

# Implicit Spatial Contextual Learning in Healthy Aging

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Three experiments investigated the aging of implicit spatial and spatiotemporal context learning in 2 tasks. In contextual cuing, people learn to use repeated spatial configurations to facilitate search for a target, whereas in higher order serial learning, they learn to use subtle sequence regularities to respond more quickly and accurately to a series of events. Results reveal a dissociation; overall contextual cuing is spared in healthy aging, whereas higher order sequence learning is impaired in the same individuals. This finding suggests that these 2 forms of implicit learning rely on different neural substrates that age differently; the results are also consistent with recent evidence that fronto-striatal circuits are particularly susceptible to decline in health aging.

Research has shown that the spatial relationships among objects in a complex scene play an important role in object recognition (Biederman, Mezzanotte, & Rabinowitz, 1982; Chun & Marois, 2002; Ullman, 1996). Chun and his colleagues have introduced the contextual cuing paradigm to study how spatial context is learned (Chun & Jiang, 1998). People are required to identify the orientation of a target (e.g., a left- or right-pointing horizontal *T*) located in an array of distractors (rotated *L*s) on each of a series of trials. The spatial configuration of the array elements provides a context that is either determined randomly or repeated across the experiment for some configurations. Results reveal that with practice, people respond faster to repeated than to new configurations (e.g., Chun, 2000; Olson & Chun, 2002; Peterson & Kramer, 2001), suggesting that they learn the invariance between the locations of the array elements and the target location in the repeated configurations. Furthermore, Chun and his colleagues demonstrated that this learning is implicit in that people do not develop declarative knowledge of the invariance. In fact, they are unable either to recognize the repeated configurations (Chun, 2000) or to guess the target location in the repeated displays (Chun & Jiang, 2003) in an explicit test, despite revealing knowledge of spatial context in their reaction times (RTs). In the present research we investigated whether contextual cuing changes with healthy aging.

No published studies have investigated the aging of contextual cuing, and it is not possible to develop a clear prediction on the basis of related cognitive or neuropsychological findings. In a study of patients with amnesia, Manns and Squire (2001) reported that a control group of older healthy participants (mean age = 66.9 years) did reveal contextual cuing, but without a younger comparison group it is impossible to know whether they were impaired in doing so.<sup>1</sup> The voluminous literature on visual search has shown that older people can use display characteristics to guide their search to likely target locations (Atchley & Kramer, 2000; Greenwood, Parasuraman, & Haxby, 1993), but in some cases they do so less effectively than young people (Fisk & Rogers, 1991; Madden, Gottlob, & Allen, 1999). Hence, we know that older people can learn to use simple cues for target location, but we do not know if age deficits occur in learning more complex spatial contexts as in contextual cuing. The fact that age-related impairments occur in a variety of spatial memory tasks (e.g., Uttl & Graf, 1993) suggests that deficits in contextual cuing may occur with healthy aging. On the other hand, there is considerable evidence that many implicit learning tasks are spared in healthy aging (Prull, Gabrieli, & Bunge, 2000). Because contextual cuing involves implicit learning, one could also argue that age-related deficits will not occur. There is growing evidence that contextual cuing involves the medial temporal lobe (see Chun & Jiang, 2003). However, this does not permit an unambiguous prediction because the degree to which medial temporal lobe structures decline in healthy aging is controversial (e.g., Peters, 2002; Raz, 2000).

Hence, a credible argument can be made for either age constancy or age deficits in contextual cuing. In the present article we report three experiments to distinguish between these possibilities. In the first experiment we compared young and healthy older people in a standard contextual cuing task. The results show that although age deficits do occur for some individuals, overall, con-

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<sup>1</sup> Two posters presented at the April 2002 Cognitive Aging Conference suggest that contextual cuing is spared. One poster was a preliminary report of the present data (J. H. Howard, Howard, Dennis, Vaidya, & Japikse, 2002), and the other compared the role of context and abrupt onset in capturing attention (Peterson, Kramer, & Colcombe, 2002).

textual cuing is spared in healthy aging. In the second experiment we show that this sparing cannot be explained by the large overall difference in RT between the two age groups. Finally, in the third experiment we show that the same individuals who show age constancy in contextual cuing reveal age deficits in learning spatiotemporal context in a modified serial RT (SRT) task.

## Experiment 1

### Method

**Participants.** Thirty-six young and 36 older volunteers participated. The young participants were college students recruited by flyers placed on the campuses of Georgetown (18 students) and the Catholic University of America (18 students), and the older participants responded to advertisements placed in the Health section of *The Washington Post*. None of the participants had been in a similar study. Each was paid for participating in the 1.5-hr session. As may be seen in Table 1, the two age groups were well matched in gender distribution, vocabulary, and self-rated health. The older participants were highly educated, but, as is typical, they performed more poorly than the young participants on several neuropsychological tests from the Wechsler Adult Intelligence Scale (3rd ed.; Wechsler, 1997a) and the Wechsler Memory Scale (3rd ed.; Wechsler, 1997b).

**Design.** The design was a  $2 \times 2 \times 6$  (Age Group  $\times$  Configuration  $\times$  Epoch) mixed factorial, with age group (young vs. older) as a between-subjects variable and configuration (repeated vs. new) and epoch (1 through 6) as within-subjects variables.

**Stimuli and apparatus.** The stimuli consisted of 12-element arrays of 11 distractors and a single target shown on an Apple iMac 15-in. (38-cm) monitor as white characters on a gray background. The target was a horizontal *T* with the tail pointing either left or right, and the distractors were *L*s randomly rotated by 0°, 90°, 180°, or 270°. The *L* leg was offset by 3 pixels to increase similarity with the target, as used in Chun and Phelps (1999), Experiment 2. Each element subtended approximately 1.1° of visual angle at a viewing distance of 56 cm. Arrays were generated by randomly placing the 12 items into cells of an invisible  $6 \times 8$  (rows  $\times$  columns) grid. Across arrays, target location was balanced for eccentricity with respect to the center of the screen as well as for left and right screen half. Targets never appeared in the four center cells or at the extreme

corners of the display grid. Every element was randomly repositioned within its cell by  $\pm 2$  pixels along each axis to avoid colinearity with other elements. A set of 12 arrays was constructed for repeated presentation across the experiment (details are given below). Individuals within each age group received a different set of new and repeated configurations, but the same sets were used across groups with their presentation order randomized.

