Adolescent-specific memory effects: evidence from working memory, immediate and long-term recognition memory performance in 8–30 yr olds

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Working memory and recognition memory develop across adolescence, but the relationship between them is not fully understood. We investigated associations between n-back task performance and subsequent recognition memory in a community sample (8–30 yr, n = 150) using tasks from the Adolescent Brain Cognitive Development Study (ABCD Study) to cross-sectionally assess memory in an age range that will be sampled longitudinally. We added a 24-h delay condition to assess long-term recognition. Overall working memory, immediate and long-term recognition performance peaked in adolescence. Age effects in recognition memory varied by items (old targets, old distractors, and new items) and delay (0 and 24 h). For immediate recognition, accuracy was higher for targets and new items than for distractors, with accuracy for targets peaking in adulthood and accuracy for new items peaking during adolescence. For long-term recognition, adolescents’ accuracy was higher for targets than distractors, while adults showed similarly high accuracy for targets and distractors and children showed low accuracy for both. This pattern appeared to be specific to recognition of items from the high working memory load condition. The results suggest that working memory may facilitate long-term recognition of task-relevant over irrelevant items and may benefit the detection of new information during adolescence.

[Supplemental material is available for this article.]
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and long-term recognition memory for different stimulus types across the developmental span of childhood, adolescence and adulthood. Although both working memory and recognition memory change with age, there has been inconsistent evidence on working memory’s influence on subsequent recognition (Hartshorne and Makovski 2019). In adults, some studies show that working memory maintenance does indeed support subsequent recognition (Davachi et al. 2001; Ranganath et al. 2005; Blumenfeld and Ranganath 2006) with significant neural overlap of these memory systems (Nee et al. 2008). However, other studies demonstrate less of an association between working memory and long-term recognition memory or conflicting evidence as to how exactly working memory influences subsequent recognition (Jacoby 1973; LaRocque et al. 2015; Bartsch et al. 2018). Developmentally, associations between working memory and subsequent recognition memory have been shown in children (Gathercole and Adams 1994; Lloyd et al. 2009; Thompson et al. 2019; Rosenberg et al. 2020). For example, using Bayesian probabilistic principal components analysis of data from the neurocognitive battery of the Adolescent Brain Cognitive Development Study (ABCD Study) of >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 et al. (2020) subsequently showed that performance during both 0- and 2-back conditions of the ABCD Study n-back task were similarly 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. However, neither of these studies investigated long-term memory recognition of information encoded during a working memory task (e.g., following a 24-h delay), to determine whether immediate recognition effects are observed long-term. Moreover, neither study assessed recognition beyond childhood to determine whether their findings change at other developmental time points (e.g., adolescence).

The primary goal of this study was to examine whether working memory differentially influences what information is subsequently recognized 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 Study (ABCD Study) to assess working memory and immediate recognition memory (Casey et al. 2018), but added a 24-h delay condition to also assess long-term recognition memory (Fig. 1). Based on evidence of continued changes in working memory and long-term recognition 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 twenties (Sawyer et al. 2018), we included participants from childhood to adulthood (8–30 yr) to test for adolescent-specific patterns of performance (Somerville 2013). We also selected this age range to have overlap with the ages to be assessed ultimately in the 10-yr ABCD longitudinal study of 9- to 10-yr-old children. By assessing an age range that ultimately will be sampled longitudinally in the ABCD Study, we may be able to provide specific developmental predictions from the current cross-sectional study for future studies analyzing data from these same tasks in the ABCD Study.

We had two primary hypotheses: (1) Working memory and immediate and long-term recognition memory performance would improve into the early twenties (Satterthwaite et al. 2013; Weintraub et al. 2013), and (2) recognition for task-relevant items (old targets) compared with task-irrelevant items (old distractors) from the working memory task would be enhanced, especially

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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 h 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 memory load conditions (0-back and 2-back) each with four types of stimuli (neutral, fearful and 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, participants were asked to respond “match” whenever a stimulus was the same as the stimulus presented two trials back. Each condition also included distractors/lures (stimuli that repeated, but were not the target item) and nonlures (items that never repeated) to which participants were instructed to respond “no-match” (Fig. 1A; for further information on this task see the Materials and Methods).

