

Developmental Differences in Implicit Learning of Spatial Context

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The authors examined whether a form of implicit memory that has been unambiguously dissociated from conscious awareness—learning of spatial context on the contextual cuing task introduced by M. M. Chun and Y. Jiang (1998)—is mature in childhood as predicted by an evolutionary view of cognition. School-aged children did not show reliable learning relative to adults who performed the same version of the task or another version that slowed responses to match those of children. Thus, unreliable learning in childhood was mediated by immature implicit representations of spatial context rather than by slower baseline response speed. The present finding is inconsistent with the prediction of the evolutionary view of cognition but consistent with incomplete maturation of medial temporal lobes known to mediate contextual learning.

Keywords: declarative memory, procedural learning, visual attention, visual search

A long held view of memory development is that implicit memory, the retrieval of past experience without intention or awareness, matures earlier than explicit memory, the conscious recollection of past experience. Indeed, explicit memory performance reaches adult levels in late childhood or later in adolescence (e.g., strategic memory tests; Cycowicz, 2000), owing to maturation of the medial temporal lobes and projections to prefrontal cortex during childhood and adolescence (de Haan, Mishkin, Baldeweg, & Vargha-Khadem, 2006). Different developmental time courses of implicit and explicit memory are predicted by an influential model of cognition based on evolutionary principles (Fletcher & Roberts, 1998; Mayberry & O'Brien-Malone, 1998; Reber, 1992). This model states that cognitive processes that are independent of conscious awareness (e.g., implicit memory) rely on phylogenetically older brain structures that develop early in childhood, whereas those dependent on conscious awareness (e.g., explicit memory) rely on phylogenetically newer brain structures that develop later in childhood. However, in positing the earlier ontogenetic maturation of implicit memory based on the role of

conscious awareness and the phylogenetic status of neurocognitive substrates, the evolutionary model overlooks current knowledge of memory organization and the developing brain.

Current evidence suggests that the phylogenetic status of neural substrates does not determine dissociations between forms of memory or the sequence of brain development. First, studies with patients who have brain damage indicate that implicit memory is not unitary but rather comprises multiple forms subserved by distinct neuroanatomical structures, some phylogenetically old, such as the striatum, and some new, such as the neocortices (Squire, 2004). Striatal structures subserve skill learning involving sequential (Knopman & Nissen, 1991) and probabilistic (Knowlton, Mangels, & Squire, 1996) information. Sensory and association neocortices subserve perceptual and conceptual processes, respectively, that underlie repetition priming, a facilitation of performance with familiar compared with novel stimuli (Fleischman et al., 2005; Vaidya, Gabrieli, Verfaellie, Fleischman, & Askari, 1998). Further, the medial temporal lobes that are crucial for explicit memory include phylogenetically older (e.g., hippocampus) and newer (e.g., surrounding cortex) zones. Current findings suggest functional specialization within the medial temporal lobes, with only some regions supporting mnemonic function dependent on conscious awareness (Daselaar, Fleck, Prince, & Cabeza, 2006). Thus, there is weak support for systematic correspondence between the implicit–explicit memory distinction and old–new phylogenetic status of underlying neuroanatomy. Second, brain development does not appear to follow a phylogenetic sequence. Striatal nuclei that support implicit skill learning are phylogenetically older but continue to show reductions in grey matter volume through adolescence (Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). The hippocampal formation that supports explicit memory, despite being part of the phylogenetically older limbic lobe, continues maturation past adolescence (Gogtay et al., 2006; Utsunomiya, Takano, Okazaki, & Mitsudome, 1999). Thus, phylogenetically older structures continue to mature in adolescence and support putatively early and late-maturing forms of memory.

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This work was supported by National Science Foundation Grant BCS-0121933 and Georgetown University Institutional funds to Chandan J. Vaidya and National Institute on Aging Grant R37AG15450 to Darlene V. Howard and James H. Howard, Jr. Portions of Experiment 1 were presented at the annual meeting of the Cognitive Neuroscience Society, San Francisco, April 2002. We thank Marvin Chun for providing stimuli materials and Casey Hoffman and Vanessa Rakaczky for assistance with data collection.

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In light of the multiple neural correlates of implicit memory, the developmental time course of a form of memory ought to depend on the maturational status of underlying neuroanatomy. However, this prediction is difficult to evaluate conclusively in the extant literature. First, although most studies examining repetition priming show developmental stability, there are two exceptions. Magnitude of perceptual priming did not differ in children and adults on tasks of perceptual identification (Drumme & Newcombe, 1995) and word fragment completion (Billingsley, Smith, & McAndrews, 2002; Naito, 1990), but findings were mixed for picture fragment completion: Children showed reduced priming in one study (Cycowicz, Friedman, Snodgrass, & Rothstein, 2000) but not in others (Hayes & Hennessy, 1996; Landrum, 1997; Mecklenbrauker, Hupbach, & Wippich, 2001; Perez, Peynircioglu, & Blaxton, 1998; Russo, Nichelli, Gibertoni, & Cornia, 1995). Further, magnitude of conceptual repetition priming on the category exemplar test did not differ developmentally in some studies (Anooshian, 1997; Billingsley et al., 2002; Greenbaum & Graf, 1989; Perez et al., 1998) but was reduced in children selectively for some stimuli (e.g., atypical category exemplars; Mecklenbrauker, Hupbach, & Wippich, 2003; Murphy, McKone, & Slee, 2003; Perruchet, Frazier, & Lautrey, 1995).¹ In evaluating conceptual priming in childhood, it is important to consider that incomplete acquisition of conceptual knowledge may influence expression of priming separately from developmental changes in mnemonic processes.

