Aging Neuropsychology and Cognition
2003, Vol. 10, No. 2, pp. 108–121

1382-5585/03/1002-108$16.00

Age-Related Differences in Implicit Learning of Non-Spatial Sequential Patterns

Selamawit Negash[1], Darlene V. Howard[1], Karin C. Japikse[1], and James H. Howard, Jr.[2]
[1]Georgetown University, Washington, DC, USA, and [2]The Catholic University of America, Washington, DC, USA

ABSTRACT

This experiment investigated whether there are age differences in implicit learning of non-spatially arranged sequential patterns. We tested 12 young and 12 old participants for five sessions each in a non-spatial alternating serial reaction time (ASRT) task, in which predictable pattern events alternated with random, unpredictable ones. People of both ages were able to learn the sequence, but older people showed less pattern sensitivity than younger ones. Neither group was able to exhibit declarative knowledge of the pattern or to discriminate between pattern and random sequences on a recognition test, suggesting that the learning was indeed implicit. These findings indicate that the age deficits previously observed in the learning of spatial sequences are not due solely to age-related deficits in visuo-spatial attention or control of eye movements, but rather reflect a more general deficit in the ability to learn subtle sequential regularities.

People need to be sensitive to sequences of events if they are to learn a new language, to type, to play the piano, to operate appliances, or to use new computer software. Developing such sensitivity often calls upon implicit learning, that is, learning about the structure of a stimulus environment without conscious effort to learn and without ability to describe what has been learned (Reber, 1989). Implicit learning is distinct from explicit, conscious forms of learning in which people are aware of what they have learned and can describe it.

Neuroimaging studies and analyses of neuropsychologically impaired patients reveal that implicit and explicit learning are mediated by independent systems and call upon different neural substrates (e.g., Curran, 1998; Knopman & Nissen, 1987). For example, amnesic patients with an explicit system deficit due to damage to the medial temporal lobe reveal normal implicit learning (e.g., Nissen, Willingham, & Hartman, 1989). In contrast, Parkinson's disease patients and patients with focal unilateral lesions to the cerebellum show severe impairment on some forms of implicit learning even though their explicit learning system remains intact (e.g., Gomez-Beldarrain, Garcia-Monco, Rubio, & Pascual-Leone, 1998; Helmuth, Mayr, & Daum, 2000; Jackson, Jackson, Harrison, Henderson, & Kennard, 1995).

Age-related deficits in explicit forms of learning have been well documented, but less is known about implicit learning. Classical conditioning and some kinds of skill learning decline with normal aging, but the results have been mixed for other forms of implicit learning (e.g., Prull, Gabrieli, & Bunge, 2000), including learning sequences of the sort we investigate here.

The task most widely used to investigate implicit sequence learning is the serial reaction

Address correspondence to: Selamawit Negash, Interdisciplinary Program in Neuroscience, Georgetown University, Washington, DC 20007, USA. Tel.: +1-202-687-4900. Fax: +1-202-687-6050. E-mail: negashs@georgetown.edu
Accepted for publication: July 11, 2002.

time (SRT) task developed by Nissen and Bullemer in 1987. In this task, a computer displays four boxes arranged horizontally across the screen, and a stimulus (e.g., an asterisk) appears in one of the boxes. Participants are told to respond to the location of each stimulus by pressing the key under that box as quickly as possible. Typically, what they are not told is that the stimulus follows a predetermined pattern of spatial positions. Implicit sequence learning is said to occur when participants demonstrate knowledge of the pattern by the speed and/or accuracy of their responses, but are unable to explicitly describe what they have learned.

Research on the aging of implicit sequence learning suggests that under some conditions there are age-related deficits. Earlier studies using the original SRT task indicated that implicit learning of sequences does not decline with normal aging (Frensch & Miner, 1994; Howard & Howard, 1989, 1992). However, more recent studies using higher order patterns that follow subtle regularities have reported age deficits (Curran, 1997; Howard & Howard, 1997).

The mechanisms underlying these age deficits in pattern sensitivity are not known. Most explanations, however, assume that implicit learning of relatively complex sequences calls upon mechanisms for detecting co-variations among stimulus events (e.g., Cleeremans, Destrebecqz, & Boyer, 1998). It is further assumed that such co-variation detection draws on limited working memory capacity, in that stimulus events must be activated simultaneously in memory in order for their co-variation to be detected. Aging is accompanied by a decline in processing speed and in working memory capacity, and hence in the number of events that can be activated simultaneously (e.g., Salthouse, 1996). This decline in capacity could be causing the age-deficits in implicit sequence learning (e.g., Curran, 1998; Feeney, Howard, & Howard, 2002; Frensch & Miner, 1994; Howard & Howard, 1997, 2001). Consistent with this explanation, normal aging is accompanied by prefrontal losses which are associated with a decrease in working memory capacity (e.g., Prull et al., 2000), and patients with prefrontal lesions are impaired in sequence learning (Gomez-Beldarrain, Grafman, Pascual-Leone, & Garcia-Monco, 1999).