**Procedure.** Participants signed an informed-consent form approved by the institutional review boards of both Georgetown University and The Catholic University of America. The experimental task was the same as that used by Chun and his colleagues (e.g., Chun & Jiang, 1998). People completed a 24-trial practice block after receiving instructions. Trials began with a white fixation dot (approximately 0.5°) centered on the screen. After 1 s the dot was replaced by a search array and the participant was to press a key indicating the target orientation (*z* for left and */* for right pointing). They were told to “locate the ‘T’ on the screen, determine which way it is facing and press the key that corresponds to that direction as QUICKLY and as ACCURATELY as possible” and were informed that “an occasional error is acceptable (e.g., one error per block of 24 trials).” Auditory feedback was provided after every response (a beep or tone to signal correct or error responses, respectively). A different search array was presented on each trial in the practice block.

Participants completed 30 learning blocks of 24 trials each. Learning was similar to practice except that only 12 of the search arrays were new in each learning block (new configurations). The remaining 12 arrays (repeated configurations) were repeated across blocks, appearing once in each block. The repeated configurations predicted the location of the target element, but not its orientation. Presentation order was randomized within blocks, and people were encouraged to take a short break between blocks. As in previous studies (Chun & Phelps, 1999; Manns & Squire, 2001), trials on which a response did not occur within a 6-s time-out interval were aborted—a tone sounded, and the experiment went on to the next trial.

After the final learning block, people were asked a series of questions to obtain insights into their strategy and their declarative knowledge of the task. The first three questions were open-ended: (a) “Do you have anything to report regarding the task?” (b) Did you notice anything special about the task or the material? (c) “Did you notice anything special about the way in which the stimuli were presented? If so, please explain.” The last three questions asked specifically about repetitions: (d) “Did you notice whether

Table 1  
*Participant Characteristics*

Characteristic	Young			Older			<i>t</i> (70)
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	
Gender							
Male	18			17			
Female	18			19			
Age		19.92	1.57		71.92	4.53	65.04***
Education (years)		13.97	1.20		17.22	5.61	7.01***
Self-rated health <sup>a</sup>		4.47	0.62		4.19	0.82	1.58
WAIS-III Digit Copy		126.44	12.22		103.25	25.86	4.75***
WAIS-III Vocabulary		33.76	10.49		35.58	7.59	0.83
WMS-III Digit Span		22.47	3.46		20.28	4.29	2.34*
Computation Span Test <sup>b</sup>		5.50	2.36		2.53	1.83	5.79***
WMS-III Logical Memory I Recall		45.15	10.53		38.97	9.38	2.59*
WMS-III Logical Memory II Recall		31.27	8.22		25.11	7.55	3.25**

*Note.* WAIS-III = Wechsler Adult Intelligence Scale (3rd ed.); WMS-III = Wechsler Memory Scale (3rd ed.).

<sup>a</sup> Health was self-rated on a scale ranging from 1 (*poor*) to 5 (*excellent*). <sup>b</sup> Modeled after Salthouse & Babcock (1991).

\*  $p < .05$ . \*\*  $p < .01$ . \*\*\*  $p < .001$ .

certain configurations (spatial layout or locations of the items) were being repeated from block to block?" (e) "If so, when did you begin to notice this repetition?" (f) "Did you explicitly try to memorize any of the configurations?"

Next, people were given a single 24-trial recognition block, consisting of the 12 repeated configurations and 12 others not presented during learning, in random order. On each trial people judged whether they had seen "a display with items in the same screen positions as this earlier in the experiment." They responded by pressing either a key labeled *yes* or one labeled *no*. They were urged to guess if they were unsure. No feedback was provided.

### Results and Discussion

Incorrect responses occurred on only 2.5% of the trials (2.4% and 2.6% for the young and older groups, respectively). A mean RT was determined separately for correct responses to new and repeated configurations for each block and participant. These were then averaged across blocks to obtain a single RT for each individual and configuration type (new or repeated) on each of 6 five-block epochs. A statistical criterion of .05 was used in all significance tests.

**Response time analysis.** The mean response times are plotted in Figure 1. Although the older people responded more slowly than the young, both groups showed evidence of both skill learning and spatial context learning. This was confirmed by an Age Group  $\times$  Configuration  $\times$  Epoch analysis of variance (ANOVA) with repeated measures on the latter two factors. Skill learning is reflected in the significant main effect of epoch,  $F(5, 350) = 84.24$ ,  $MSE = 0.04$ , whereas the significant main effect of configuration,  $F(1, 70) = 19.25$ ,  $MSE = 0.08$ , and significant Configuration  $\times$  Epoch interaction,  $F(5, 350) = 3.32$ ,  $MSE = 0.02$ , reveal contextual cuing. Furthermore, a significant Age Group  $\times$  Epoch interaction,  $F(5, 350) = 2.80$ ,  $MSE = 0.04$ , indicates that the young group showed a greater overall improvement in RT with practice. This suggests that the young people showed somewhat greater skill learning than the older people. In contrast, the fact that the three-way interaction did not approach significance indicates that the two groups showed equivalent contextual cuing. Furthermore, separate Configuration  $\times$  Epoch ANOVAs carried out on the two groups revealed significant main effects of configuration for both groups,  $F(1, 35) = 15.24$ ,  $MSE = 0.075$ , and

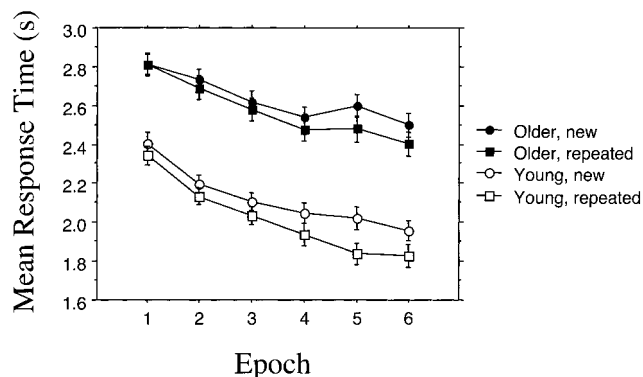


Figure 1. Mean response time (in seconds) as a function of epoch for new and repeated configurations for both young and older groups in Experiment 1.

$F(1, 35) = 5.31$ ,  $MSE = 0.076$ , for the young and older groups, respectively, confirming that both did show contextual cuing. The substantial difference in overall RT between young (mean RT = 2,071 ms) and older (mean RT = 2,603 ms) groups was also significant,  $F(1, 70) = 64.87$ ,  $MSE = 0.94$ .