We first examined the effects of age, memory load (0-back and 2-back), and stimulus type (neutral, fear, and happy faces and places), on n-back task 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 with the null model ($\chi^2 (16) = 62.603, P < 0.0001$) and revealed a main effect of age ($\chi^2 (2) = 11.249, P = 0.0047$) with performance peaking in the late teens and early twenties (Fig. 2A; Supplemental Table 1). There was a significant main effect of memory load ($\chi^2 (1) = 12.274, P = 0.0005$) such that 0-back performance was better than 2-back performance, and a main effect of stimulus type ($\chi^2 (3) = 30.389, P < 0.0001$) with worse performance for places compared with all three categories of faces (see Supplemental Text S3; Supplemental Fig. 3). Neither stimulus type nor memory load interacted with age or any other predictors. There was also a main effect of I.Q. ($\chi^2 (1) = 5.871, P = 0.0154$), which was treated as a covariate in analyses for age effects (see Supplemental Table 2 for results from additional model not including I.Q. as a covariate showing similar results). These results suggest that overall n-back task performance peaks during the late teens and early twenties regardless of stimulus type or memory load.

To determine whether the effects of age on d' were differentially influenced by hit rate or false alarm rate, we again fit age polynomial models for each of these dependent variables including load (0-back and 2-back) as a factor of interest while adjusting for stimulus type, sex and I.Q. For hit rate, the quadratic age model fit best compared with the null model ($\chi^2 (4) = 36.855, P < 0.0001$) and revealed a main effect of age ($\chi^2 (2) = 37.1437, P = 0.0004$) with performance again peaking in the late teens and early twenties (Fig. 2B). There was no main effect of load ($\chi^2 (1) = 2.3701, P = 0.1237$), nor was there an interaction between load and age ($\chi^2 (2) = 2.7396, P = 1.000$).

For false alarm rate, a quadratic model again outperformed the other models relative to the null model ($\chi^2 (4) = 36.2422, P < 0.0001$) with the fewest false alarms in the late teens and early twenties (Fig. 2C) and of load with better performance on the 0-back than 2-back items ($\chi^2 (1) = 207.5081, P < 0.0001$). There was no interaction between age and load ($\chi^2 (2) = 5.5174, P = 0.3804$). These results suggest that both hit rate and false alarm rate contributed similarly to d' across age as reflected by similar adolescent-specific patterns in Figure 2 (see Supplemental Tables 3, 4).

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 distractors) from the n-back task as well as new items participants had never seen and were asked to respond either “Old” or “New” on each trial (Fig. 1B,C; for specific task details see the Materials and Methods). Participants were either tested immediately (0 h) after the n-back task (Fig. 1D) was enhanced in the late teens to early twenties relative to younger and older ages for both load conditions, but there was no age by load interaction, only a main effect of load. (B) Hit rate was equivalent on the 0-back and 2-back conditions and peaked in the late teens and early twenties relative to other ages. (C) False alarm rate was lower on the 0-back than the 2-back condition, with fewer false alarms in the late teens and early twenties relative to other ages.

Figure 2. n-back task performance overall and as a function of memory load by age. (A) Performance (d') was enhanced in the late teens to early twenties relative to younger and older ages for both load conditions, but there was no age by load interaction, only a main effect of load. (B) Hit rate was equivalent on the 0-back and 2-back conditions and peaked in the late teens and early twenties relative to other ages. (C) False alarm rate was lower on the 0-back than the 2-back condition, with fewer false alarms in the late teens and early twenties relative to other ages.
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Study design or 24 h after the n-back task to see if a similar pattern was observed long-term (n = 53) (see the Materials and Methods for participant demographics for each delay condition). We assessed recognition memory performance (d'), by age (linear, cubic, and quadratic polynomial terms of exact age), delay (0 vs. 24 h), and stimulus type (neutral, fear, and happy faces and places) controlling for memory load since load did not interact with age on n-back performance. The quadratic model was the best fit compared with the null model (F(1) = 3.078, P < 0.0001). The quadratic model revealed a main effect of age (F(3) = 6.957, P = 0.0062) 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 = 0.0093) with better immediate recognition memory compared with long-term (24-h delay) recognition. There was a main effect of stimulus type (F(1) = 9.904, P < 0.0001), that showed better recognition memory for places than for faces (see Supplemental Text S3; Supplemental Fig. 3), but stimulus type and delay did not interact with age or other predictors. Overall, these results suggest that overall recognition memory performance peaks during late adolescence regardless of stimulus type or delay (see Supplemental Tables 5, 6 for full model with and without I.Q.).