According to this view, then, the observed age deficits in sequence learning reflect a general decrease in the ability to detect co-variations in the environment, that is, a general learning deficit. However, there are alternative explanations, which assume a more limited domain-specific deficit. Such alternatives gain credence from growing evidence that there are multiple neural systems underlying sequence learning; individuals with circumscribed brain injury show deficits in learning certain kinds of sequences while remaining unimpaired on others (e.g., Goschke, Friederici, Kotz, & van Kampen, 2001).

We seek to rule out one such alternative explanation here, that is, that age deficits in learning spatial sequences result from visuo-spatial deficits that accompany normal aging. So far, all studies of aging and sequence learning have used a spatial task, in which stimuli are laid out spatially on the computer screen and participants are asked to respond to the location of the targets (e.g., Curran, 1997; Frensch & Miner, 1994; Howard & Howard, 1997, 2001). However, evidence from human as well as animal studies suggests that a visuo-spatial attentional deficit accompanies normal aging. For example, older adults exhibit more spatial localization problems compared to younger adults when performing visual search tasks (Owsley, Burton-Danner, & Jackson, 2000). Older adults are slower than young to redirect attention when cues are not valid (Greenwood & Parasuraman, 1994). There is also a relatively larger increase in cerebral blood flow in older adults when performing tasks in which it is necessary to divide attention among display positions, suggesting that these tasks impose higher attentional demands in older people compared to those which do not require visuo-spatial processing (Madden et al., 1997). Further, recent evidence using Transcranial Magnetic Stimulation suggests that the role of the dorsolateral prefrontal cortex during sequence learning is specific for spatial information (Robertson, Tormos, Maeda, & Pascual-Leone, 2001).

In animal model studies, aged rats have been shown, for example, to have deficits in learning on

a five-choice reaction time task in which they are required to shift visuo-spatial attention from one choice location to another, but not on a simpler one-choice task where such visuo-spatial processing is not necessary (Jones, Barnes, Kirkby, & Higgins, 1995). Thus, taken together, these findings suggest the possibility that age deficits in learning spatial sequences could be due to age deficits in visuo-spatial attention, rather than to a generalized deficit in pattern learning.

In addition to covert visuo-spatial deficits, older people also show a decline in the use of overt eye movements to learn a sequence. Eye movement learning plays a role in spatial sequence learning in that it allows people to make valid anticipatory responses, and minimizes the time required to move eyes from one location to another once stimuli appear on the screen (Mayr, 1996). With aging, however, there is evidence of a decline in the control of eye movements. Older people exhibit longer latencies when shifting their eyes in response to a stimulus (Carter, Obler, Woodward, & Albert, 1983), and they also make more saccades when searching for targets (Scialfa & Joffe, 1997). Older adults are poorer than young at actively inhibiting automatic eye movements toward highly salient visual cues (Nieuwenhuis, Ridderinkhof, de Jong, Kok, & van der Molen, 2000). Further, age deficits in visual processing such as peripheral acuity, contrast sensitivity, and luminance sensitivity are also said to contribute to a decline in eye movements in older people (e.g., Crassini, Brown, & Bowman, 1988). Thus, these findings seem to further suggest that the observed age deficits in learning spatial sequences on the SRT task could be due to age-related deficits in the adaptive control of eye movements, rather than to a generalized deficit in sequential pattern learning.

The purpose of this study is to decide between these theoretical accounts by determining whether older people show age deficits in implicit learning of subtle sequential patterns, even when these patterns are non-spatial. To this end, we use a variation of the Alternating Serial Reaction Time (ASRT) task (Howard & Howard, 1997). In the ASRT task, alternating stimuli follow a predetermined pattern while the remaining stimuli are selected randomly. For example, a person assigned the pattern 1432 (where 1 stands for the left-most position and 4 for the right-most), would encounter the following series, where ''r'' stands for a randomly chosen position: 1r4r3r2r1r4r3r2, and so on. Thus, predictable pattern events are embedded in random, unpredictable ones.

In the ASRT task, implicit learning is measured by comparing speed and/or accuracy on pattern trials versus random trials, a difference score we call the trial type effect. If performance on pattern and random trials diverges, then the lowest level of regularity people could have learned is second order (i.e., which triplets are more likely to occur). This is because pattern and random trials do not differ either in 0th order information (i.e., in the frequency with which individual events occur) or in 1st order information (i.e., in the frequency with which individual pairs of items occur). In addition, earlier research using a spatial version of the ASRT task indicates that it yields relatively pure implicit learning in the absence of declarative learning. Even after the extensive training used here, neither young nor older people are able to describe the pattern (e.g., Howard & Howard, 1997, 2001; Howard et al., submitted). Thus, the present study taps the implicit learning of relatively high order and subtle patterns.

We use a non-spatial variation of the ASRT task in this study. Unlike the original ASRT task, where four open circles are evenly spaced across the middle of the screen, in the present non-spatial version, stimuli are target letters (A, B, C, or D) which appear in a box in the center of the screen. This non-spatial stimulus array is modeled on Gomez-Beldarrain et al.'s (1998) adaptation of the original SRT task. This variation has the advantage of minimizing the need to shift visuo-spatial attention from one target location to another, and the use of eye movements to learn the sequence.

