Brief Report

Developmental dissociation between the maturation of procedural memory and declarative memory

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ABSTRACT

Declarative memory and procedural memory are known to be two fundamentally different kinds of memory that are dissociable in their psychological characteristics and measurement (explicit vs. implicit) and in the neural systems that subserve each kind of memory. Declarative memory abilities are known to improve from childhood through young adulthood, but the developmental maturation of procedural memory is largely unknown. We compared 10-year-old children and young adults on measures of declarative memory and working memory capacity and on four measures of procedural memory that have been strongly dissociated from declarative memory (mirror tracing, rotary pursuit, probabilistic classification, and artificial grammar). Children had lesser declarative memory ability and lesser working memory capacity than adults, but children exhibited learning equivalent to adults on all four measures of procedural memory. Therefore, declarative memory and procedural memory are developmentally dissociable, with procedural memory being adult-like by age 10 years and declarative memory continuing to mature into young adulthood.

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Introduction

Evidence has converged on a fundamental distinction between two forms of memory: declarative and procedural (Cohen & Squire, 1980). Declarative memory ("knowing that") refers to conscious memory for events and facts, is assessed by explicit tests of recall and recognition, and depends on medial temporal lobe and diencephalic brain structures. Procedural memory ("knowing how") refers to unconscious memory, is assessed by experience-dependent learning of skilled performance, and depends on structures in the basal ganglia, cerebellum, and neocortex (Gabrieli, 1998). Declarative memory abilities improve across child and adolescent development (e.g., Kail, 1990), but surprisingly little is known about the development of procedural memory. Here we asked whether procedural memory continues to develop past middle childhood, as does declarative memory, or whether instead procedural memory matures at an earlier age.

There is evidence that some forms of nondeclarative memory mature earlier than declarative memory. Perceptual priming, based on stimulus form, appears to be adult-like early in development (Carroll, Byrne, & Kirsner, 1985; Drummey & Newcombe, 1995). Conceptual priming, based on stimulus meaning, develops more slowly (e.g., Billingsley, Smith, & McAndrews, 2002; Murphy, McKone, & Slee, 2003), perhaps because it relies on the growth of semantic knowledge through development.

Several studies have examined the development of sensorimotor sequence learning. Sequence learning of visuospatial locations appears to mature during infancy when measured by visual saccades (Amso & Davidow, 2012; Lum, Kidd, Davis, & Conti-Ramsden, 2010). Sequence learning for locations can also be measured by reaction times to button presses on the serial reaction time task. Developmental findings using this task have been mixed, with findings of learning in children that is equal to adults (Meulemans, Van der Linden, & Perruchet, 1998; Thomas & Nelson, 2001), less than adults (Thomas et al., 2004), or greater than adults (Janacsek, Fiser, & Nemeth, 2012). The inconsistent developmental findings may relate to factors that influence explicit awareness of the to-be-learned sequence such as the nature of the sequences (Willingham & Goedert-Eschmann, 1999).

Here we examined age differences in learning on four diverse measures of procedural memory selected because they have been dissociated from declarative memory in studies of patients with global amnesia. Therefore, if children exhibit reduced procedural memory relative to adults on these tasks, it is unlikely to be a secondary consequence of immature declarative memory. Two tasks, mirror tracing (Milner, 1962) and rotary pursuit (Corkin, 1968), were the motor skill learning tasks on which the amnesic patient "H.M." and patients with impaired declarative memory due to Alzheimer's disease have shown successful learning (Gabrieli, Corkin, Mickel, & Growdon, 1993; Heindel, Salmon, Shults, Walicke, & Butters, 1989). Despite their landmark status in memory research, neither of these tasks has been used to examine development.

We also examined two cognitive examples of procedural memory. One task was probabilistic classification, which has also revealed intact learning in amnesic patients (Knowlton, Squire, & Gluck, 1994). The other task was artificial grammar learning, the original example of implicit learning (Reber, 1967) and one that has also revealed intact learning in amnesia (Knowlton, Ramus, & Squire, 1992). Artificial grammar learning has been studied in children ages 9 to 11 years (Fischer, 1997) and 5 to 8 years (Witt & Vinter, 2012), but neither study compared learning between children and adults.

Method

Participants

In total, 32 children (mean age = 10.46 years, range = 10.04–10.94; 16 female) and 29 adults (mean age = 23.68 years; 16 female) participated. Of this total sample, 26 children and 27 adults completed all tasks detailed below; some participants were not able to complete all tasks for one or more reasons: ran out of time (children, $n = 5$; adults, $n = 0$); a program crashed (children, $n = 4$; adults, $n = 2$); data were overwritten (children, $n = 1$; adults, $n = 0$) (see Appendix A). Both adults and children received Amazon gift cards for participation ($60) and gave written consent (along with parents of minors).