To examine whether the effects of age on d' were driven by hit rate or false alarm rate, we also fit age models predicting these dependent variables including delay (0 and 24 h) as a variable of interest while controlling for stimulus type, sex and I.Q. For hit rate, the linear age model fit best compared with the null model (F(1) = 7.8705, P = 0.0026), revealing a main effect of age (F(1) = 9.7163, P = 0.0115) and delay (F(1) = 25.8897, P < 0.0001) with better performance with age and for the 0-h than the 24-h delay condition (Fig. 3B; Supplemental Table 7). For false alarm rate, a quadratic model fit best against the null model (F(2) = 9.7129, P < 0.0001) with performance peaking again in the early twenties (Fig. 3C; Supplemental Table 8). The quadratic model showed a main effect of age (F(2) = 15.0580, P < 0.0001) and delay (F(1) = 6.4463, P = 0.0114). Given the differential contribution of hit rate (linear) and false alarm rate (quadratic) by age in the calculation of d', and that composite measures like d' can mask effects in the components measures (Brady et al. 2021), we report overall performance using d' and specific trial type (old targets and distractors and new items) performance using accuracy to show general and specific associations between working memory and recognition memory performance, respectively.

Associations between working memory and recognition memory performance with age

An overall aim of this study was to examine whether associations between working memory and long-term recognition vary with age, especially during adolescence. We first tested for associations between overall n-back task performance (d') and subsequent immediate and long-term recognition memory performance (d'). The no-age model fit best and revealed only a main effect of working memory on recognition memory performance (F(1) = 24.421, P < 0.0001) regardless of delay. Similarly, analyses assessing the association between n-back (d') and subsequent recognition hit rate for 0-back and 2-back items separately, we again found that the no-age model fit best (see Supplemental Tables 9–11 for overall, 0-back, and 2-back results). These results indicate that overall performance on the n-back task was related to overall performance on the recognition task across age, working memory load and delay.

To test our adolescent-specific hypothesis for better recognition of task-relevant (old targets) compared with task-irrelevant (old distractors) items from the n-back task, we examined recognition memory accuracy (proportion correct out of total) for each trial type (old targets and distractors and new items) by age (linear, cubic and quadratic polynomial terms of exact age) and delay (0 vs. 24 h). As there were no effects of stimulus type or memory load by age for either working memory or recognition memory, these variables were treated as covariates in the model. The cubic age polynomial model fit best compared with the no-age model (F(18) = 7.956, P < 0.0001). There was a main effect of trial type (F(1) = 189.046, P < 0.0001) such that recognition accuracy was highest for new items, followed by targets and then distractors (see Supplemental Table 12), and for delay with higher accuracy.

Figure 3. Recognition memory performance as a function of delay by age. (A) Recognition memory performance (d') varied by age with enhanced performance in the late teens and early twenties relative to younger and older ages with overall better performance for the 0-h than 24-h delay. (B) Hit rates increased linearly with age and were overall higher for the 0-h than 24-h condition. (C) False alarm rates varied by age with the fewest false alarms in the late teens to early twenties relative to other ages and overall fewer false alarms for the 0-h than 24-h condition.
for the 0-h than the 24-h delay condition ($F_{1,11} = 64.085, P < 0.0001$). There was also a main effect of I.Q. ($F_{1,11} = 6.9743, P = 0.00083$), which was treated as a covariate in analyses for age effects (see Supplemental Table 13 for additional model not including I.Q. as a covariate showing similar results).

Central to our developmental hypotheses were interactions with age in this model. There was a two-way interaction of trial type by age ($F_{6,60} = 4.2490, P = 0.0017$) and a three-way interaction of delay by trial type by age ($F_{6,60} = 5.660, P < 0.0001$, Fig. 4A). Visual inspection of the polynomial fits for the two-way interaction showed higher accuracy for new and target items relative to distractors, 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 this pattern was specific for the 0-h delay, but not the 24-h delay. For the 24-h delay condition, accuracy was highest for new items, especially for adolescents. Importantly, for the 24-h condition, adolescents unlike children and adults, showed higher accuracy for targets than distractors. Adults showed similarly high accuracy for targets and distractors and children showed diminished accuracy for both targets and distractors.