Our hypothesis is that age deficits in sequence learning observed in earlier SRT studies are not due to covert and overt visual-spatial deficits, but rather reflect a generalized deficit in the ability to detect co-variations in the environment. Therefore, we predict that there will be age-related deficits in sequence learning even with the non-spatial stimuli used here.

METHOD

Participants

There were 12 young and 12 old participants. The young adults were recruited from the student body of Georgetown University and the old by advertisement in the Health and Senior Sections of the *Washington Post*. All were paid for participation. The mean age of the young group was 20.67 years (range = 19–24, SD = 1.6) and that of the old was 69.33 years (range = 65–79, SD = 4.4). All participants were right handed. Data from 2 additional young participants were discarded because they exceeded the maximum number of days between sessions (described below). Data from 1 older participant were discarded because he did not complete all the sessions. The characteristics of the participants are summarized in Table 1. As the table shows, the age groups did not differ in their years of education, self-rated health, WAIS III vocabulary score, or WMS III Digit Span score. All participants in both age groups earned at least 29 of the total possible 30 points on the Mini-Mental Status Exam, thus indicating that no participant showed signs of dementia. Nonetheless, as is typical, the age groups differed significantly on measures of speed (e.g., WAIS III Digit Symbol), working memory (e.g., WMS III Letter-Number Sequencing, Spatial Span, Computation Span), and verbal memory (e.g., WMS III Verbal Paired Associates Recall).

Design

The design was a $2 \times 2 \times 5$ (Age × Trial Type × Session) mixed factorial, with age (young adults vs. old adults) as a between-subjects variable and trial type (pattern vs. random) and session (1–5) as within-subjects variables.

Stimuli and Apparatus

For the ASRT task, participants were seated in front of an Apple personal computer facing a 13-in. monitor.

Table 1. Mean Participant Characteristics.

	p	Young	Old
Sex			
Female		6	6
Male		6	6
Age (in years)		20.67 (1.56)	69.33 (4.39)
Education (in years)	*ns*	14.58 (1.31)	15.50 (2.54)
Self-rated health[a]	*ns*	4.83 (0.38)	4.36 (0.67)
WMS III Digit Span	*ns*	19.83 (2.82)	17.92 (4.44)
WAIS III vocabulary	*ns*	60.25 (6.68)	59.58 (9.89)
WAIS III Digit Symbol: Coding***	.0002	90.17 (14.24)	64.17 (14.32)
WAIS III Digit Symbol: Pairing**	.0063	16.08 (3.65)	11.17 (4.30)
WAIS III Digit Symbol: Free Recall**	.0098	8.75 (0.62)	7.75 (1.05)
WAIS III Digit Symbol: Copy***	.0002	130.33 (5.06)	100.58 (23.35)
WMS III Letter-Number Sequencing*	.0197	12.75 (1.91)	10.25 (2.86)
WMS III Spatial Span***	< .0001	20.00 (2.2)	13.00 (1.76)
WMS III Mental Control**	.0039	31.81 (4.04)	25.08 (5.69)
Mini-Mental Status Exam	*ns*	29.82 (0.41)	29.41 (0.66)
Computation Span: Total***	.0005	73.33 (51.59)	10.83 (14.34)
Computation Span: Simple***	.0002	62.75 (41.35)	8.00 (12.11)
Computation Span: Absolute***	.0002	5.92 (2.71)	2.08 (1.31)
Benton's Verbal Fluency	*ns*	52.00 (9.89)	47.50 (8.91)
WMS III VPA I: Score*	.0202	24.91 (5.83)	16.33 (9.83)
WMS III VPA I: Slope	*ns*	3.63 (2.33)	2.58 (2.46)
WMS III VPA II: Recall	*ns*	7.00 (2.41)	5.25 (2.56)
WMS III VPA II: Retention	*ns*	80.45 (40.03)	84.66 (59.20)
WMS III VPA II: Recognition	*ns*	24 (0)	24 (0)

Note. Standard deviations are indicated in parentheses. WAIS = Wechsler Adult Intelligence Scale; WMS = Weschler Memory Scale; VPA = Verbal Paired Associates.

[a]Possible responses ranged from 1 (*poor*) to 5 (*excellent*).

*$p < .05$; **$p < .01$; ***$p < .001$. Two-tailed t tests ($df = 22$ for all tests except Mental control, Mini-Mental, and Verbal Paired Associates where $df = 21$). *ns* = not significant.

The computer displayed a 2 cm by 2 cm square box in the center of the screen, and on each trial, a target, one of the four letters (A, B, C, or D) in black upper case 16-font size, appeared in the box. Participants were instructed to place the four fingers of their right hand on the j, k, l, and; keys to respond to targets A, B, C, and D, respectively. For example, if the letter B appeared in the box, they pressed the k key under their middle finger. The letter remained in the box until participants pressed the key that corresponded to it, at which time it disappeared and another letter appeared after a delay of 120 ms. The four response keys were covered with circular blue stickers so that their usual labeling could not be seen, and so as to remind participants of which keys were to be used.