Second, studies of skill learning also show mixed findings. Learning of sequences on a perceptual-motor task (serial reaction time) did not differ between children and adults in some studies (Meulemans, Van der Linden, & Perruchet, 1998; Thomas & Nelson, 2001) but was reduced in children in other studies (Thomas et al., 2004; Thomas & Nelson, 2001). Using functional neuroimaging, Thomas et al. (2004) found that recruitment of cortical and subcortical (e.g., striatal) regions differed between children and adults. In contrast, developmental stability was found on other perceptual-motor tasks, such as rotary pursuit (Don, Schellenberg, Reber, DiGirolamo, & Wang, 2003) and drawing (Homberg, Bickmann, & Muller, 1993; Vinter & Perruchet, 2000, 2002), and cognitive tasks, such as artificial grammar learning (Don et al., 2003) and Tower of Hanoi (Homberg et al., 1993). Visual learning of the covariance of stimuli, however, was reduced in younger relative to older children (Maybery, Taylor, & O'Brien-Malone, 1995). Together, studies of repetition priming and skill learning suggest that developmental differences in implicit memory cannot be accurately predicted by either form of implicit memory or the nature of the implicit task.

One explanation of these contradictory findings that is consistent with the evolutionary view is that developmental differences represent cases in which participants gained awareness of learned information and used it to boost implicit memory (Drumme & Newcome, 1995; Guttentag & Dunn, 2003). Indeed, implicit and explicit visual learning of covariance between stimuli was correlated, and, furthermore, both forms of learning were greater for participants with higher intelligence whose explicit memory abilities are likely to be superior (Fletcher, Maybery, & Bennett, 2000). On picture fragment completion, methodological differences often determine the extent to which explicit recollection is evoked (Verfaellie, Gabrieli, Vaidya, Croce, & Reminger, 1996). However, conscious awareness is neither necessary nor routinely

evoked during priming of atypical category exemplars and sequence learning on the serial reaction time task, the other measures that showed reductions in children. In those studies, the role of conscious awareness was not always assessed (e.g., for primed category exemplars) and remained ambiguous when assessed: Although more sequence learning was observed in children who gained awareness (Thomas et al., 2004), children did not become aware in the other studies that found developmental stability (Meulemans et al., 1998) and differences (Thomas & Nelson, 2001). Thus, although the contradictory developmental findings cannot be explained by the variable influence of conscious awareness, its role cannot be conclusively ruled out either.

Whether implicit memory matures early in childhood, as predicted by the evolutionary view, cannot be definitively determined unless it has been unambiguously dissociated from conscious awareness. In the present study, we examined implicit learning of spatial context using the contextual cuing task that allows evaluation of learning guided by spatial representations formed implicitly, without contribution of conscious awareness (Chun & Jiang, 1998). On this task, participants search for a target (e.g., left-right-oriented *T*) among distracters (e.g., rotated *L*s). The spatial configuration of the distracters that forms the context for target search is repeated during the task with respect to its embedded target. Faster visual search for repeated relative to novel spatial configurations with increasing practice indexes learning of spatial contextual cues that predict target location. This task is well suited for the current purpose for several reasons. First, any developmental differences in learning cannot be due to differences in mechanisms of visual search because attentional properties of search in children were similar to adults by 4 years of age (Gerhardstein & Rovee-Collier, 2002) and learning on the current task is indexed by a relative measure (facilitation by invariant properties of the search display) that is apparent despite age-related response speed differences (Hommel, Li, & Li, 2004). Second, learning is immune to the influence of conscious awareness because adult participants cannot reliably recollect the learned information (Chun, 2000). Third, learning depends on integrity of the medial temporal lobes (Chun & Phelps, 1999; Manns & Squire, 2001) that continue maturation during childhood and adolescence (Gogtay et al., 2006; Utsunomiya et al., 1999). Dependence of implicit contextual learning on the medial temporal lobes suggests that there are forms of implicit memory that rely on circuitry known to support explicit memory; however, whether the same structures within the medial temporal lobe support both explicit memory and this form of implicit memory remains to be elucidated. For the present purposes, however, the contextual cuing task allows examination of a form of learning that minimizes the contribution of conscious awareness but maximizes sensitivity to neuroanatomical maturational differences.

Experiment 1

Developmental differences in implicit learning of spatial context and recognition memory for spatial context were examined in

¹ Whether prototypical exemplars were used in studies that found similar conceptual priming in children and adults is not known because typicality ratings were not reported (Anooshian, 1997; Billingsley et al., 2002; Greenbaum & Graf, 1989; Perez et al., 1998).

school-aged children and adults on the contextual cuing task introduced by Chun and Jiang (1998). Consistent with past studies using this task, recognition memory ought to be at chance in both children and adults. For implicit learning, if access to conscious awareness determines developmental differences as predicted by the evolutionary model of cognition, then children ought to show as much learning as adults because learned information is not amenable to conscious awareness on this task. In contrast, if immaturity of underlying neuroanatomy determines developmental differences, then children ought to show reduced learning because maturation of the medial temporal lobes is ongoing in childhood.