To examine whether these developmental patterns in recognition memory (trial type by delay by age) were associated with working memory demand, we analyzed recognition accuracy separately for the 0-back and 2-back conditions, with the latter condition more closely aligning with definitions of working memory (Baddeley 1986; Rosenberg et al. 2020). We found a quadratic age polynomial was the best fitting model for the 0-back items compared with the no-age model ($F_{1,12} = 9.494, P < 0.0001$) (see Supplemental Table 14) and similar to our overall analysis, a cubic age polynomial was the best fitting model for the 2-back items compared with the no-age model ($F_{1,12} = 7.137, P < 0.0001$) (see Supplemental Table 15). For both the 0-back and 2-back models there were significant three-way interactions of trial type, delay and age ($F_{1,11} = 3.516, P = 0.0428, F_{1,10} = 5.312, P = 0.0001$, respectively) (Fig. 4B,C). Visual inspection of the three-way interaction for 0-back items shows an advantage for targets (and new items) in both the 0-h and 24-h delays during the late teens and early twenties (Fig. 4B). Distractor item performance was flat across age for the 0-h condition but increased into the early twenties before flattening for the 24-h condition. The pattern for the three-way interaction for 2-back items revealed relatively similar performance across age for targets and distractors for the 0-h delay. However, like the overall analysis across load conditions, the recognition of 2-back items 24 h later showed better accuracy of targets than distractors for adolescents, but not for the older or younger ages. For visualization purposes, we plotted a difference score between target and distractor items by delay separately for the 0- and 2-back conditions to further illustrate greater accuracy in detection of targets versus distractors for adolescence (Supplemental Fig. 4A) in the 2-back condition for the 24-h delay condition (Supplemental Fig. 4C) but not in the 0-back condition or the 0-h delay condition for either memory load (Supplemental Fig. 4B). Accuracy for new items was generally high for all ages but peaked by the mid-teens and early twenties for both delay conditions. Together, these results suggest that our overall findings of better recognition accuracy of task-relevant (target) than task-irrelevant (distractor) items for adolescents by 24 h are predominantly driven by the higher memory load condition (2-back condition).

**Ancillary control analyses**

Given the difference in sample size between the 0- and 24-h delay subsamples ($n = 97, n = 53$, respectively), a subsidiary analysis with an even-odd split of the larger 0-h 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
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by trial type across the two halves as seen in the originally combined sample (see Supplemental Text S2; Supplemental Fig. 2; Supplemental Tables 18, 19) suggesting that both delay conditions may have been robust to differences in sample size to detect the cubic age effects in memory recognition.

Given the high accuracy for new items across age, especially for adolescents, we performed a response bias analysis to test for an overall tendency by adolescents to reject all items during the recognition task as new. 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 (e.g., 1.00 or 0) and non-normal response distributions than other measures of response bias like beta (Stanislaw and Todorov 1999; Pallier 2002). This analysis revealed no main effect of age or interactions with age (Supplemental Text S4), but does not necessarily rule out a contribution of response bias to our results.

To further assess potential effects of sensitivity in discriminating targets from distractors and response bias on our polynomial age models, we calculated $d'$ separately for targets and distractors (accuracy of old items relative to new items) and F1 scores that combine both sensitivity (accuracy by trial type) and precision (accuracy relative to new and old items) for each participant (see Powers 2011; Ngo et al. 2021). Similar to our accuracy results, we found the cubic age model was the best fitting age model compared with the no-age model for both $d'$ ($F_{(8)} = 6.2651, P < 0.0001$) and F1 scores ($F_{(12)} = 5.1536, P < 0.0001$), but no three-way interactions of trial type by delay by age for these measures (Supplemental Tables 16, 17). We based our primary analyses of trial type on the dependent variable of accuracy given that (1) hit rates and false alarm rates differentially contributed to $d'$ as a function of age (Fig. 3B,C), (2) composite measures like $d'$ and F1 scores can mask developmental effects in component measures like hits and false alarms (Brady et al. 2021), and (3) similar cubic patterns in the overall age effect across all three dependent measures. However, for visualization purposes, we plot all three dependent measures ($accuracy, d'$ and F1 scores) by trial type and delay as a function of age (Fig. 5).

Discussion

The current study examined whether working memory differentially influences what information is recognized 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 early-twenties. As expected, 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) 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-teens. 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. Specific to our developmental hypothesis, adolescents showed better long-term recognition of targets than distractors compared with adults, who showed high accuracy for targets and distractors, and children, who showed low accuracy for both. This adolescent-specific difference between long-term recognition of targets and distractors was observed for the high rather than the low memory load condition of the working memory task. Together the findings suggest enhanced discrimination of task-relevant from irrelevant items in working memory has subsequent effects on long-term recognition of information, especially for adolescents.