Procedure

Participants completed a consent form and a biographical questionnaire at the beginning of the first session. Then, for the ASRT task, they were seated at the computer and were given the following instructions: ''In this study, we are trying to learn more about how practice affects motor performance. We want to find out just how much people are able to speed their responses when they are given extended practice on a simple reaction time task.'' They were not given any information about the regularity that was embedded in this task. The computer screen displayed a target letter (A, B, C, or D) in a box in the center of the screen, as described above, and the participant's task was to press the key corresponding to the target letter as quickly as possible while maintaining an accuracy level of about 92%.

Participants completed five 1-hr sessions, where each session contained 20 blocks of the ASRT task and each block contained 90 trials (thus, altogether, there were 9000 trials presented to participants over the five sessions). Each block began with 10 random trials (for warm-up), and was followed by 80 experimental trials. These 80 trials consisted of an 8-item sequence, in which pattern trials alternated with random trials, for example, ArBrCrDr (where r stands for random trials), and the 8-item sequence repeated 10 times in a block (Howard & Howard, 1997). One of the following six sequences was given to 2 participants in each age group so that all the possible sequences were represented equally often in each age group: ArBrCrDr, ArBrDrCr, ArCrBrDr, ArCrDrBr, ArDrBrCr, and ArDrCrBr.

At the end of each block, the computer displayed the speed and accuracy information for the most recent block and the immediately preceding block, and guided participants to an accuracy level of about 92% by telling them to focus more on accuracy or on speed as necessary. Participants were also asked to read out their most recent speed and accuracy scores to the experimenter, who in turn told them to focus on accuracy if their accuracy scores on the last three blocks were less than 86%, or on speed if they were greater than 98%. Our purpose in choosing the 92% accuracy was to match the age groups as closely as possible on overall accuracy. In order to minimize fatigue, participants were asked to rest their eyes for at least 30 s in between blocks, and to take additional breaks as needed.

Participants completed the five sessions over the course of several days, with no more than 2 days between sessions and no more than two sessions per day. When they completed two sessions per day, they were required to have a break of at least 45 min between sessions.

In order to investigate more fully how learning can be expressed in this task, we also included a questionnaire at the end of each session and a post-experimental interview at the end of the final session. In addition, we gave two pattern judgment tasks, Recognition and Preference tests, on the final session, prior to the post-experimental interview.[1]

The written questionnaire given at the end of each session contained the following questions:

1. Did you use any strategy to try to improve your performance on the first computer task you performed today (responding to targets on the screen)? If so, what was your strategy?
2. Do you think your strategy worked? Why or why not?
3. Any other comments?

For the Recognition task, participants were shown 20 randomly ordered trials, 10 containing all-random and 10 containing pattern sequences. Each trial consisted of 16 stimuli, where, for pattern trials, the 8-item sequence was repeated twice, and for random trials, the stimuli were all randomly determined. The pattern trials contained the same sequence arrangement as the ones participants encountered during their ASRT sessions. At the end of each trial, the computer displayed the following:

> ''Did this sequence occur before?
> (certain it did not) 1 . . . 2 . . . 3 . . . 4 (certain it did)''

[1]Participants were also given a free generation test after the end of each ASRT task (prior to the end-of-session questionnaire) in which they were asked to create a sequence like the ones to which they had been responding during the ASRT task. No mention was made of the regularity. Data from this test are not included here, however, because analyses yielded unsystematic results. For example, there were no changes over sessions for either age group, suggesting this measure does not detect learning.

Their task was to observe the sequence on each trial closely and indicate their certainty of its occurrence in the previous five sessions by entering numbers 1, 2, 3, or 4 on the numerical keypad. They were told to enter number 4 if they were certain that the sequence occurred before, and to enter number 3 if they were somewhat certain that it occurred. On the other hand, they were to enter number 1 if they were certain that the sequence did not occur before, and number 2 if they were somewhat certain that it did not occur.

Participants were then given the Preference task, where they were also presented with 20 trials, 10 all-random and 10 patterned sequences, and here, the computer displayed the following:

"Rate how much you like this sequence?
(strongly dislike) 1 . . . 2 . . . 3 . . . 4 (strongly like)"

Participants were asked to judge how much they liked the sequence, again by entering numbers 1, 2, 3, or 4 in a similar manner, with 1 representing "strongly dislike" and 4 representing "strongly like."

After completing the computer tasks on the final session, participants were given a post-experimental interview, which contained the following questions:

1. Do you have anything to report regarding the task?
2. Did you notice anything special about the task or the material?
3. Did you notice any regularity in the way the stimulus was moving on the screen? (If the participant answered yes, the experimenter probed for more specifics, and then asked the following.)
4. Did you attempt to take advantage of the regularities you noticed in order to anticipate subsequent targets? If so, did this help?
5. In fact, there was some regularity to the sequences you observed. What do you think it was? That is, try to describe any regularity you think might have been there. (The experimenter encouraged people to describe any regularities at all that they noticed, even if they were vague or unsure.)