Method

Participants

Twenty-one Georgetown University undergraduates (11 women, 10 men) ranging in age from 18 to 22 years ($M = 21.1$ years, $SD = 1.2$) and 21 children (11 females, 10 males) from the Washington, DC metropolitan area ranging in age from 6 to 13 years ($M = 10.3$ years, $SD = 2.3$) participated for payment. In light of the wide age range in the children's group, correlational analysis and comparison of younger and older children were performed. All participants were in good health and were without diagnoses of neurological, psychiatric, or learning disorders (self-report for adults and parent report for children). Informed consent was obtained from adults and parents of children and assent was obtained from children according to guidelines of the Georgetown University Institutional Review Board.

Stimulus Materials

Stimuli were displays of spatial configurations of 12 elements in white on a grey background and comprised one target and 11 distracters. The target was a *T* pointing to the left or right and the distracters were *Ls* randomly rotated by 0°, 90°, 180°, and 270°. Following Chun and Phelps's (1999) work, the leg of the *L* was offset by 3 pixels. Each configuration was generated by random assignment of the 12 elements, each to a cell within an invisible grid of eight columns and six rows (for positioning details, see Howard, Howard, Dennis, Yankovich, & Vaidya, 2004). Twelve configurations were repeated through the course of the experiment, and the remaining configurations were novel. On repeated configurations, the location of the target was the same but its orientation was different; therefore, the spatial configuration of the distracters predicted the location of the target but not the response to the target. The same set of repeated and novel configurations was presented within each group, with order of presentation counter-balanced.

Procedure

On each trial, a central fixation dot appeared for 1 s, followed by the visual display that remained on the screen until participants pressed a key indicating orientation of the target (*Z* for left and *slash* for right). Following a keypress, a tone or a beep sounded, indicating an error or accurate response, respectively. Participants were instructed to search the visual display for a *T* pointing left or right as quickly and accurately as possible. Trials without a re-

sponse were aborted after 6 s. Participants performed one practice block of 24 trials followed by 6 epochs, each comprising five blocks and each block comprising 24 trials. Each block comprised 12 trials of novel configurations and 12 trials of configurations that repeated across blocks, each occurring once within each block. Participants could take breaks between blocks. Following visual search, participants performed recognition memory judgments on 24 configurations, 12 of which were not presented during visual search and 12 that were repeatedly presented during visual search. Participants were told to examine the positions of the elements within each configuration and to press a *yes* or *no* key to indicate whether they had seen the configuration earlier in the experiment during visual search. No feedback was provided.

Results

Visual Search

For each participant, the mean percentage of two types of errors was computed, left-right incorrect keypresses and trials without a response for 6 s (time-out). For each participant, mean response latency on correct trials was computed for each epoch for trials with repeated and novel configurations. Younger and older children are considered as one group in the present analyses but are considered separately later. Measures of effect size (partial eta-squared for analysis of variance [ANOVA] and Cohen's *d* for means) are presented for effects assessing learning.

Response Latency

Mean response latencies were analyzed with an Age (child, adult) \times Configuration (repeated, novel) \times Epoch (1-6) repeated-measures ANOVA (see Figure 1). As expected, adults' responses were faster than children's responses (main effect of age), $F(1, 40) = 16.63$, $p < .001$. Both groups exhibited learning of visual search skill because responses were faster with increasing practice (main effect of epoch), $F(5, 200) = 71.19$, $p < .0001$, independent of spatial context. Although overall responses were faster to repeated than to novel configurations (main effect of configuration), $F(1, 40) = 15.15$, $p < .001$, adults but not children exhibited context-dependent learning, that is, faster responses to repeated relative to novel configurations with increasing practice (Age \times Configuration \times Epoch interaction), $F(5, 200) = 3.00$, $p = .01$, partial $\eta^2 = .07$. No other interactions reached significance. The developmental difference in context-dependent learning was confirmed by separate Configuration \times Epoch ANOVAs that revealed a significant interaction in adults, $F(5, 100) = 3.58$, $p < .01$, partial $\eta^2 = .15$, but not in children ($p = .28$). Further, children did not show a significant main effect of configuration ($p = .10$). In adults, paired *t* tests revealed that response latencies to repeated relative to novel configurations were significantly faster for Epochs 3-6 ($ps < .01$) but not Epochs 1 and 2. Thus, reliable contextual learning was obtained in adults but not in children.

To determine whether the developmental difference in contextual learning was an artifact of the substantially slower response times in children relative to adults, we computed learning in each participant as a proportion of their baseline response time ($[\text{novel} - \text{repeated}] / \text{novel}$) for each epoch (see Figure 2). An Age \times Epoch ANOVA on the proportional measure revealed that learning was greater in adults than in children (main effect of age),