These findings suggest that contextual cuing is preserved in healthy aging. However, it is possible that the contextual cuing effect we found for older participants was inflated by their slower overall responding. To investigate this possibility, we calculated the cuing effect for each individual normalized by the RT to new configurations,  $[(\text{new} - \text{repeated})/\text{new}]$ , for each epoch. An Age Group  $\times$  Epoch ANOVA carried out on these data revealed a significant main effect of epoch,  $F(5, 350) = 4.32$ ,  $MSE = 0.007$ , but neither the main effect of age group,  $F(1, 70) = 2.25$ ,  $MSE = 0.029$ , nor the age group by epoch interaction,  $F(5, 350) < 1.00$ ,  $MSE = 0.007$ , was significant. Hence, the age constancy we obtained for contextual cuing occurs even when a proportional measure is used.

**Error analysis.** Although people in both groups made relatively few errors (2.5% overall), we carried out a similar analysis of the error data. This revealed only a significant main effect of epoch,  $F(5, 350) = 5.54$ ,  $MSE = 0.001$ , reflecting an overall decrease in errors with practice (from 3.5% on Epoch 1 to 1.9% on Epoch 6).

**Time-out analysis.** The 6-s time-out criterion we used resulted in 3.3% of the trials being aborted. Because time-out errors are obviously related to response latency, one might expect the pattern of time-out errors to mirror that reported above for response time. Figure 2 shows the mean proportion of time-out errors by group and configuration over sessions. As expected, these results are reminiscent of the RT data, but with a floor effect for the young group. The older group experienced more time-outs than the young, the number of time-outs decreased with practice, and more time-outs occurred for new configurations than for old. An ANOVA revealed results very similar to those found for RT. The main effects of age group,  $F(1, 70) = 39.73$ ,  $MSE = 0.008$ ; epoch,  $F(5, 350) = 36.37$ ,  $MSE = 0.001$ ; and configuration,  $F(1, 70) = 4.37$ ,  $MSE = 0.001$ , as well as the Age Group  $\times$  Epoch interaction,  $F(5, 350) = 3.83$ ,  $MSE = 0.001$ , were all significant.

Because more responses timed out for new than for repeated configurations, mean response time underestimates the search time to a greater degree for new than repeated configurations. Furthermore, because the disparity in time-outs for new and repeated configurations is larger for the older than for the young participants (see Figure 2), this underestimate is greater for the older than the young group. Thus, in the present study response time provides a conservative estimate of spatial context learning, particularly for the older participants, and these findings support the conclusion that contextual cuing is preserved in healthy aging.<sup>2</sup>

<sup>2</sup> We also reanalyzed the RT data using median rather than mean RTs. This revealed a pattern of results nearly identical to that reported for the means. The only difference was that the epoch by age group interaction was not significant for the median RTs as it was for the mean RTs. In other words, the two groups were even more similar in the medians analysis than in the means analysis.

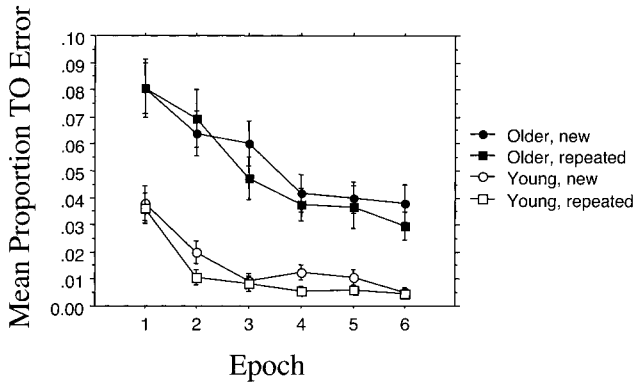


Figure 2. Mean proportion of time-out (TO) errors (greater than 6 s) as a function of epoch for new and repeated configurations for both young and older groups in Experiment 1.

*Interview.* Comments from the postexperimental interview were examined for insight into the strategies people used. There was a wide range of responses to the three open-ended questions with people frequently indicating incorrectly that the target did not occur on some of the trials. Only 3 participants (2 older and 1 young) volunteered that they thought some displays were repeated. However, 43% of the participants agreed (15 older and 16 young) when asked specifically whether some configurations were repeated. Others simply indicated that they performed the task without noticing repetitions or structure within the displays.

*Recognition analysis.* Previous studies have shown that despite revealing a contextual cuing effect, people are unable to recognize the repeated configurations in a subsequent recognition test, suggesting that learning occurs implicitly (Chun & Jiang, 1999). To investigate if this was also true here, we calculated the hit (responding “familiar” to a repeated configuration) and false-alarm (“familiar” to a new configuration) rates on the recognition block for each person. The hit and false-alarm rates were nearly identical for the young (hit = .57, false alarm = .55) and older (hit = .54, false alarm = .56) groups. This was confirmed in an Age Group  $\times$  Trial Type (hit, false alarm) ANOVA in which none of the effects approached significance. Thus, as in previous studies, context learning was implicit for both the young and older participants.

As we reported above, when asked in the interview, nearly half of the participants indicated that they were aware that some configurations were repeated. We decided to investigate whether answers to this question were related to recognition accuracy by comparing the hit and false-alarm rates separately for the aware and unaware participants (see Figure 3). The figure suggests that awareness was related to recognition accuracy because both the young and older aware participants produced slightly more hits than false alarms (.63 vs. .56), whereas the reverse was true for the unaware participants (.50 vs. .54, for hits and false alarms, respectively). This was supported in a three-way ANOVA that revealed a significant main effect of awareness,  $F(1, 68) = 4.43$ ,  $MSE = 0.048$ , and a significant Awareness  $\times$  Hit versus False Alarm interaction,  $F(1, 68) = 5.65$ ,  $MSE = 0.021$ .

Although the aware participants revealed only a very minimal recognition advantage over their unaware colleagues, this finding

raises the possibility that people adopt different strategies in carrying out the task. The aware people may be actively searching for repetitions, whereas the unaware may focus more on locating the target on each trial. In the following section we describe our investigation of the possibility that the contextual cuing effect may also be related to awareness.

*Awareness and response time.* Figure 4 shows the RT data of Figure 1, split by awareness, with the aware people shown in the upper graph and the unaware in the lower graph. These results suggest that awareness is related to contextual cuing. The most striking aspect of these data is that the 15 older people who expressed awareness (solid points, upper graph) showed no contextual cuing effect. Three-way (Age Group  $\times$  Epoch  $\times$  Configuration) ANOVAs were carried out separately on the aware and unaware individuals. These analyses confirmed the above observation in revealing a significant Configuration  $\times$  Age Group interaction for the aware group,  $F(1, 29) = 4.24$ ,  $MSE = 0.058$ , but not for the unaware group. Furthermore, although the three-way interactions did not reach significance for either group, the four-way interaction (Awareness  $\times$  Age Group  $\times$  Epoch  $\times$  Configuration) in an omnibus analysis of these data was marginally significant,  $F(5, 240) = 2.09$ ,  $MSE = 0.020$ , despite the relatively low power one would expect for this test.