In addition, supplementary tasks were administered at the end of each computer session in the following order: Session 1: Weschler Memory Scale III Digit Span and WAIS III vocabulary; Session 2: WAIS III Digit Symbol (Coding, Free Paired, and Copy) and Weschler Memory Scale III Letter-Number Sequencing; Session 3: a health questionnaire (from Christensen, Moye, Armson, & Kern, 1992), Mini-Mental Status Exam (Folstein, Folstein, & McHugh, 1975), Weschler Memory Scale III Spatial Span and Mental Control; Session 4: Benton's Verbal Fluency Form A and Computation Span; Session 5: Weschler Memory Scale III Verbal Paired Associates I & II with several Visual Puzzles (MENSA Mighty Visual Puzzles 1997 [John Brenner Barnes and Nobles Books, NY 1997]) used as fillers during the retention interval of the test.

A .05 level of significance was adopted throughout, with results meeting the .10 level being reported as marginal. *t* tests were always two-tailed.

RESULTS

Did Both Age Groups Learn the Sequence?

In this task, sequence learning is revealed by better performance on pattern trials than on random trials (trial-type effect) on the response time and/or accuracy measures. Figure 1 shows the mean of the median response time for pattern versus random trials across sessions for young and old groups, and Figure 2 shows the mean accuracy. On both measures, the pattern and random trials diverged for both age groups, suggesting that people learned the sequence. With practice, responses speeded up overall, but more so for pattern than random trials. Accuracy remained high on pattern trials throughout all sessions, but declined on random trials.

These observations were confirmed using a three-way repeated measures ANOVA with Age as a between-subjects variable and Session and Trial Type as within-subjects variables. This analysis revealed significant main effects of Trial Type and Trial Type by Session interactions for both measures. For the RT analysis, the Trial Type effect yielded $F(1, 22) = 105.24$, $MSE = 196.50$ and the Trial Type by Session interaction yielded $F(4, 88) = 7.93$, $MSE = 38.81$. For the accuracy analysis, these values were respectively, $F(1, 22) = 227.56$, $MSE = 0.0002$ and $F(4, 88) = 13.53$, $MSE = 0.0001$.

There is also evidence of significant sequence learning when the groups are examined separately. For the young group, a subsequent two way ANOVA on the response time measure revealed a significant main effect of Trial Type, $F(1, 11) = 57.18$, $MSE = 244.81$ and Trial Type $\times$ Session interaction, $F(4, 44) = 6.55$, $MSE = 39.31$. Similarly, on the accuracy measure, the young group showed a significant main effect of Trial Type, $F(1, 11) = 194.09$, $MSE = 0.0003$, and a Trial Type $\times$ Session interaction, $F(4, 44) = 9.56$, $MSE = 0.0002$.

