Load	18.5009	1	105.3046	0.0000
StimulusType	9.5166	3	18.0557	0.0000
IQ_Z	1.2253	1	6.9743	0.0083
SEX	0.4465	1	2.5412	0.1109
TrialType:Delay	2.3364	2	6.6493	0.0013
TrialType:poly(ExactAge, degree = 3)	4.4791	6	4.2490	0.0017
Delay:poly(ExactAge, degree = 3)	1.6014	3	3.0383	0.1670
TrialType:Delay:poly(ExactAge, degree = 3)	5.9660	6	5.6596	0.0000
Residuals	2422.9328	13791	NA	NA

Supplemental Table 8. Recognition memory models testing for interactions with working memory not including I.Q. A. Binomial cubic age model main effects and interactions from Figure 4B in the main text not including I.Q. as a covariate. Results are qualitatively similar.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
TrialType	35.9245	1	203.4260	0.0000
Delay	10.2937	1	58.2889	0.0000
poly(ExactAge, degree = 3)	12.0609	3	22.7654	0.0000
Load	19.6127	1	111.0588	0.0000
StimulusType	9.8286	3	18.5518	0.0000
SEX	0.3750	1	2.1234	0.1451
TrialType:Delay	1.6987	2	4.8096	0.0082
TrialType:poly(ExactAge, degree = 3)	3.7817	6	3.5691	0.0093
Delay:poly(ExactAge, degree = 3)	2.5402	3	4.7947	0.0146
TrialType:Delay:poly(ExactAge, degree = 3)	6.7628	6	6.3825	0.0000
Residuals	2537.3511	14368	NA	NA

Tables showing main effects and interactions of significant models from the supplemental text. Below (tables 9-13) are all the main effects and interactions of each the linear models reported in the supplemental text including the first and second half split (S3), recognition memory by trial type for 0-back (S5D) and 2-back (S5F) items separately, and overall recognition memory including stimulus type, but controlling for load (S6). All significant p-values for age-effect and their interactions were corrected for using Bonferroni correction as they were in the main text.

Supplemental table 9. First half split. Cubic age model including only the odd numbered participants, or one-half of the 0-hour data participants from Figure S3. Key results are qualitatively similar when including the full sample and is still best fit by a cubic model.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
TrialType	21.2284	1	120.7391	0.0000
Delay	12.1196	1	68.9316	0.0000
poly(ExactAge, degree = 3)	10.5861	3	20.0699	0.0000
StimulusType	4.8997	3	9.2893	0.0000
Load	14.8561	1	84.4956	0.0000
IQ_Z	0.5131	1	2.9181	0.0876
SEX	0.3249	1	1.8478	0.1741
TrialType:Delay	1.5858	2	4.5096	0.0110
TrialType:poly(ExactAge, degree = 3)	5.6236	6	5.3308	0.0001
Delay:poly(ExactAge, degree = 3)	0.6189	3	1.1734	0.3182
TrialType:Delay:poly(ExactAge, degree = 3)	3.6504	6	3.4604	0.0122
Residuals	1648.4951	9376	NA	NA

Supplemental table 10. Second half split. Cubic age model including only the even numbered participants or one-half of the 0-hour data participants from Figure S3. Key results are qualitatively similar when including the full sample, and to the first-half split, results are still best fit by a cubic model.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
TrialType	20.3409	1	111.9654	0.0000
Delay	5.2203	1	28.7348	0.0000
poly(ExactAge, degree = 3)	9.7290	3	17.8509	0.0000
StimulusType	7.5478	3	13.8488	0.0000
Load	11.2579	1	61.9685	0.0000
IQ_Z	0.8506	1	4.6821	0.0305
SEX	0.9124	1	5.0223	0.0250
TrialType:Delay	2.1303	2	5.8631	0.0029
TrialType:poly(ExactAge, degree = 3)	2.9606	6	2.7161	0.0738
Delay:poly(ExactAge, degree = 3)	3.4257	3	6.2856	0.0018
TrialType:Delay:poly(ExactAge, degree = 3)	6.0640	6	5.5632	0.0000
Residuals	1703.1664	9375	NA	NA

Supplemental table 11. 0-back model. Quadratic age model including only ‘old’ recognition memory trials that were tested in the 0-back condition of the working memory task (see Figure S5D).

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
(Intercept)	318.6918	1	2061.6171	0.0000
TrialType	73.7863	2	238.6617	0.0000
Delay	2.4315	1	15.7292	0.0001
poly(ExactAge, degree = 2)	0.0058	2	0.0188	0.9814
StimulusType	7.2893	3	15.7182	0.0000
IQ_Z	0.1245	1	0.8051	0.3696
SEX	0.9738	1	6.2995	0.0121
TrialType:Delay	0.8359	2	2.7037	0.0670
TrialType:poly(ExactAge, degree = 2)	2.5997	4	4.2043	0.0127
Delay:poly(ExactAge, degree = 2)	1.7846	2	5.7723	0.0187
TrialType:Delayn:poly(ExactAge, degree = 2)	2.1737	4	3.5155	0.0428
Residuals	1601.1748	10358	NA	NA

Supplemental table 12. 2-back model. Cubic age model including only ‘old’ recognition memory trials that were tested in the 2-back condition of the working memory task (see Figure S5E). This fit most resembles the results when collapsing across load in the original model included in the main text (see Figure 4B).

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
TrialType	139.0880	2	425.8396	0.0000
Delay	7.4317	1	45.5063	0.0000
poly(ExactAge, degree = 3)	10.3603	3	21.1464	0.0000
IQ_Z	1.4524	1	8.8934	0.0029
SEX	1.0093	1	6.1801	0.0129
StimulusType	10.3522	3	21.1299	0.0000
TrialType:Delay	2.3225	2	7.1107	0.0008
TrialType:poly(ExactAge, degree = 3)	4.6680	6	4.7640	0.0004
Delay:poly(ExactAge, degree = 3)	0.7399	3	1.5103	0.2096
TrialType:Delay:poly(ExactAge, degree = 3)	5.2049	6	5.3119	0.0001
Residuals	1688.3017	10338	NA	NA

Supplemental table 13. Interactions with trial type and stimulus type. Cubic age model including stimulus type as a factor to investigate interactions between stimulus type, age and trial type (Figure S6). All stimulus types show an overall adolescent advantage for new items as well as an adolescent advantage for targets and distractors for places.

<i>Conditions</i>	<i>Sum Sq</i>	<i>Df</i>	<i>F value</i>	<i>Pr(>F)</i>
TrialType	33.2151	1	188.6666	0.0000
StimulusType	9.5273	3	18.0389	0.0000
poly(ExactAge, degree = 2)	12.6580	2	35.9496	0.0000
Load	18.4149	1	104.5992	0.0000
Delay	10.9858	1	62.4008	0.0000
IQ_Z	0.9445	1	5.3647	0.0206
SEX	0.4623	1	2.6260	0.1051
TrialType:StimulusType	1.6025	6	1.5171	0.1680
TrialType:poly(ExactAge, degree = 2)	2.8644	4	4.0676	0.0161
StimulusType:poly(ExactAge, degree = 2)	1.0208	6	0.9664	0.4462
TrialType:StimulusType:poly(ExactAge, degree = 2)	6.1765	12	2.9236	0.0028
Residuals	2426.1704	13781	NA	NA