Our overall findings are in part 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 early twenties based on neurocognitive development (Sawyer et al. 2018). However, in the current study we also showed diminished 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 could be due to greater variability in performance by adults over age 25, but regardless the findings are consistent with the literature of improvements in working memory and recognition memory extending beyond the mid-teen years (Satterthwaite et al. 2013; Weintraub et al. 2013).

Consistent with our developmental hypothesis, recognition memory of task relevant (target) items over irrelevant (distractor) items from the working memory task varied with age. For immediate recognition, accuracy was higher for targets (and new items)
than distractors. Accuracy for targets peaked by the early to mid-twenties and accuracy for new items emerged by the mid-teen years. In contrast, for long-term recognition, accuracy was highest for new items, especially for adolescents. Thus, adolescents were better at identifying new items relative to old items for both immediate and long-term recognition. However, adolescents also performed better on targets relative to distractors after a 24-h delay. This is in contrast to adults, who showed similarly high accuracy for both targets and distractors, and children, who showed low accuracy for targets and distractors 24 h later. The finding of better accuracy for targets than distractors by adolescents may be consistent with changes in inhibitory processes with age including suppression of irrelevant distractors in favor of relevant targets (Bjorklund and Hamishfeger 1990). These findings suggest that discrimination of task-relevant from task-irrelevant items during our working memory task has subsequent effects on what information adolescents subsequently recognize long-term.

A primary goal of this study was to examine the effects of working memory demands on recognition memory. Our working memory task assessed both low (0-back) and high (2-back) memory load conditions, which tap different cognitive processes. Whereas the 0-back condition predominantly taps sustained attention for a single rare target for an entire block of trials, the 2-back condition requires maintenance of several potential targets and dropping prior targets from working memory when new ones occur. The 2-back condition aligns more closely with definitions of working memory (Baddeley 1986, 2000). Our analyses of these load conditions by trial type revealed that only the high memory load condition (2-back) showed better long-term recognition of targets relative to distractors in adolescents as compared with children and adults. Thus, items maintained in working memory (targets) are better recognized by adolescents than items not maintained in working memory (distractors). Importantly, this was the case even though the distractor items that were tested in the recognition task were lures and so presented a similar number of times as the targets (see the Materials and Methods). Remembering information that was previously essential to a goal and letting-go of tangential information may be an important mechanism for rapidly learning about key features of new environments during adolescence.

We also observed enhanced performance on new items by adolescents, which may reflect a heightened sensitivity for novel information. Alternatively, this developmental pattern may reflect an impulsive tendency in adolescents (Steinberg et al. 2008) simply to reject items as unfamiliar, regardless of whether the item was old or new. However, a response bias analysis showed no effect or interactions of age on response bias suggesting that the enhanced accuracy for new items by adolescents may not solely be attributed to an overall impulsive tendency to reject all items more than other ages. Moreover, if better recognition accuracy of new items were simply due to adolescents responding that every item was unfamiliar, then their accuracy for old items should be well below chance and worse than younger ages, which was not the case. Still, we cannot rule out this possibility and future research using forced choice designs or that include confidence ratings may be useful for disentangling developmental changes in memory from developmental changes in response bias.

Our results should be interpreted in the context of potential limitations. First, for recognition memory, there were fewer participants in the 24-h delay condition than in the immediate memory condition. Although our immediate and 24-h 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 recognition effects by age. Our split-half analysis of the 0-h condition revealed similar developmental results that replicated across both halves of the data (n = 49 and n = 48) and were similar to the full 0-h delay sample (n = 97) (Supplemental Text S2), suggesting our results were robust to differences in sample sizes between the 0-h and 24-h groups. Replication of the results would strengthen these findings. Additionally, we used a between-subjects design to test immediate and long-term recognition memory similar to prior developmental memory research (Johnson and 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-h vs. 24-h delay). This design, although potentially more powerful, was less feasible given the limited number of recognition items in the ABCD task design.

The current study provides evidence of adolescent-specific enhancements in working memory, recognition memory and long-term recognition memory, with evidence of better recognition of task-relevant versus irrelevant items 24-h later. We also show better recognition accuracy by adolescents for new items 0 and 24 h later. Because we used tasks from the ABCD Study that is currently in progress and included ages in the current study that will ultimately be assessed by that 10-yr longitudinal study (i.e., 9–10 to 19–20 yr), our results from this cross-sectional sample provide developmental predictions for future studies based on the ABCD Study. Moreover, the ABCD Study only tests recognition memory immediately after the n-back task, but not 24 h 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 work using the ABCD Study data about the development of different memory processes. In sum, adolescents show better long-term recognition of information previously maintained in working memory than irrelevant information, which may be an important mechanism for rapidly learning about key features of new environments during adolescence.