Thus, unlike young people and unaware older people, older participants who expressed awareness that some configurations were repeated did not show contextual cuing. This is consistent with the strategic difference we suggest above as well as with other results from our laboratory. In particular, we found that explicit instructions to search for a regularity in an SRT task impaired implicit learning for older but not young people (D. V. Howard & Howard, 2001). Hence, if awareness reflects an explicit search for repetition, then this strategy may have interfered with context learning for older people here as it does in sequence learning. However, in the present study we cannot determine whether this reflects interference with learning per se or merely disruption of performance and the expression of learning (see Frensch, Lin, & Buchner, 1998; Seidler et al., 2002; Willingham, Greenberg, & Thomas, 1997). Before considering the implications of these findings in more detail, we return to the overall response time difference between young and older people in Experiment 2.

## Experiment 2

Chun and his colleagues have found that contextual cuing is larger when the search task is made more difficult by increasing the similarity of the distractors to the target (e.g., Chun & Phelps, 1999). This raises the possibility that in the first experiment the slower responding of the older people may have magnified their cuing effect, thereby masking a true age deficit. Although our analysis of proportional RTs suggested otherwise, we investigated this further in Experiment 2 by testing a group of young people in a more difficult version of the contextual cuing task in which they responded as slowly as older people did in the first experiment. This was achieved by increasing the leg offset on the distractors ( $L_s$ ) from 3 (Experiment 1) to 5 pixels, making them appear more like the target ( $T$ ). If the age constancy observed in Experiment 1 is an artifact of the slower responding by older people, then an age

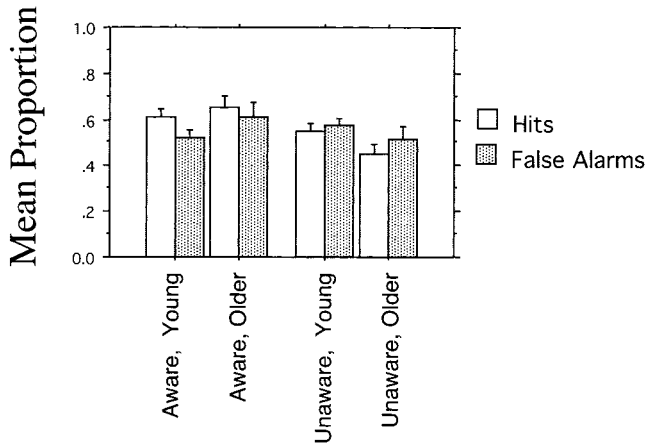


Figure 3. Mean proportion of hits and false alarms on the recognition trials for young and older groups in Experiment 1 split by aware and unaware participants.

deficit should emerge when the RT-matched young group in this experiment is compared with the older group from the first experiment.

### Method

**Participants.** Eighteen paid undergraduates at the Catholic University of America participated. None had been in a similar study.

**Design.** The design was a  $2 \times 6$  (Configuration  $\times$  Epoch) repeated measures factorial.

**Stimuli and apparatus.** These were identical to Experiment 1 except that the distractor ( $L$ ) tail was offset by 5 rather than 3 pixels, rendering the task more difficult.

**Procedure.** The procedure was identical to that used in Experiment 1.

### Results and Discussion

**Response time analysis.** Five people indicated that they were aware of the repeating configurations. Because these individuals showed evidence of explicit recognition (see below), further analyses were carried out on only the 13 unaware people. A mean correct response time was determined for each repetition-unaware person on each five-block epoch separately for the new and repeated configurations. These means are plotted, together with the unaware older group data from Experiment 1, in Figure 5. The graph indicates, and statistics confirm, that the increase in task difficulty succeeded in matching the initial response times of the young-difficult group to the older group in the first experiment,  $t(66) = 1.27$ . It also suggests that, despite this, the slowed young did not reveal greater contextual cuing than the older people. These observations were tested statistically in a Group  $\times$  Configuration  $\times$  Epoch ANOVA that produced significant main effects of epoch,  $F(5, 160) = 18.68$ ,  $MSE = 0.047$ , and configuration,  $F(1, 32) = 6.54$ ,  $MSE = 0.118$ , and a marginally significant Epoch  $\times$  Configuration interaction,  $F(5, 160) = 1.91$ ,  $MSE = 0.025$ . Most important for our present purposes, however, neither the main effect nor any of the interactions with age group approached significance. Thus, the age constancy of contextual cuing shown in Experiment 1 cannot be explained by age differences in overall RT.

**Error analysis.** The slowed young people in this experiment made significantly more response errors ( $M = 7.3\%$ ) than both the older ( $M = 2.6\%$ ),  $t(52) = 4.31$ , and the young people ( $M = 2.4\%$ ),  $t(52) = 4.53$ , on the easier task in Experiment 1. Furthermore, the pattern of these errors in Experiment 2 mirrored the response time results in revealing a decrease across epochs,  $F(5, 265) = 5.21$ ,  $MSE = 0.001$ , as well as greater accuracy for repeated than new configurations,  $F(1, 53) = 10.72$ ,  $MSE = 0.001$ , that increased with practice,  $F(5, 265) = 2.60$ ,  $MSE = 0.001$ . The higher error rate reflects the greater difficulty of the 5-pixel task and suggests that response errors do reveal evidence of contextual learning when a difficult search task is used.

**Time-out analysis.** The more difficult task used here led to significantly more time-outs than did the simpler task in Experiment 1 ( $M_s = 1.4\%$  and  $3.6\%$  for the young participants in Experiments 1 and 2, respectively),  $t(52) = 5.14$ . The time-out rate for the slowed young group ( $M = 3.6\%$ ) did not differ significantly from that observed for the older group in Experiment 1 ( $M = 5.2\%$ ),  $t(52) = 1.84$ . Although the pattern of time-outs resembled the response time and response error findings in this experiment, only the main effect of epoch reached significance,  $F(5, 265) = 34.48$ ,  $MSE = 0.001$ .