Apparatus, stimuli, and tasks

Participants were tested in a quiet room with one experimenter. They completed the tasks in the following order, with opportunities to take breaks every 30 min: probabilistic classification, California Verbal Learning Test, rotary pursuit, mirror tracing, count span, artificial grammar learning, and Kaufman Brief Intelligence Test.

IQ
Kaufman Brief Intelligence Test–Second Edition. This test (Kaufman & Kaufman, 2004) consisted of three sections—verbal knowledge, riddles, and matrices—and was administered by an experimenter using a booklet. Reponses were scored and standardized in keeping with procedures recommended by the publisher.

Procedural memory
Rotary pursuit. A photoelectric pursuit rotor (Lafayette Instruments, Model 30014C*C) was used, and participants were asked to use a stylus to maintain contact with a photoelectric target that rotated in the shape of a rectangle with truncated corners. Participants first completed a 20-s practice trial to establish baseline speed (15, 30, 45, or 60 rotations per minute). The speed at which a participant's time-on-target was closest to 5 s was selected as the baseline and used for all subsequent trials. Participants then completed four 20-s trials, took a break for 1 min, and then completed four more 20-s trials. After 30 min of performing other tasks, participants completed eight more 20-s trials, taking a 1-min break after the first four trials as before. The dependent measure was time-on-target per trial.

Mirror tracing. Participants traced the outline of a six-sided star while watching their hands in a mirror (Gabrieli et al., 1993; Milner, 1962) using a Lafayette Instruments Auto-Scoring Mirror Tracer (Model 58024A*C). In this device, the stylus is metal and the test plate is metal except for the star pattern. When the stylus goes off the star and touches the metal plate, it completes an electrical circuit and an error is recorded. Participants were instructed to stay inside the outline of the star and to trace as quickly and accurately as possible. Participants first completed a practice trial and then traced four times. After 30 min of performing other tasks, participants traced five more times. The dependent measures were completion time and number of errors per trial.

Probabilistic classification task. This task was modeled after prior weather prediction tasks (Knowlton et al., 1994; Shohamy et al., 2004) (see Supplementary Table 1 and Supplementary Fig. 1a in online Supplementary material). Participants viewed a series of cards on a computer and were asked whether a particular combination of cards indicated sun or rain. At first, participants did not know whether a set of cards indicated sun or rain; after deciding, they were given feedback in the form of a smiling or frowning face. Participants completed 100 trials. The dependent measure was the percentage of chosen optimal outcomes (which was more probable given prior feedback).

Artificial grammar learning. During the initial study phase, participants viewed a series of letter strings on a computer screen and were instructed to write these down. There was no time limit. After copying each string, participants were asked to cover their response before moving on to the next string. A total of 23 study strings were generated from a Markov chain grammar (Supplementary Fig. S1b) and were presented twice each in two sets, with 23 strings presented in random order once and then the same 23 strings presented in random order again (46 training trials). Next, during the test phase, participants were asked unexpectedly to decide whether new strings were grammatical; of these new strings, 16 were grammatical and 16 were not, and half of each kind were high-chunk strength and half were low-chunk strength (high = frequent letter pairings during the study phase). The dependent measure was the proportion of items endorsed correctly as grammatical.

Declarative memory
California Verbal Learning Test–Second Edition (CVLT-II). Both adult and child versions of this standardized test of declarative memory (Delis, Kramer, Kaplan, & Ober, 2000) were used. These versions are

the same in terms of procedure but differ in the words that are to be remembered and the list lengths (16 for adults and 15 for children). The long-delay measure, in which participants were asked to remember words from a study list after a 20-min delay, was the dependent measure. Standardized scores were used to compare the two groups relative to their age peers; a raw percentage correct score was used to compare the two groups directly.

Complex working memory
Count span. This task was modeled after previous work (Case, Kurland, & Goldberg, 1982; Cowan et al., 2005). Participants viewed an array on a computer with blue circles, blue triangles, and red circles and were instructed to count only the blue circles (targets), after which they were instructed to press the spacebar to move forward. If they did not press within 5 s, the screen would forward automatically. After anywhere from one to six consecutive arrays were presented, participants were prompted to enter the number of targets per array in the order that they were presented. The dependent measure was calculated by determining the highest load (from one to six) at which two of three trials were answered correctly plus 0.5 if one of three trials at the next highest load was answered correctly.