Materials and Methods

Participants

A community sample (n = 175, 8–30 yr) was recruited from the greater New Haven, Connecticut, area. Exclusion criteria included estimated I.Q., as measured by the Wechsler Abbreviated Scale of Intelligence (WASI-II) (Weschler 2011), of <70. Ten of the 175 recruited participants were excluded from analyses due to a full-scale I.Q. of <70. Of the remaining 165 participants, four were excluded for chance performance on the working memory task (<60% accuracy). Eight additional participants were excluded because of experimenter error in administering the recognition memory task (i.e., old items tested were different from those tested during the n-back task), and three more were excluded for not returning for their second appointment 24 h 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). Participants were assigned to either a 0-h delay condition (n = 97; 48 males and 49 females; mean age = 18.97; SD = 6.49) (Fig. 6A) or a 24-h delay condition (n = 53; 26 males and 27 females; mean age = 19.41; SD = 6.13) (Fig. 6B).

To determine whether recognition memory results for the ABCD task held 24 h later, we added a 24-h delay recognition condition, not included in the ABCD Study design. We had a larger sample to test for initial effects and a smaller sample (half) for replication purposes. However, rather than simply replicating our initial results, we showed a unique pattern of results when testing recognition memory 24 h later versus only 0 h later for specific trial types.

Welch two-sample tests of mean age and variance of the 0-h and 24-h 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), indicated that the 0-h and 24-h participants likely drawn from the same population \( D (150) = 0.093, P = 0.927 \) (see Supplemental Text S1; Supplemental Fig. 1 for density plots of ages by group). 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 four stimulus categories including happy, fearful and neutral faces and places (see Fig. 1A for design of n-back task; Casey et al. 2018). Validity and reliability of the emotional face stimuli have been reported previously and faces were harmonized for luminosity, head size, and head position (Tottenham et al. 2009; Casey et al. 2018; Conley et al. 2018). Place stimuli were from previously published stimulus sets (O’Craven and Kanwisher 2000; Kanwisher 2001; Park and Chun 2009; Casey et al. 2018).

The task consisted of two runs. In each run, there were four blocks of each load (0-back and 2-back) condition by stimulus type (happy, fearful and neutral faces and places) for a total of eight blocks, with 10 trials per condition (2.5 sec each) and four fixation blocks (15 sec each). Each trial consisted of a 2-sec stimulus presentation, followed immediately by a 500-msec 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 (two of each n-back memory task; two face blocks, two 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: One target repeated three times per block, two distractors/lures repeated three times per block, and six distractors/nonlures shown only once each. In the 2-back condition, there were the same trial types: Two targets repeated twice, two distractors/lures repeated twice per block, and six distractors/nonlures 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.

Data analyses

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 & Memory).
We performed ancillary analyses to test for response bias and sensitivity in detection of targets and distractors during the recognition memory task using nonparametric response bias (B'), d' and F1 scores (see Supplemental Text S4; Supplemental Tables 16, 17). d' and F1 scores were calculated separately for targets and distractors for each participant for both delay conditions. F1 scores were calculated by dividing the product of precision and recall by the sum of precision and sensitivity and multiplying that value by 2. The highest possible F1 score is 1.0, indicating perfect precision and sensitivity, and the lowest possible value is 0. These d' and F1 scores were analyzed as a function of trial type, delay, and age, controlling for stimulus type, load, I.Q., and sex (Supplemental Tables 16, 17).

Data Deposition
We intend that the data that support the findings of this study will be made available on OSF (Center for Open Science) at the time of publication.

Acknowledgments
This work was in part supported by U01 DA041174 (B.J.C.) and a National Science Foundation SBE Postdoctoral Research Fellowship Grant 1714321 (A.O.C.). We thank two anonymous reviewers for their constructive comments that significantly strengthened this manuscript and all the participants and families who were a part of this study.

Competing interest statement
The authors declare no competing interests.

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Adolescent-specific memory effects


Received October 21, 2021; accepted in revised form July 7, 2022.
Adolescent-specific memory effects: evidence from working memory, immediate and long-term recognition memory performance in 8–30 yr olds


Learn. Mem. 2022, 29:
Access the most recent version at doi:10.1101/lm.053539.121

Supplemental Material
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