**Recognition analysis.** The five repetition-aware people made significantly more hits than false alarms on the recognition test (.63 vs. .40, respectively),  $t(4) = 2.89$ , indicating that they had acquired explicit knowledge of at least some of the repeated configurations. Although the 13 unaware people also had a greater

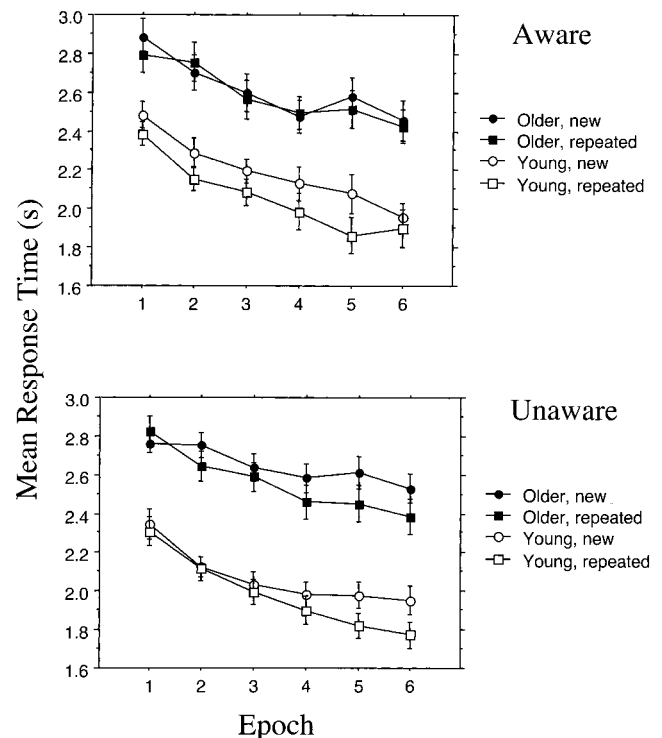


Figure 4. Mean response time (in seconds) as a function of epoch for new and repeated configurations for both young and older groups in Experiment 1, split by aware and unaware participants.

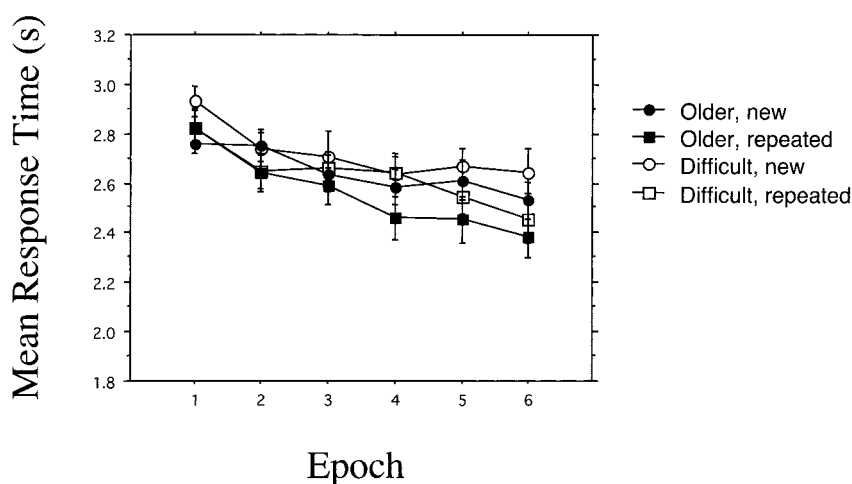


Figure 5. Mean response time (in seconds) as a function of epoch for new and repeated configurations for the young in Experiment 2 and the older group in Experiment 1.

hit than false-alarm rate, this difference was not statistically significant (.55 vs. .49),  $t(12) = 1.60$ . Hence, the unaware participants who performed the more difficult task did not gain explicit knowledge of the repeated configurations.

### Experiment 3

The first two experiments demonstrate age constancy in contextual cuing. This finding suggests that spatial context learning is preserved in healthy aging. However, age constancy is not always found in context learning. For example, age-related deficits occur on the Continuous Performance Test (Braver & Barch, 2002) in which responding to a target event is conditioned on its context—the presence of a preceding “cue word.” A number of previous studies have observed age deficits in spatiotemporal context learning using variations on the popular SRT task (see Prull et al., 2000). In the original SRT task, people respond to each of a series of four spatial locations by pressing a corresponding key (Nissen & Bullemer, 1987). Unknown to the learner, the locations follow a simple repeating sequence. Results provide evidence of learning because people speed up with practice on the repeating sequence but respond more slowly when the regularity is replaced by random trials. In this case the context is spatiotemporal because the predictability of any event location is determined by events that occurred in the recent past.

Previous aging research using the SRT task has shown that although high-ability older adults learn simple regularities as well as do young adults (Frensch & Miner, 1994; D. V. Howard & Howard, 1989, 1992; Salthouse, McGuthry, & Hambrick, 1999), age deficits occur when more subtle, higher order sequences are used (Curran, 1997a; Curran, Smith, DiFranco, & Daggy, 2001; Feeney, Howard, & Howard, 2002; D. V. Howard & Howard, 2001; J. H. Howard & Howard, 1997). For example, we have demonstrated age-related learning deficits for sequences in which alternate stimuli followed a repeating pattern, with the remaining stimuli selected at random (J. H. Howard & Howard, 1997). This alternating SRT (ASRT) task requires learning of higher order temporal relationships, in that all individual events and pairs of

events occur equally often. Curran (1997a) reported similar age deficits for sequences in which each event is predicted by the previous two. These findings suggest that older people have difficulty in learning contextual relationships among temporally non-contiguous events.

In Experiment 3 half the participants in Experiment 1 were tested in an ASRT task to determine whether age deficits occur in spatiotemporal context learning for a group that showed age constancy in contextual cuing. A dissociation would strengthen the conclusion that age constancy occurs in spatial contextual cuing. It would also support the argument that older people learn spatial relationships among simultaneous stimuli more readily than they do relationships among temporally discontinuous stimuli.

### Method

*Participants.* Eighteen older people (9 female) and 18 college students (9 female) from Experiment 1 returned for a second session of testing on a different day.<sup>3</sup>

*Stimuli and apparatus.* Four open circles (0.5° each) were displayed horizontally on the iMac computer screen. The entire display subtended 12° of visual angle at the 56-cm viewing distance. An event occurred when an open circle became solid black. Four labeled keys were used for responding with the middle and index finger of each hand. Target locations were determined by a repeating eight-element structure in which fixed and random locations alternated. Three participants in each group were assigned one of the six unique permutations of the fixed sequence locations (i.e., *ArBrCrDr*, *ArBrDrCr*, *ArCrBrDr*, *ArCrDrBr*, *ArDrBrCr*, *ArDrCrBr*, ordered from left to right). On random trials, the events were sampled from a uniform distribution such that the four locations were equally likely. Hence, unlike in many previous sequence learning studies, the same event could repeat on immediately successive trials.