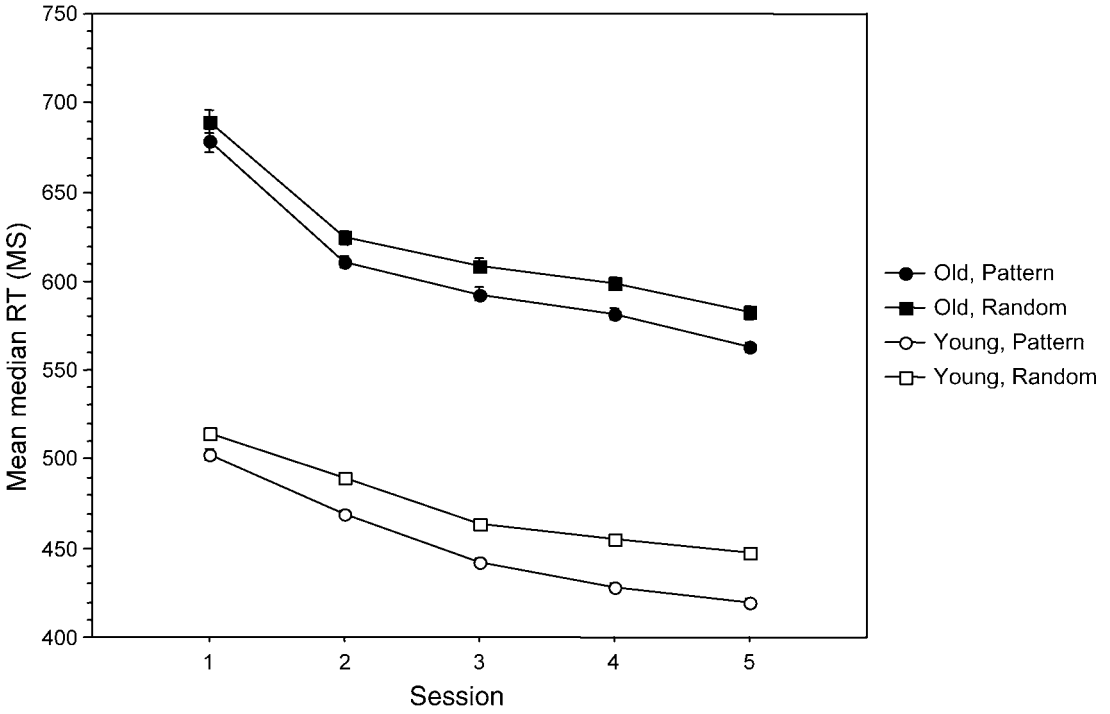

Fig. 1. Mean of median response times for pattern and random trials across sessions for young and old groups. Filled-in circle = pattern trials for old group, Filled-in square = random trials for old group, open circle = pattern trials for young group, open square = random trials for young group. The error bars are ± 1 *SE* (and smaller than the symbols where they do not appear).

The old group showed significant main effects of Trial Type for both response time, $F(1, 11) = 48.81$, $MSE = 148.19$ and accuracy, $F(1, 11) = 50.22$, $MSE = 0.00002$. Although the old groups' Trial Type $\times$ Session interaction did not reach significance for the response time measure, $F(4, 44) = 2.05$, $MSE = 38.31$, it did so for accuracy, $F(4, 44) = 4.52$, $MSE = 0.00007$.

The fact that random trials accuracy actually declines with practice (Fig. 1) might at first seem surprising. However, this same pattern occurred in all of our previous ASRT studies (e.g., Dennis, Howard & Howard; Feeney et al, 2002; Howard & Howard, 1997, 2001, submitted) and in research from other laboratories using probabilistic sequences (e.g., Curran, 1997; Schvaneveldt & Gomez, 1998). It appears that as people build up a mental model of the regularity present in the sequence, they come to respond more quickly overall and to maintain high accuracy on predictable pattern trials on which their mental model enables correct anticipations of which stimulus will occur. However, the model often leads to incorrect anticipations on random trials which do not adhere to the pattern. In fact, people usually report that they feel as though their fingers are taking over as they practice the task, and that they find themselves making errors they did not think they would make. These reports are consistent with our findings and suggest that as people develop sensitivity to the regularity, they make more anticipatory errors, errors based on expectancies (albeit unconscious ones) resulting from implicit knowledge of the statistical structure of the sequence.

We conclude that people of both age groups learned the non-spatial sequence in the present study in that they showed significant trial type effects which increased across sessions.

Are There Age Differences in Learning the Sequence?

Figure 1 shows that as is typical, older people responded more slowly than younger people,

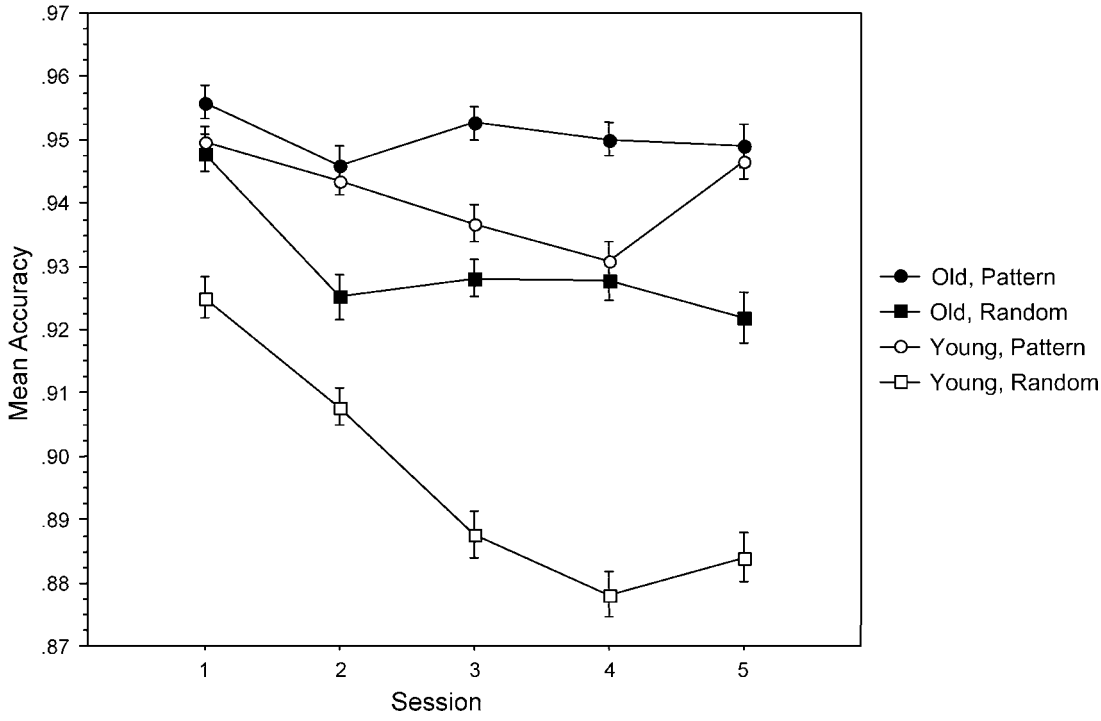

Fig. 2. Mean accuracy for pattern and random trials across sessions for young and old groups. Filled-in circle = pattern trials for old group, Filled-in square = random trials for old group, open circle = pattern trials for young group, open square = random trials for young group. The error bars are ±1 *SE*.