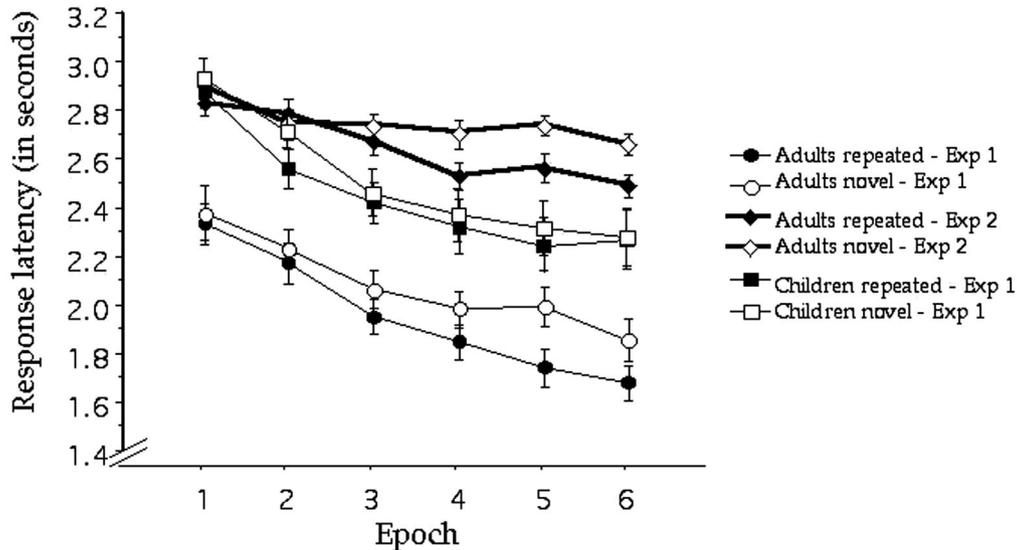


Figure 1. Mean response latencies (in seconds) and standard errors for repeated (filled) and novel (open) configurations for each epoch in children (squares), adults on the same task in Experiment 1 (circles), and adults on the modified task in Experiment 2 (diamonds). Exp = experiment.

$F(1, 40) = 3.77, p = .05$, and that it increased with practice (main effect of epoch), $F(5, 200) = 2.76, p = .01$, in adults but not in children (Age \times Epoch interaction), $F(5, 200) = 3.53, p < .01$, partial $\eta^2 = .08$. The developmental difference in proportional learning was confirmed by separate one-way ANOVAs that revealed a significant main effect of epoch in adults, $F(5, 100) = 4.80, p < .001$, partial $\eta^2 = .15$, but not in children ($p = .30$). Further, unpaired t tests indicated that learning was greater in adults than in children in Epoch 5, $t(40) = 3.0, p = .003, d = .94$, and Epoch 6, $t(40) = 2.8, p = .007, d = .87$, but not in Epochs 1–4 ($ps < .10$). These findings concur with those from the analysis of response latencies.

One reason for the lack of reliable contextual learning in children could be a wide variation in learning among individuals. We

performed three analyses to determine whether amount of learning varied by age within the children's group. First, following a median split on age ($Mdn = 11.05$ years), we divided the children's group into younger ($M = 8.29$ years, $SD = 1.48; n = 8$) and older ($M = 12.03$ years, $SD = 0.70; n = 13$) age groups. An Age (young, old) \times Configuration (novel, repeated) \times Epoch (1–6) ANOVA on response latencies revealed no significant main effects or interaction ($ps > .19$), indicating that response latencies and contextual learning did not differ between younger and older children (see Figure 3). Perhaps the small sample sizes did not provide adequate power to detect interactions. Total amount of learning (computed as the sum of the magnitude of proportional learning in Epochs 1–6) for the younger children was $M = .01$ ($SD = .32$) and for the older children was $M = .17$ ($SD = .36$).

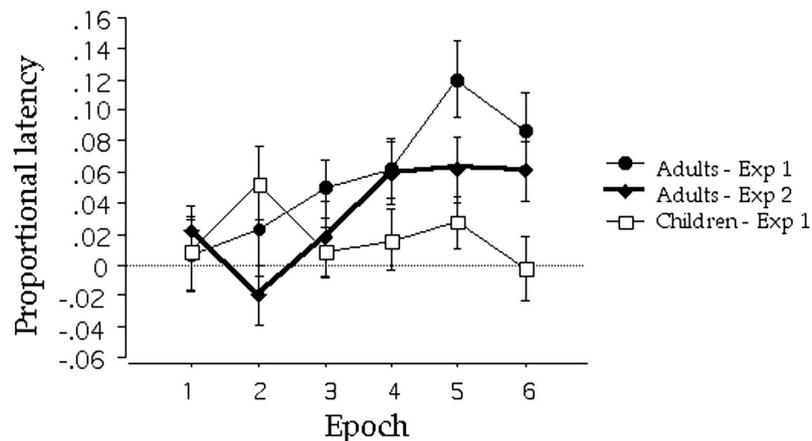


Figure 2. Mean proportional response latencies ($[\text{novel} - \text{repeated}] / \text{novel}$) and standard errors in children (squares), adults on the same task in Experiment 1 (circles), and adults on the modified task in Experiment 2 (diamonds). Exp = experiment.

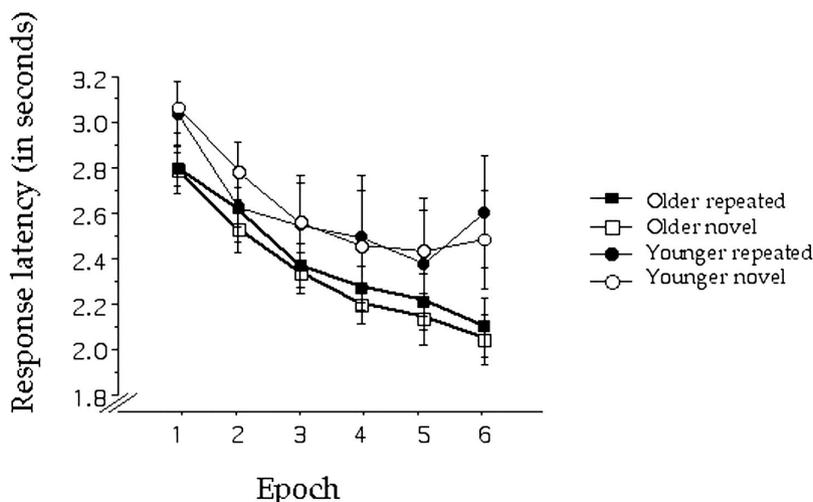


Figure 3. Mean response latencies (in seconds) and standard errors for repeated (filled) and novel (open) configurations for each epoch in older (squares) and younger (circles) children in Experiment 1.