*Design.* The design was a  $2 \times 2 \times 4$  (Age Group  $\times$  Trial Type  $\times$  Epoch) mixed factorial, with age group (young vs. older) as a between-

<sup>3</sup> Analysis of the contextual cuing data (Experiment 1) from the 36 people who also participated in Experiment 3 revealed a pattern of results identical to that reported for the full group in Experiment 1.

subjects variable and trial type (pattern vs. random) and block (forty 90-trial blocks) as within-subjects variables.

**Procedure.** People were seated at the computer and read instructions regarding the task. The sequence regularity was not mentioned. Two 20-block sessions were completed with a rest period between sessions. Each block began with 10 random trials followed by 80 learning trials. On each trial one of the circles darkened until a correct response occurred. Response time was measured from target onset to the first response. The next stimulus followed the response after a fixed 120-ms interval. People received feedback at the end of each block to encourage about 92% accuracy. In all, each person responded to 3,600 learning trials across the two sessions.

After completing the learning blocks, people were given a single recognition block in which they observed a sequence of 16 events on each of 20 trials. After observing the sequence, people were asked to evaluate whether it had occurred during the response trials using a scale of 1 (*certain it did not*) to 4 (*certain it did*). On half the trials the events consisted of two passes through the alternating sequence that was used on the response trials (e.g., *BrCrArDr*, beginning at a random starting point). On the remaining trials the events were produced by a foil sequence made up of the alternating response sequence in reverse (i.e., *DrArCrBr*, again from a random starting point). The regularity was not mentioned, and no feedback was provided.

Following recognition, people completed a sorting task. They were given a deck of 64 cards, each of which portrayed three successive trials as three rows of four circles each, with one circle darkened on each trial (the event). There was 1 card for each of the 64 possible three-trial sequences, or triplets. People were asked to examine each card carefully and sort it into one of three categories, reflecting the frequency with which that triplet occurred during the experiment (*most frequent, somewhat frequent, or least frequent*). In previous research we have shown this sorting task to be a good indicator of explicit knowledge in the ASRT task (Japikse, Howard, & Howard, 2001).

The experiment concluded with an interview to probe people's declarative knowledge of the sequence. People were asked a series of increasingly specific questions, ranging from "Do you have anything to report regarding the task?" to "Did you notice any regularity in the way the stimulus was moving on the screen?" Finally, they were told that there was in fact a regularity in the sequences they observed and that it occurred on every other trial. They were then asked to color in one in each of a series of four circles "to depict the predictable events in their sequence."

## Results and Discussion

Median RTs were determined separately for correct pattern and random trials on each block. These were then averaged across blocks to obtain a mean RT for each individual and trial type (pattern or random) in each 10-block epoch. A similar data reduction was performed on accuracy.

**Trial type effects on speed and accuracy.** To examine people's sensitivity to spatiotemporal context, we compared performance on the predictable pattern trials with that on unpredictable random trials across epochs. In Figure 6 the mean RT (upper graph) and accuracy (lower graph) data for both groups are plotted. As expected, older people responded more slowly,  $F(1, 34) = 41.64$ ,  $MSE = 37,376.137$ , and more accurately,  $F(1, 34) = 9.88$ ,  $MSE = 0.008$ , than did the young overall. More important, however, both young and older participants showed evidence of spatiotemporal context learning because pattern and random trials diverge in both speed and accuracy with practice. This was confirmed by significant Trial Type  $\times$  Epoch interactions,  $F(3, 102) = 4.36$ ,  $MSE = 32.671$ , and  $F(3, 102) = 11.03$ ,  $MSE = 1.92E-4$ , for response time and accuracy, respectively. Although

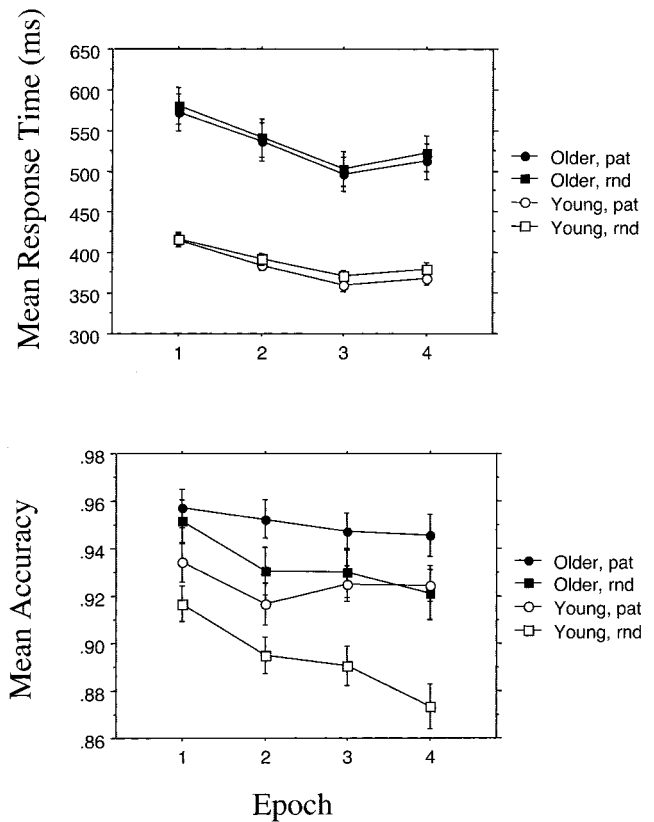


Figure 6. Mean response time (in milliseconds) and accuracy as a function of epoch on pattern (pat) and random (rnd) trials for both young and older groups in Experiment 3.

both age groups showed context learning, the young showed significantly greater learning than the older group as revealed by significant three-way interactions,  $F(3, 102) = 3.03$ ,  $MSE = 32.67$  (response time), and  $F(3, 102) = 3.01$ ,  $MSE = 1.92E-4$  (accuracy). There were also significant main effects of epoch and trial type on both measures as well as a significant trial type by age group interaction for accuracy. These results are consistent with a number of previous studies in demonstrating age-related deficits in higher order sequence learning (Curran, 1997a; Feeney et al., 2002; D. V. Howard & Howard, 2001; J. H. Howard & Howard, 1997). These findings also provide evidence for a dissociation between contextual cuing and higher order sequence learning in healthy older people.