Results

IQ, declarative memory, and working memory

Adult and child groups did not differ significantly on standardized measures of IQ, including the composite score, $t(57) = 0.51$, $p = .62$, $d = -0.136$ (adults = 119.0; children = 117.2), verbal subscale, $t(57) = 0.46$, $p = .644$, $d = -0.124$ (adults = 117.97; children = 116.03), and nonverbal subscale, $t(57) = 0.18$, $p = .86$, $d = -0.046$ (adults = 114.72; children = 114.17). Adults had superior declarative memory performance (California Verbal Learning Test: $t(59) = 2.80$, $p = .007$, $d = -0.719$; adults = 0.84; children = 0.72) and working memory performance (count span: $t(55) = 5.56$, $p < .001$, $d = -1.47$; adults = 5.41; children = 3.57). When CVLT-II scores were age-normed, there was no significant difference between groups, $t(59) = 0.37$, $p = .71$, $d = -0.10$. See Supplementary Table 2 for means and standard deviations.

Procedural memory
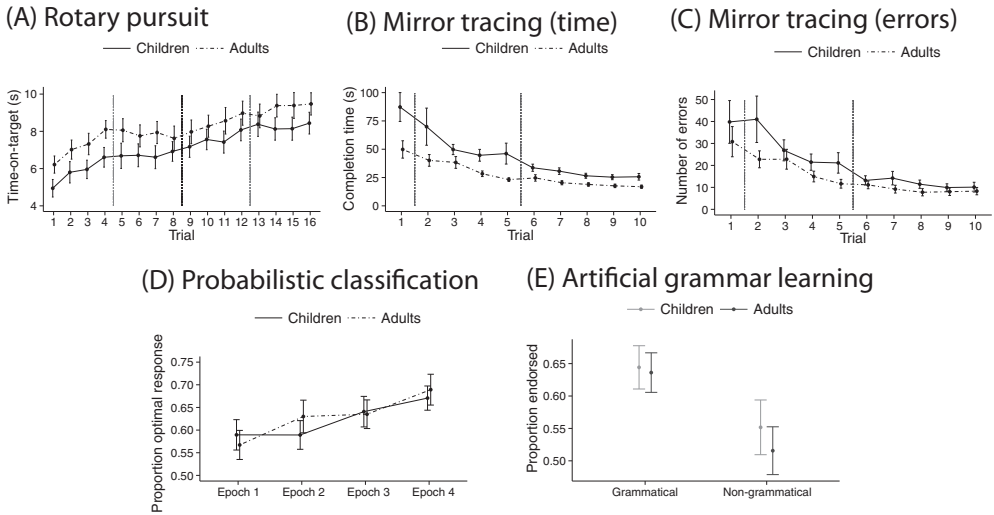
Rotary pursuit
A repeated measures analysis of variance (ANOVA) with time-on-target as the dependent measure revealed a main effect of trial number, $F(15, 885) = 23.50$, $p < .001$, $n_p^2 = .285$ (Fig. 1A), but no main effect of age, $F(2, 59) = 2.10$, $p = .153$, $n_p^2 = .034$, and no trial number by age group interaction, $F(15, 885) = 0.570$, $p = .899$, $n_p^2 = .01$. Adults performed the task at a faster initial speed (mean of 34.66 rotations per minute) than children (mean of 26.25 rotations per minute): independent samples t-test, $t(56) = 2.96$, $p = .004$, $d = 0.762$.

Mirror tracing
A repeated measures ANOVA with completion time as the dependent measure revealed a main effect of trial number (Trials 2–10 because the first trial was practice), $F(8, 464) = 16.23$, $p < .001$, $n_p^2 = .219$, Bonferroni adjusted $\alpha = .025$ (Fig. 1B), a main effect of age, $F(1, 58) = 7.31$, $p = .009$, $n_p^2 = .112$, Bonferroni adjusted $\alpha = .025$, and no trial number by age group interaction, $F(8, 464) = 1.86$, $p = .065$, $n_p^2 = .031$, Bonferroni adjusted $\alpha = .025$. The trend toward an interaction reflected greater learning in children, which may have resulted from the children's slower initial performance. When baseline speed was taken into consideration (the average of Trials 2 and 3 minus the average of Trials 9 and 10 divided by the sum of those trials), there was no trend toward a group difference, $t(58) = 0.725$, $p = .472$, $d = 0.188$, Bonferroni adjusted $\alpha = .025$.
The same analysis using number of errors as the dependent measure yielded a main effect of trial number (Trials 2–10), $F(8, 464) = 16.78$, $p < .001$, $n_p^2 = .224$, Bonferroni adjusted $\alpha = .025$ (Fig. 1C), no main effect of age, $F(1, 58) = 2.46$, $p = .122$, $n_p^2 = .042$, Bonferroni adjusted $\alpha = .025$, and no trial by