Second, in light of the large standard deviations in the amount of learning, we examined its correlation with age within the children’s group. The correlation between age and amount of learning was positive but marginally significant ($r = .27, p = .09$), suggesting a trend for age-related increases in contextual learning during late childhood. Third, we examined whether variability in learning related to visuospatial ability as measured by the Digit Symbol Substitution task of the Wechsler Intelligence Scale for Children (3rd ed.; Wechsler, 1991). The correlation between raw scores on that task and the total amount of learning was not significant ($r = -.05, p = .85$). Thus, chronological age but not visuospatial ability appears to relate to the amount of contextual learning in children.

Error Rates

Time-out trials. Percentage of time-out trials relates to response speed and therefore was submitted to Age \times Configuration \times Epoch ANOVA, similar to analyses of response latency (see Table 1). Consistent with slower response latencies in children, the percentages of time-out trials were greater in children than in adults (main effect of age), $F(1, 40) = 8.85, p < .01$. Overall time-out errors decreased with practice (main effect of epoch), $F(5, 200) = 27.33, p < .0001$, but practice-related decreases were greater for children than for adults (Age \times Epoch interaction), $F(5, 200) = 4.77, p < .001$, suggesting a developmental difference in context-independent visual skill learning.

Table 1
Mean (and Standard Deviation) Percentage of Errors for Repeated and Novel Configurations by Epoch in Children, Adults Who Performed the Same Task in Experiment 1, and Adults Who Performed a Modified Task in Experiment 2

Epoch	Children		Adults (Exp 1)		Adults (Exp 2)	
	R	N	R	N	R	N
Time-out trials						
Epoch 1	9.1 (7.4)	10.1 (9.1)	2.5 (3.1)	3.5 (3.0)	6.7 (4.0)	8.2 (4.5)
Epoch 2	5.2 (6.9)	4.4 (5.1)	1.0 (1.5)	2.1 (2.2)	3.7 (3.3)	5.2 (4.1)
Epoch 3	2.8 (4.6)	3.9 (4.8)	0.24 (.60)	1.2 (1.4)	2.6 (3.2)	3.3 (2.2)
Epoch 4	2.5 (5.5)	2.6 (5.3)	0.16 (.50)	0.32 (.67)	2.9 (3.1)	3.2 (3.1)
Epoch 5	2.5 (5.5)	3.5 (5.4)	0.16 (.50)	0.15 (.50)	2.9 (3.1)	3.3 (2.7)
Epoch 6	3.7 (8.4)	2.3 (4.8)	0.16 (.50)	0.16 (.50)	1.7 (1.6)	2.0 (2.9)
Left-right errors						
Epoch 1	7.9 (9.5)	6.5 (5.8)	3.0 (4.1)	3.3 (3.9)	4.3 (4.0)	3.7 (2.9)
Epoch 2	7.5 (8.2)	7.5 (8.6)	2.9 (3.9)	2.8 (4.9)	5.2 (4.9)	4.4 (5.0)
Epoch 3	5.6 (5.5)	7.2 (7.8)	2.3 (3.6)	2.9 (4.6)	4.1 (4.0)	4.3 (4.1)
Epoch 4	7.3 (7.5)	6.8 (7.4)	2.5 (4.6)	2.5 (4.4)	2.8 (2.5)	2.6 (2.9)
Epoch 5	7.3 (8.7)	7.5 (8.0)	2.9 (6.4)	4.0 (7.3)	4.1 (3.3)	4.0 (4.5)
Epoch 6	7.4 (7.5)	7.9 (9.0)	2.5 (6.0)	3.6 (7.8)	3.2 (3.5)	5.3 (4.6)

Note. Exp = experiment; R = repeated configuration; N = novel configuration.

However, adults' time-out errors in Epochs 4–6 are low, suggesting a floor effect that prevented further improvement. In contrast to the response latency analysis, however, overall time-out errors were not significantly greater for novel than for repeated configurations (main effect of configuration, $p = .09$) and there were no developmental differences in contextual learning because the Age \times Configuration \times Epoch interaction was not significant ($p = .26$).

Left–right errors. An Age \times Configuration \times Epoch ANOVA on percentage of errors revealed that children made more errors than did adults (main effect of age), $F(1, 40) = 6.46, p = .01$, but the pattern of errors did not differ with practice or context (other main effects and interactions; $ps > .15$; see Table 1).

Recognition

Percentage of hits ("yes" response to a repeated configuration) and false alarms ("yes" response to a novel configuration) were analyzed within an Age (child, adult) \times Trial Type (hits, false alarms) ANOVA. None of the main effects or the interaction were significant ($ps > .16$), indicating that neither children (hits: $M = 50.79, SD = 14.88$; false alarms: $M = 50.39, SD = 14.06$) nor adults (hits: $M = 52.50, SD = 20.43$; false alarms: $M = 45.00, SD = 23.16$) consciously recognized the repeated configurations.