**Expectancy-based errors.** The analyses of accuracy carried out so far were based on the relative frequency of errors on pattern and random trials. In this section, we ask what proportion of the errors that do occur are expectancy based (i.e., consistent with the spatiotemporal structure of the sequence). Because errors on pattern trials are structure inconsistent by definition, this analysis focuses on random trials. We defined consistency in terms of the triplet structure of the sequence because, in earlier work, we showed that, without being aware of doing so, people become sensitive to the relative frequencies of three consecutive events, or triplets (J. H. Howard & Howard, 1997). Hence, for the sequence *ArDrCrBr . . .*, if the events *AB* occur on trials  $n - 2$  and  $n - 1$ ,

a person would be more likely to expect a *D* on trial *n* than a *C* because *ABD* is a structure-consistent triplet whereas *ABC* is not. This expectancy would be correct for pattern trials but incorrect for 75% of the random trials. Although people are quite accurate on random trials (*M*s = 92% and 94% overall for young and older participants, respectively), some errors do occur.

The mean proportion of structure-consistent, random trial errors was calculated for young and older people. These data indicate that although both young (mean proportion = .38) and older participants (mean proportion = .30) made significantly more structure-consistent errors than would be expected by chance,<sup>4</sup>  $t(35) = 9.61$  and  $t(35) = 2.98$ , for young and older participants, respectively, the young produced significantly more of these than the older participants,  $t(70) = 3.34$ . Thus, the age deficit in spatiotemporal context learning is seen in the kinds of errors people make as well as in the difference in performance between types of trials.

*Recognition analysis.* The recognition data were analyzed by determining hit (responding with a 3 or 4 to a target) and false-alarm (responding 3 or 4 to a foil) rates for each individual. The hit and false-alarm rates were nearly identical for both the young (hit = .50, false alarm = .49) and older (hit = .54, false alarm = .56) groups. This was confirmed by a two-way ANOVA that yielded no significant effects. Thus, people were unable to express knowledge of the sequence structure in an explicit recognition task, despite revealing sensitivity to it in their responding. This is consistent with previous findings in revealing that learning in the ASRT task is implicit.

*Sorting task analysis.* To determine whether people were able to judge explicitly the relative frequency with which various triplets occurred, we calculated the mean proportion of times structure-consistent and -inconsistent triplets were sorted into the *most often*, *often*, and *least often* categories. An ANOVA carried out on these data revealed only a significant main effect of rating category, indicating that neither young nor older people were able to distinguish the consistent and inconsistent triplets in their sorting. Hence, in keeping with our previous findings, people were not able to express their knowledge of the temporal structure in an explicit sorting task, adding to the evidence that learning occurs implicitly.

*Interview.* As in our previous research with this task, responses on the postexperimental interview revealed no evidence of declarative knowledge. No one recognized the alternating structure of the sequences, and, although many people thought that they must be regular (13 young and 9 older), none were able to describe the regularity. Several of these people inaccurately thought that events were likely to repeat, and most described something that had no apparent relationship to the sequence they experienced. Even after being told about the alternating structure of the sequence and being encouraged to guess, people could not identify the four repeating events with greater than chance accuracy.

With regard to strategy, people often reported trying to avoid thinking about what they were doing. For example, some reported strategies such as “relax and allow my fingers to follow what my eyes see without thinking about it” or “try to stop thinking and just try to respond like a robot.” Others mentioned the role of anticipation: “only anticipated the targets subconsciously,” and “sometimes I pressed the wrong button because I anticipated where the dot would be.” Furthermore, there was no systematic difference

between the comments of the older and young participants that might account for the age deficits we observed. Thus, the interview is consistent with the recognition and sorting data in revealing no evidence of explicit, declarative knowledge of the sequence structure.

## General Discussion

These findings demonstrate a dissociation between spatial context learning in the contextual cuing task and spatiotemporal context learning in the ASRT task. Overall age constancy was observed in contextual cuing, whereas age deficits occurred for the same individuals in higher order visuospatial sequence learning.

It is unlikely that this dissociation reflects differences in task difficulty or fatigue. With regard to task difficulty, there is no independent evidence that sequence learning is more difficult than contextual cuing for either age group. On the contrary, most participants reported that contextual cuing was more difficult, an observation consistent with the substantially longer response times that occur in this task. Furthermore, older people were actually more accurate than young people on the sequence learning task, and the young participants who were challenged with the more difficult contextual cuing task in Experiment 2 revealed no evidence of impaired learning. Finally, we have shown in previous work that the age deficit in higher order sequence learning persists even after extensive practice (D. V. Howard et al., in press), a finding inconsistent with a simple task-difficulty argument.

A fatigue account also seems improbable. Although the ASRT task was always performed after contextual cuing in the present study, raising the possibility of greater fatigue, the two tasks were administered on separate days and each required less than an hour to complete. Furthermore, the sequence learning deficit we observed was not unexpected. A number of previous studies using higher order sequences have shown similar age deficits (Curran, 1997a; Feeney et al., 2002; D. V. Howard & Howard, 2001; Negash, Howard, Japikse, & Howard, 2003). Thus, the dissociation reported above is not likely to reflect either simple differences in task difficulty or participant fatigue.

So why does the dissociation occur? There is growing evidence that contextual cuing and sequence learning are mediated by different underlying brain substrates, and the present findings likely reflect differences in the aging of these brain systems. Chun and Phelps (1999) reported impaired contextual cuing in patients with medial temporal lobe lesions that included the hippocampus. Although these patients were described as “hippocampal,” their lesions extended well beyond this structure. In a more recent study

<sup>4</sup> We determined chance by counting the number of possible ways to make a structure-consistent error and dividing by the total number of errors that can occur. To calculate the denominator, we noted that there are four possible responses to each of the 64 event triplets, three of which produce an error. Hence, there are 192 possible errors (64 triplets  $\times$  3 errors). For the numerator, we determined the number of errors that would be structure consistent. Of the 64 possible triplets, 16 are structure consistent ( $4 \times 4 \times 1$ ) and 48 are structure inconsistent ( $4 \times 4 \times 3$ ). Errors occurring for the 16 remaining structure-consistent event triplets are structure inconsistent by definition. For the 48 possible inconsistent event triplets only one of the three error responses will be structure consistent, making a total of 48 structure-consistent errors. Therefore, chance responding will produce one of the 48 structure-consistent errors with probability .25 (i.e., 48/192).



of patients with amnesia, Manns and Squire (2001) demonstrated that although these deficits do not occur when damage is confined to the hippocampus, they do occur when damage extends to surrounding medial temporal lobe structures with accompanying damage to the lateral temporal cortex in some individuals. They concluded that contextual cuing appears to rely on medial temporal lobe structures, but not on an intact hippocampus per se (Manns & Squire, 2001). Preliminary evidence from our laboratory that contextual cuing is impaired in older patients with mild cognitive impairment believed to have extensive medial temporal lobe pathology supports this conclusion (Negash, Howard, Aisen, Ward, & Howard, 2002). Converging evidence has also been reported in a functional magnetic resonance imaging study that showed greater activation in medial temporal lobe structures, including hippocampus and parahippocampal gyrus, for repeated compared with novel configurations (Preston, Saladis, & Gabrieli, 2001).