Fig. 1. Procedural memory performance. Shown is performance for adults (dash-dotted lines) and children (solid lines) plotted across trials for rotary pursuit (A), mirror tracing (B, C), probabilistic classification (D), and artificial grammar learning (E). For probabilistic classification, proportion of optimal responses is plotted by epoch (binning all 100 trials into four 25-trial epochs). For artificial grammar learning, adults (black) and children (gray) endorsed more grammatical than non-grammatical items as grammatical. In this and all other graphs, error bars reflect standard errors. Dashed vertical lines reflect task breaks.

age group interaction, $F(8, 464) = 1.84$, $p = .067$, $n_p^2 = .037$, Bonferroni adjusted $\alpha = .025$, with a trend for greater learning in the children. When baseline errors were taken into consideration (same calculation as in completion time), there was no trend toward a group difference, $t(58) = 0.911$, $p = .366$, $d = 0.236$, Bonferroni adjusted $\alpha = .025$.

Probabilistic classification task

A repeated measures ANOVA in which performance was binned into four epochs (25 trials each) revealed a main effect of epoch, $F(3, 168) = 6.40$, $p < .001$, $n_p^2 = .103$ (Fig. 1D), no main effect of age group, $F(1, 56) = 0.01$, $p = .95$, $n_p^2 = .001$, and no epoch by group interaction, $F(3, 168) = 0.84$, $p = .48$, $n_p^2 = .015$. Furthermore, children and adults did not differ in their learning of any of the 14 card combinations (which ranged in their association with an outcome; see Supplementary material).

Artificial grammar learning

A repeated measures ANOVA with grammaticality (grammatical or not) and chunk strength (low or high) as factors revealed a main effect of grammaticality, $F(1, 52) = 13.81$, $p < .001$, $n_p^2 = .210$, a main effect of chunk strength, $F(1, 52) = 38.99$, $p < .001$, $n_p^2 = .428$, and no main effect of age group, $F(1, 52) = 0.28$, $p = .596$, $n_p^2 = .005$. There was no interaction between grammaticality and age, $F(1, 52) = 3.08$, $p = .085$, $n_p^2 = .056$, or among grammaticality, chunk strength, and age, $F(1, 52) = 0.98$, $p = .326$, $n_p^2 = .019$, but there was a marginal interaction between chunk strength and age, $F(1, 52) = 3.96$, $p = .052$, $n_p^2 = .071$, such that children were more likely to incorrectly endorse low-chunk strength items. Both groups learned the artificial grammar, as shown by selecting grammatical strings significantly more often than non-grammatical strings (paired t-test, $t(53) = 4.18$, $p < .001$, $d = 0.578$) (Fig. 1E), and did so to a similar extent.

Overall pattern of learning and memory

To provide an overview of age-related differences and similarities in learning and memory, z-scores were calculated for the six main dependent measures (percentage errors for mirror tracing) (Fig. 2).

Children had worse scores on the declarative memory and working memory tasks but had scores similar to adults on the skill learning tests of procedural memory.

Discussion

There was a clear dissociation between the age groups' declarative memory ability, which was lesser in the children, and procedural memory, which was mature or adult-like in the children. Although the procedural tasks varied in their nature, children exhibited adult-like skill learning on all of the tasks. The comparison between these children and adults was valid because both groups scored similarly relative to their age group peers on standardized tests of IQ and declarative memory (Supplementary Table 2).

The findings that children had lesser declarative memory ability and lesser working memory capacity are consistent with many studies reporting age-related growth of declarative memory ability (e.g., Kail, 1990) and working memory capacity (e.g., Gathercole, Pickering, Ambridge, & Wearing, 2004) into young adulthood. In sharp contrast, children exhibited adult-like rates of learning on all four skill learning tests of procedural memory. The skill learning tasks varied on several dimensions. Two were perceptual–motor tasks, and two were cognitive tasks. The nature of feedback also varied across the tasks—from none at all, to observed motor-based, to explicit. In three tasks, learning was measured continuously, but not in artificial grammar for which there was a final test phase. Despite this variation, children exhibited adult-like learning on all of the tests of procedural memory.