$F(1, 22) = 97.38$, $MSE = 13832.21$. Older people were also more accurate overall than young people, $F(1, 22) = 13.67$, $MSE = 0.002$. These age differences in overall performance do not speak about whether sequence learning declines with age. However, three aspects of the data do reveal such age deficits. These are (1) the magnitude of the trial type effect, (2) the onset of the trial type effect, and (3) the types of errors people make.

First, there are age deficits in the magnitude of the trial type effect. As Figures 1 and 2 suggest, older people showed less divergence than young between pattern and random trials, particularly on the accuracy measure. This Trial Type × Age interaction was not significant for response time, $F(1, 22) = 2.82$, $MSE = 196.50$, but it was for accuracy, $F(1, 22) = 31.09$, $MSE = 0.0002$. In fact, when the pattern trials were considered alone, the age groups did not differ significantly in accuracy, $t(22) = 1.63$, but they did when random trials were considered alone, $t(22) = 5.00$. Thus, the age difference in overall accuracy mentioned above was primarily due to the greater number of errors young people made on random trials. The three-way interaction was marginally significant for accuracy, $F(4, 88) = 2.07$, $MSE = 0.0001$, but not for response time, $F(4, 88) = 0.73$, $MSE = 38.81$. This lack of three-way interactions is likely due to the fact that the young people are in the direction of showing a larger trial type effect than the old people as early as the first session. Thus, age deficits in the trial type effect emerge early.

In keeping with this interpretation, the second form of evidence for age deficits is that older people showed a later onset of learning compared to young people. To determine onset of learning, for each measure (response time and accuracy) we determined the first session on which each person showed a significant trial type effect and continued to do so for the rest of the sessions ($p < .05$ on a matched t test using blocks as observations, $df = 20$). Participants who had not

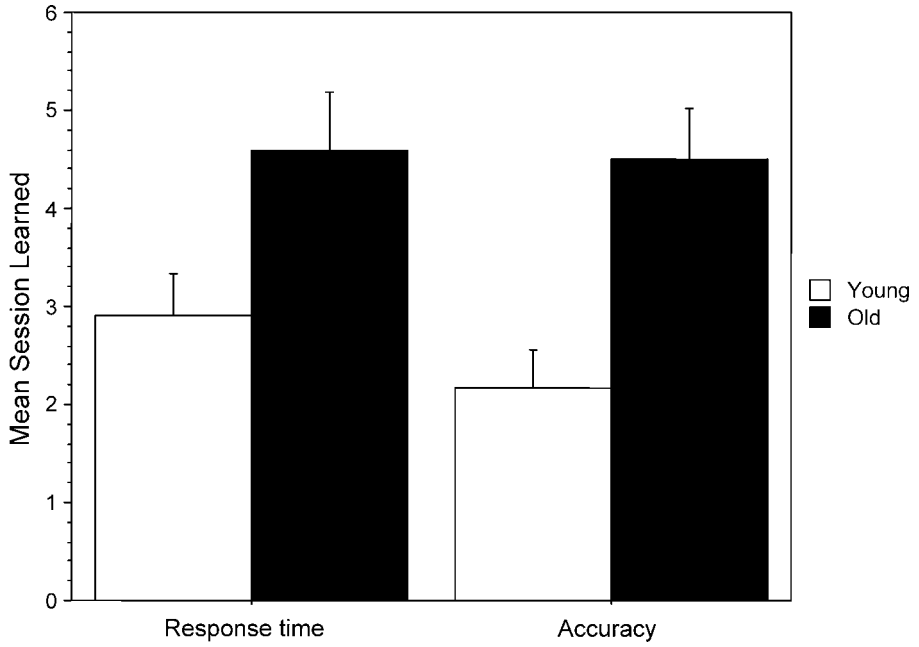

Fig. 3. Mean of the first session in which each age group showed a trial type effect and continued to do so for the rest of the sessions on the response time and accuracy measures. Filled-in bar = old, open bar = young.

reached this criterion by the fifth and final session were coded as learning on session 6. Figure 3 shows the mean session of learning for each age group on response time and on accuracy. The onset of learning was significantly earlier for the young people than the old on both the response time, $t(22) = 2.91$, and accuracy measures, $t(22) = 3.63$.