In contrast to contextual cuing, there is evidence from a variety of sources that spatial sequence learning depends on fronto-striatal-cerebellar circuitry (Prull et al., 2000; Robertson, Tormos, Maeda, & Pascual-Leone, 2001). For example, patients with focal cerebellar or frontal lesions reveal impaired learning in an SRT task (Gomez-Beldarrain, Garcia-Monco, Rubio, & Pascual-Leone, 1998; Gomez Beldarrain, Grafman, Pascual-Leone, & Garcia-Monco, 1999; Gomez Beldarrain, Grafman, Ruiz De Velasco, Pascual-Leone, & Garcia-Monco, 2002) as do individuals with striatal disorders such as Huntington's disease (Willingham, Koroshetz, & Peterson, 1996) and Parkinson's disease (e.g., Dominey & Jeannerod, 1997; Helmuth, Mayr, & Daum, 2000; Jackson, Jackson, Harrison, Henderson, & Kennard, 1995). Converging evidence has been obtained from functional neuroimaging studies (e.g., Grafton, Hazeltine, & Ivry, 1995; Rauch et al., 1997; Seidler et al., 2002) and using transcranial magnetic stimulation (Robertson et al., 2001) with young people. Thus, unlike contextual cuing, the SRT task appears to depend on fronto-striatal-cerebellar circuits, although Curran (1997b) reported evidence that the medial temporal lobe may also be involved when higher order sequences are used (similar to those used in the present study).

The age-related dissociation observed in the present study between a medial temporal lobe task (contextual cuing) and a frontal-striatal-cerebellar task (sequence learning) is consistent with emerging evidence regarding the aging of these brain regions. Although in earlier studies evidence of extensive neural loss in neocortex and hippocampus with increasing age has been reported (Coleman & Flood, 1987), more recent findings indicate little or no neuronal loss to the hippocampus in the absence of neurodegenerative disease (Morrison & Hof, 1997; Peters, 2002; Prull et al., 2000; Raz, 2000). Recent neuroimaging studies of healthy individuals also have revealed little age-related change in volume of the surrounding paralimbic structures (parahippocampal and entorhinal cortices; Raz et al., 1997). Although these results are mixed and the conclusions controversial, the present finding that contextual cuing is preserved in healthy aging is consistent with preserved medial temporal lobe function.

In contrast, there is a growing consensus that the prefrontal cortex is particularly vulnerable to aging in that there are reductions in synaptic density and dendritic arborization even in healthy individuals (see Raz, 2000). These changes are accompanied by corresponding alterations to the neurochemistry of this region. For example, in vivo radioligand imaging studies of healthy older

adults have found age-related declines in the density of dopamine D<sub>2</sub> receptors in frontal lobe structures that correlate with performance on neuropsychological tests of frontal (Wisconsin Card Sorting Test) and motor (finger tapping) function (Volkow et al., 1998). Overall, the widespread evidence for age-related deficits across a range of tasks mediated by frontal lobe function has given rise to the frontal aging hypothesis (West, 1996).

Recently proposed contextual processing deficit theories of cognitive aging also point to frontal lobe and striatal impairment (Braver & Barch, 2002; Li & Srikstrom, 2002). According to these theories, healthy older people experience impaired contextual encoding because of an age-related decline in dorso-lateral prefrontal cortex and dopamine system function. The age deficits we have observed in the ASRT task in this and previous studies are consistent with this perspective. Compared with young people, older adults show an impaired ability to use the temporal context embedded in the higher order sequences.

It is also possible that the dissociation obtained in the present study reflects an age deficit in higher order motor sequencing. Willingham has argued that the SRT task has a strong motor component (Seidler et al., 2002; Willingham, 1999), and previous studies have indicated age-related motor deficits in even very simple motor tasks (Mortimer, 1988). Although this account cannot explain why age constancy occurs in the SRT for simple repeating sequences (D. V. Howard & Howard, 1989, 1992; Salt-house et al., 1999), it is possible that age-related motor deficits only become significant when higher order sequences are used. Because the contextual cuing task does not entail motor sequencing, the possibility that the dissociation observed here reflects age-related impairments in motor sequencing cannot be ruled out.

In summary, we believe that the dissociation between contextual cuing and sequence learning reflects the differential aging of the brain systems underlying the two context learning tasks. Sequence learning depends on the relatively impaired fronto-striatal-cerebellar system, whereas contextual cuing relies instead on relatively preserved medial temporal lobe structures.

Why then did our post hoc analysis reveal age-related deficits in contextual cuing for the aware older people? Because there was no evidence that these "aware" participants actually memorized the repeated configurations, we interpret this to reflect a difference in strategy rather than declarative knowledge. Although this result should be interpreted cautiously, it is possible that aware participants may have adopted a different strategy than those who were unaware. In particular, aware people may have been searching for regularities in the configurations across trials while simultaneously performing the visual search task. The resulting dual-task condition may have interfered with contextual cuing in the older people, but not the young people. Consistent with this, Lindenberger and his colleagues have shown that older people incur greater dual-task costs than young people even for relatively simple cognitive tasks such as memorizing a list while walking (Lindenberger, Marsiske, & Baltes, 2000).

Furthermore, we have reported a similar result for the sequence learning task used in Experiment 3. Older people who were instructed to search for a regularity showed impaired learning compared with both older people who were not so instructed and young people under both intentional and incidental instructions (D. V. Howard & Howard, 2001). We saw this as evidence that implicit sequence learning involves some attention-demanding processes

that suffered when older people attempted the “dual task” of simultaneously searching for a pattern in and performing the button-pressing task. Although this interpretation remains speculative without additional research, it may suggest that contextual cuing entails attention-demanding components at least in older learners. This interpretation is consistent with Jiang and Chun’s (2001) finding that selective attention modulates what is learned in contextual cuing.

In conclusion, we have demonstrated a dissociation between two kinds of implicit learning in healthy aging; contextual cuing is spared, whereas higher order sequence learning is impaired in the same participants. This is consistent with the argument that contextual cuing and sequence learning involve different neural substrates that are differentially influenced by healthy aging.

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