The tests of procedural memory share the property that they do not depend on the integrity of medial temporal lobe structures, but they are heterogeneous in regard to what neural systems are necessary for learning. Procedural memory for both rotary pursuit (Gabrieli, Stebbins, Singh, Willingham, & Goetz, 1997) and probabilistic classification (Knowlton, Mangels, & Squire, 1996) depends on the integrity of the basal ganglia. Lesions to the basal ganglia, however, do not impair skill learning for mirror tracing (Gabrieli et al., 1997); instead, lesions to the cerebellum impair such learning (Sanes, Dimitrov, & Hallett, 1990). The necessary brain regions for artificial grammar learning are less well known, but they may be neocortical. Patients with basal ganglia degeneration, due to Parkinson's disease, or cerebellar degeneration have shown intact artificial grammar learning (Witt, Nuhsman, & Deuschl, 2002), and neuroimaging studies have suggested that neocortices in left occipital and parietal regions mediate such learning (e.g., Thiel, Shanks, Henson, & Dolan, 2003). Thus, mature procedural memory in children may reflect not so much the maturation of a particular neural circuit as the shared properties of multiple procedural learning mechanisms that are independent of declarative memory.
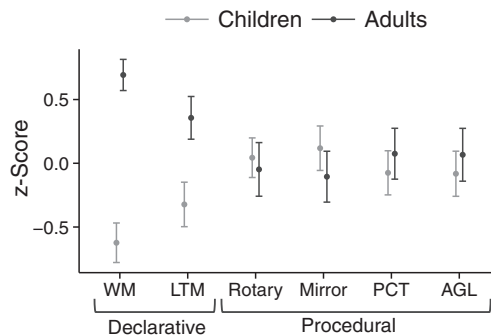
Fig. 2. Summary of performance on declarative and procedural memory tasks. The z-scores of performance across tasks for adults (black) and children (gray) show an adult advantage for declarative memory (LTM) and working memory (WM) measures, but not for procedural measures (PCT, procedural classification task; AGL, artificial grammar learning). To plot learning of procedural memory, z-scores were taken of the difference in performance later as compared with earlier in learning. For rotary pursuit, this was time-on-target during Trial 16 minus Trial 1; for mirror tracing, this was percentage change scores for errors as described in Results; for PCT, this was proportion of optimal responses in Block 4 minus Block 1; for AGL, this was overall accuracy (regardless of stimulus type).

Thus, it is unknown as to whether or not the same mechanisms support the various forms of adult-like procedural memory in 10-year-old children.

There are several important limitations to the current study. First, further research with a broader age of younger children is needed to determine at what age these forms of procedural learning become adult-like and whether the different kinds of procedural memory become adult-like at similar ages. Second, the different kinds of learning involved different kinds of measurement, with the declarative memory task having been measured by a standardized test. In patient studies, these concerns have been mitigated by double dissociations between declarative and procedural memory, but this is not possible in the study of typical development. Third, the critical findings of mature procedural learning in 10-year-olds is based on the absence of a learning difference, which could reflect limited measurement power. This concern is mitigated by the fact that children exhibited somewhat better learning than adults on two procedural learning measures.

The differential development of procedural and declarative memory may have implications for learning at various ages. For example, there is a suggestion that some aspects of language (e.g., grammar), for which there is a critical or sensitive period, may depend on procedural memory (Ullman, 2001). Indeed, adults, who have greater declarative and working memory ability, outperform children for learning words and their meanings but struggle to learn grammar as well as children (Snow & Hoefnagel-Höhle, 1978). Although more research is needed to understand the consequences of having a relatively more developed procedural than declarative memory system, this developmental imbalance during childhood could have beneficial implications for learning some aspects of one's native language (see also Ramscar & Gitcho, 2007; Thompson-Schill, Ramscar, & Chrysikou, 2009). In terms of their memory systems, the more rapid maturation of procedural relative to declarative memory may promote particular kinds of learning in children.

Acknowledgments

Appendix A. Sample size by group and task

Task	Group	Sample size
KBIT	Children	31
	Adults	29
CVLT	Children	32
	Adults	29
Count span	Children	30
	Adults	27
PCT	Children	29
	Adults	29
Rotary	Children	32
	Adults	29
Mirror	Children	31
	Adults	29
AGL	Children	26
	Adults	28

Note. KBIT, Kaufman Brief Intelligence Test; CVLT, California Verbal Learning Test; PCT, procedural classification task; AGL, artificial grammar learning.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jecp.2015.09.027.

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