Discussion

There were four main findings. First, although both adults and children showed similar improvement of visual search skills with practice, the extent to which improvement was guided by invariant properties of the search context differed between the age groups. Adults' visual search was facilitated by repetition of spatial context by Epoch 3 and increased steadily through the remainder of the session. In contrast, children's visual search was not influenced by repetition of visual context. Thus, implicit learning of spatial context is immature in late childhood. Second, consistent with the characterization of learning on the contextual cuing task as implicit, neither adults nor children consciously recognized the repeated configurations. Thus, any developmental differences observed in implicit learning cannot be explained by differences in explicit memory for the contextual information. Third, children's visual search performance was slower and less accurate than that of adults. However, the lack of reliable contextual learning in children was not an artifact of their slower response latencies because lack of contextual learning persisted in a measure that normalized learning to individuals' baseline speed (i.e., response latencies to novel configurations). Error rates were not sensitive to contextual repetition in either age group. Nevertheless, less accurate and slower performance in children suggests that they experienced the search task as more effortful than did adults. Fourth, individual variability in amount of contextual learning among children was related to chronological age, albeit weakly, but not psychomotor ability. Our observation of developmental differences on a form of implicit learning that is not amenable to conscious awareness is inconsistent with the predictions of the evolutionary model of cognition.

Prior to concluding that contextual learning is immature in childhood, it is important to determine whether age differences in performance characteristics of the visual search task influenced the extent of observed implicit learning. Slower and less accurate

responding in children suggests that they experienced the task as more effortful than did adults. Slower performance does not necessarily reduce contextual learning because older adults with slower response latencies exhibit as much learning as young adults (Howard et al., 2004). Nevertheless, we sought to eliminate the possibility that reduced learning characterizes slower performance rather than immature contextual learning.

Experiment 2

Experiment 2 examined contextual learning on a modified version of the same task that was used in Experiment 1 in a separate group of adults. All procedural characteristics of the modified task were identical to Experiment 1 except that the distracters in the display (L s) appeared visually similar to the target left–right-oriented T by a greater offset of the leg of the L than in Experiment 1. This procedure has been shown to prolong response speed in adults and, therefore, is considered to make visual search more effortful (Chun & Phelps, 1999).

In comparison with findings from Experiment 1, the present experiment disambiguates the observed developmental difference in two ways. First, it allows examination of developmental differences in contextual learning that are not confounded by differences in baseline performance speed (e.g., response latencies for novel configurations on Epoch 1) by comparing children in Experiment 1 with adults in Experiment 2. If baseline visual search speed in adults on the modified task does not differ from that of children in Experiment 1, any developmental difference in contextual learning ought to relate to the maturity of implicit learning rather than to properties of performance prior to learning. Second, it allows examination of the role of effortful responding in contextual learning. Slower overall task performance, as expected on the modified task, suggests an effortful performance experience. The extent to which an effortful experience influences contextual learning would be revealed by comparing learning in Experiment 2 with that in adults from Experiment 1. If adults in Experiment 2 show less learning than those in Experiment 1, then the manipulation that slowed search speed in adults would parallel the developmental difference observed in Experiment 1. If so, then slow visual search rather than immature implicit learning would serve as a parsimonious explanation for the developmental difference in Experiment 1.

Method

Participants

Twenty-one Georgetown University undergraduates (11 women, 10 men) ranging in age from 18 to 22 years participated for payment. All participants were in good health and were without diagnoses of neurological, psychiatric, or learning disorders (self-report).

Stimulus Materials

Stimulus materials were identical to that in Experiment 1 except that the leg of the distracters L was offset by 5 pixels. This modification makes the distracters appear similar to the target left–right-oriented letter T .

Procedure

The procedures were identical to those in Experiment 1.

Results

Visual Search

Mean response latencies and error rates were computed as in Experiment 1. First, we examined whether the modified task yielded significant contextual learning in a Configuration (repeated, novel) \times Epoch (1–6) ANOVA (see Figure 1, boldfaced lines). Adults exhibited significant contextual learning because their responses were increasingly faster to repeated than to novel configurations with extended practice (Configuration \times Epoch interaction), $F(5, 100) = 3.10, p = .01$, partial $\eta^2 = .14$.

Second, we examined whether baseline search speed (response times for novel configurations in Epoch 1) differed between adults performing the modified task and children in Experiment 1. Baseline search speed did not differ between groups ($p = .76$). Thus, similar to results of Experiment 1, significant contextual learning was obtained in adults but not in children, despite similar visual search speed prior to learning. The developmental difference cannot be attributed to slower baseline performance speed in children because their response latencies to novel configurations in Epoch 1 matched those of adults.

Third, we examined the role of baseline visual search speed differences on contextual learning by comparing performance of adults on the modified task with that of adults performing the original task in Experiment 1 in a Group \times Configuration \times Epoch ANOVA. As expected, overall response latencies were slower on the modified task than on the original task in Experiment 1 (main effect of group), $F(1, 40) = 69.34, p < .0001$. Further, this difference in speed was observed prior to learning in baseline response latencies (novel configurations in Epoch 1), $t(40) = 4.2, p = .0001$, and thus confirmed that the modified task was indeed more effortful than the task in Experiment 1. Both groups exhibited learning of visual search skill independent of spatial context because responses were faster with increasing practice (main effect of epoch), $F(5, 200) = 56.23, p < .0001$. Further, the rate of improvement in visual search skill varied for the two groups (Group \times Epoch interaction), $F(5, 200) = 7.72, p < .0001$. Overall response latencies were faster for repeated than for novel configurations (main effect of configuration), $F(1, 40) = 22.36, p < .0001$, and both groups exhibited context-dependent learning because responses were faster to repeated than to novel configurations with increasing practice (Configuration \times Epoch interaction), $F(5, 200) = 5.74, p < .0001$. Of most importance, the nature of contextual learning did not differ between the two adult groups because the Group \times Configuration \times Epoch interaction was not significant ($p = .51$). Thus, despite differences in baseline search speed, contextual learning did not differ between the adults performing the modified task and those performing the original task in Experiment 1.

Error Rates

Time-out trials. A Configuration \times Epoch ANOVA indicated that the percentages of time-out trials were fewer with increased practice (main effect of epoch), $F(5, 100) = 25.90, p < .0001$. Although there were more time-out trials for novel than for repeated configurations (main effect of configuration), $F(1, 20) = 6.51, p =$

.02, the advantage of repeated configurations did not vary with practice (Configuration \times Epoch interaction, $p = .69$). This finding is similar to that in Experiment 1. Thus, whereas manipulation of target and distracter similarity influenced response speed as expected, the characteristics of mature contextual learning remained invariant.

Left–right errors. A Configuration \times Epoch ANOVA indicated that none of the main effects or the interaction reached significance ($ps > .11$). This finding is similar to that in Experiment 1, in that left–right errors were not influenced by practice or context.

Recognition

In contrast to results of Experiment 1, adults performing the modified task consciously recognized significantly more repeated than novel configurations (hits: $M = 54.76, SD = 14.8$; false alarms: $M = 46.03, SD = 14.58$), $t(40) = 2.4, p = .02, d = .77$. This finding appears to emerge from a subset of the sample, 9 participants who had at least two or more hits than false alarms. However, total amount of contextual learning (computed as in Experiment 1) in these participants did not differ from those whose recognition memory (computed as percentage of hits – false alarms) was at chance, $t(19) = 1.5, p = .16$.

Discussion

Adult participants revealed significant contextual learning on a modified version of the contextual cuing task from Experiment 1 that prolonged baseline visual search speed. In comparison with results from Experiment 1, Experiment 2 elucidated effects of development and performance effort on contextual learning. First, baseline performance speed did not differ between adults in Experiment 2 and children in Experiment 1. However, magnitude of contextual learning in adults was greater than that observed in children. Although equating baseline response speed across children and adults in Experiment 2 does not equate the underlying cognitive processes, it suggests that response latency differences were not the sole cause of the developmental differences in contextual learning observed in Experiment 1.² Second, adults in Experiment 2 experienced the current task as more effortful than did adults in Experiment 1 because their responses were slower. Despite greater performance effort, adults in Experiment 2 exhibited contextual learning, as did adults in Experiment 1. Thus, manipulation of performance effort did not attenuate contextual learning in adults, a finding not paralleled by the manipulation of a participant variable (development) in Experiment 1. Attenuation of contextual learning in childhood relative to adulthood, therefore, must relate to immature implicit learning processes rather than to performance effort per se.

In contrast to results of Experiment 1, recognition memory was slightly above chance, driven primarily by a subset of the group.

² Whether slower baseline response speed related to lack of contextual learning in children can also be determined by examining contextual learning in children performing a modified task that speeds up visual search. We modified the contextual cuing task by including distracters without any offset in the leg of the *L* to make them more distinct from the target. Response latencies were faster relative to those using the original task in Experiment 1 because the distracters are more distinct, but significant contextual learning was not observed in children of the same ages as those in the present study (Configuration \times Epoch interaction, $p = .18$; Barnes et al., 2007).

However, amount of learning did not differ in these participants relative to those whose recognition memory was at chance. Further, those participants did not differ in baseline response speed (response time in Epoch 1 for novel configurations) relative to those with at-chance recognition, $t(19) = 1.0, p = .30$, suggesting that conscious awareness of repetition was not promoted by slower search speed. Moreover, amount of learning on this task remains unaffected when participants are asked to encode spatial context intentionally (Chun & Jiang, 2003). Although we did not assess participants' awareness of repetition during performance of the visual search task, some participants could have become aware of their familiarity for search displays during the recognition test rather than during visual search.

General Discussion

The present study revealed developmental differences in a form of implicit learning—learning of spatial relationships on the contextual cuing task—that is known to be inaccessible to conscious awareness. Relative to adults, school-aged children did not exhibit reliable learning (Experiment 1). Learning was implicit because both adults and children did not consciously recognize learned spatial layouts. Reduced learning in children did not result from slower visual search because the developmental difference was observed in comparison with adult participants performing a modified version of the task (greater similarity between target and distracters) that slowed baseline visual search to match that of children (Experiment 2). Further, learning did not differ among adults who performed the modified task and those who performed the original task. Thus, performance effort alone did not modulate contextual learning, suggesting that reduced learning in children was not a consequence of slow visual search. Together, the two experiments indicate that implicit learning of spatial contextual information is immature in school-aged children.

The present results are inconsistent with the prediction of the evolutionary view of cognition that processes independent of conscious awareness reach maturation early in development. Performance on tasks that showed immaturity in implicit mnemonic processes in children, such as serial reaction time (Thomas et al., 2004), repetition priming with atypical category exemplars (Mecklenbrauker et al., 2003; Murphy et al., 2003; Perruchet et al., 1995), and picture fragment completion (Cycowicz et al., 2000), can be enhanced by conscious awareness. Therefore, whether reduced implicit memory reflected reduced use of conscious recollection rather than immaturity of implicit representations could not be discerned with confidence. Learning of spatial context during visual search in the present task or of nonspatial visual information on other tasks is based on detection of covariance between properties of the perceptual environment and target information (Chun, 2000). Participants do not become consciously aware of those properties despite highly sensitive explicit memory tests and cannot enhance learning when explicitly instructed to use them as predictive cues in guiding performance (Chun & Jiang, 2003). Indeed, in Experiment 1, adults and children were unable to recognize accurately spatial contextual cues that facilitated visual search. On the modified task in Experiment 2 that made visual search effortful, a subset of adults recognized the repeated spatial layouts but learning did not differ from those unaware of the repetition. The present developmental differences, therefore, indi-

cate that conscious awareness of learned information is not necessary for ontogenetically slower maturation of a mnemonic process.

Why was spatial contextual learning reduced in childhood? First, although fatigue could prevent sustained expression of learning, it does not account for the current finding. Figure 1 indicates that despite similar baseline visual search speed (novel configurations in Epoch 1), children improved to a greater extent and at a more rapid rate with practice than did adults who searched the modified spatial displays in Experiment 2. Further, Table 1 indicates that time-out errors in children improved at a more rapid rate than those in adults who searched the same spatial displays in Experiment 1. Although the lack of improvement in adults may be due to floor effects, the improvement in children appears inconsistent with fatigued performance. Second, rapid improvement in children's visual search with practice raises the possibility that faster target detection reduced encoding of distracter configuration, resulting in the lack of predictive benefits in children. If so, then faster children ought to show less learning, a negative correlation between baseline visual search speed and amount of learning in children. Correlations of response latencies for searching novel configurations on Epoch 1 with total amount of learning were positive and weak for each group ($r_s < .38, p_s > .09$) and together ($r = .06, p = .60$). Thus, faster target detection in children did not relate to the reduction in amount of learning.

Third, immature selective attention processes could prevent learning in children because they might interfere with effective encoding of the spatial displays (Turk-Browne, Junge, & Scholl, 2005). Indeed, contextual learning was attenuated by manipulations that interfered with encoding, such as discouraging participants' attention to selected displays (Jiang & Chun, 2001). Further, under conditions of reduced attention (e.g., for ignored displays), increasing similarity of target and distracters eliminated contextual learning in adults. Jiang and Chun (2001) suggested that increased similarity serves to increase perceptual load, and participants may reduce attention to the irrelevant information (distracters) to conserve resources (termed "early selection" by visual attention theories). These findings parallel the observed developmental difference and suggest that differences in selective attention processes may have served to reduce learning in children. Indeed, developmental studies of visual selective attention reveal that children engaged early selection at lower perceptual loads than did adults (Huang-Pollock, Carr, & Nigg, 2002). Thus, it is plausible that children experienced higher perceptual load during visual search and thus filtered out distracter information earlier in processing than did adults, thereby effectively ignoring contextual information. However, functional neuroimaging of the development of spatial selective attention showed few differences in regional recruitment between school-aged children and adults (Booth et al., 2003). Thus, although a contributing factor, immature selective attention alone does not explain children's inability to use the distracter configurations predictively.

Fourth, lack of contextual learning in children likely relates to inefficient higher order associative processes (binding of disparate spatial elements) necessary for predictive use of context on the current task. Encoding and retention of higher order associative information has been attributed to the medial temporal lobes on the basis of studies of amnesia: Spatial contextual learning was impaired in patients with amnesia because of extensive damage

(Chun & Phelps, 1999; Manns & Squire, 2001; Ryan, Althoff, Whitlow, & Cohen, 2000), mild pathology (e.g., older adults with mild cognitive impairment, a subclinical phenotype of Alzheimer's disease; Negash et al., 2007), and pharmacological inactivation (Park, Quinlan, Thornton, & Reder, 2004; Shanks, Channon, Wilkinson, & Curran, 2006) of the medial temporal lobes. Further, spared contextual learning following circumscribed damage to the hippocampal formation suggests that it is mediated by surrounding entorhinal, perirhinal, and parahippocampal areas of medial temporal cortex (Manns & Squire, 2001). Parallel evidence for medial temporal involvement in higher order associative processing comes from studies showing that transitive inference, an ability that can be independent of conscious awareness (Greene, Spellman, Dusek, Eichenbaum, & Levy, 2001), is impaired following entorhinal damage (Buckmaster, Eichenbaum, Amaral, Suzuki, & Rapp, 2004) and is immature in late childhood (Piaget & Inhelder, 1974). It is unknown whether those regions also support learning of semantic knowledge that is known to be impaired in amnesia. Sparing of higher order associative abilities in healthy aging in humans on the current contextual cuing task (Howard et al., 2004) and in monkeys on the transitive inference task (Rapp, Kansky, & Eichenbaum, 1996) indicates that the prefrontal cortex, the lobe most compromised in healthy aging, may not play an essential role. In light of these findings, incomplete maturation of cortical regions in the medial temporal but not frontal lobes is likely to underlie the observed unreliable contextual learning in childhood. Future studies are necessary to elucidate the specific neural correlates using functional neuroimaging and to determine the developmental onset of mature higher order associative learning.

The present developmental findings extend current understanding of human cognition in three ways. First, they highlight the need for consideration of current knowledge of multiple memory systems and brain development by the evolutionary model of cognition. Current knowledge is being increasingly refined by functional neuroimaging studies of implicit and explicit memory development (e.g., Thomas et al., 2004). Second, they provide evidence from childhood development that complements adult models calling for definition of memory systems based on computational considerations rather than on the role of conscious awareness. Third, similarity of our developmental findings to mild cognitive impairment, a condition preceding dementia, rather than to healthy aging suggests that life span developmental trajectories differ for cognitive functions mediated by medial temporal and prefrontal cortex.

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Received July 19, 2006

Revision received November 16, 2006

Accepted December 11, 2006 ■