Third, the age groups differ in the types of errors they make on random trials. To determine what proportion of errors on random trials were expectancy-based and reflected sensitivity to the structure of the sequence, we classified errors on random trials into two categories. Those that resulted in a triplet that is consistent with the pattern trials were called structure-consistent, while those that resulted in a triplet that is inconsistent with the pattern trials were called structure-inconsistent. For example, if a participant whose sequence was ArBrCrDr encountered a triplet ADD, then incorrectly responding to the last item in the triplet with a B would be considered a structure-consistent error, whereas incorrectly responding with a C would be considered a structure-inconsistent error. For each participant, then, we determined the proportion of all errors on random trials that were structure-consistent. As Figure 4 shows, younger people made a larger proportion of structure consistent errors than older people. In addition, the proportion of these errors increased over sessions for the young group, but not for the old. In keeping with these observations, an Age × Session ANOVA yielded main effects of Age, $F(1, 22) = 5.07$, $MSE = 0.012$, Session, $F(4, 88) = 3.52$, $MSE = 0.004$, and an Age by Session interaction, $F(4, 88) = 3.86$, $MSE = 0.004$.

These results suggest that the observed age differences in accuracy are due to the greater number of expectancy-based errors young people made on random trials, reflecting greater sensitivity to the structure of the sequence.

How Implicit is Sequence Learning?

Verbal Reports

In order to determine whether participants had gained declarative knowledge while performing the ASRT task, we looked at their reports on the end-of-session questionnaire and

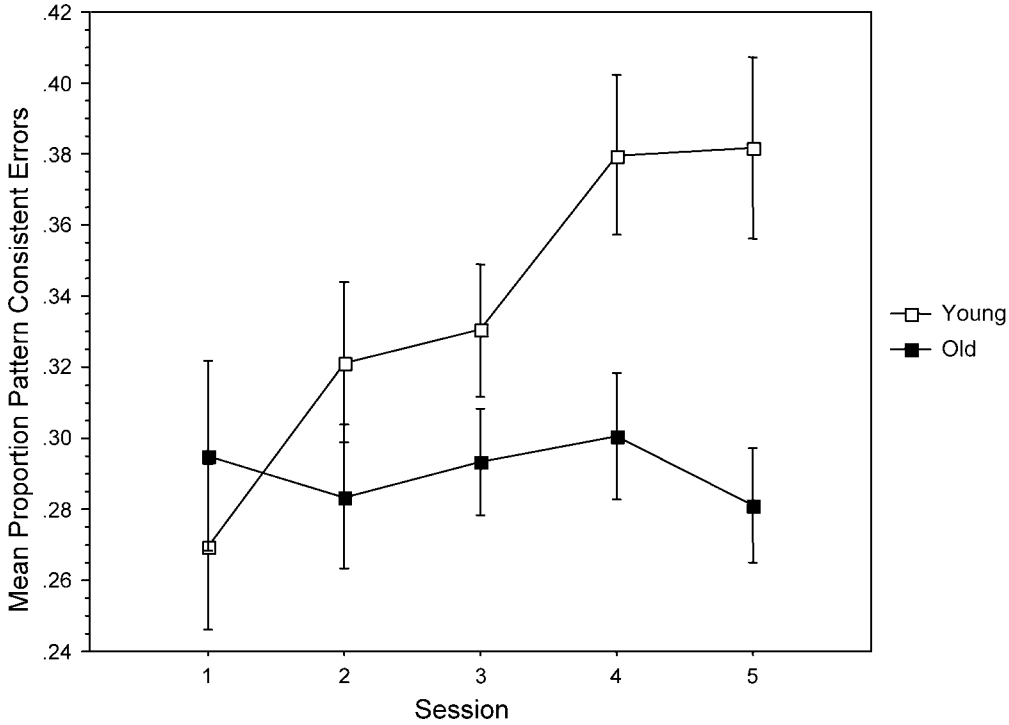

Fig. 4. Mean proportion of pattern consistent errors produced on random trials as a function of session for young and old groups. The error bars are ± 1 *SE*.

post-experimental interview. Although most people reported that they thought there must have been some kind of pattern, no one believed they had found it. The focus for most participants was to improve their speed or accuracy depending on the feedback they were getting from the computer or the experimenter. When asked to describe any regularity they thought might have been there, most people said that there was frequent repetition of letters. This guess was inaccurate because repetitions were no more likely than non-repetitions. The person who came closest to describing his pattern was one young person who reported that his pattern was ABDAC, when in fact his pattern was ArBrDrCr. None of the participants knew the length of the pattern or mentioned its alternating nature. These reports are similar to those we have obtained with the spatial version of this task (e.g., Howard & Howard, 1997), and indicate that participants have no declarative knowledge of the regularity.

Recognition and Preference tasks

We examined the Recognition and Preference tests given at the end of the final session to determine whether participants recognized pattern sequences as having occurred previously, and/or preferred them, compared to random ones. Similar pattern judgment tests have been used in other experiments where participants were given partial sequences at the end of the acquisition phase and were asked to decide whether they followed the same pattern they saw earlier in the experiment (Seger, 1997). The Preference test is usually taken to be an implicit measure of memory, in that the instructions make no reference to the earlier study episode. It relies on the mere exposure effect (Bornstein, 1989; Manza, Zizak, & Reber, 1998), that is, the phenomenon that people come to like stimuli better simply via being exposed to them. In contrast, recognition is usually viewed as a more explicit test in that the instructions refer back to earlier experience. However, neither test is completely process pure

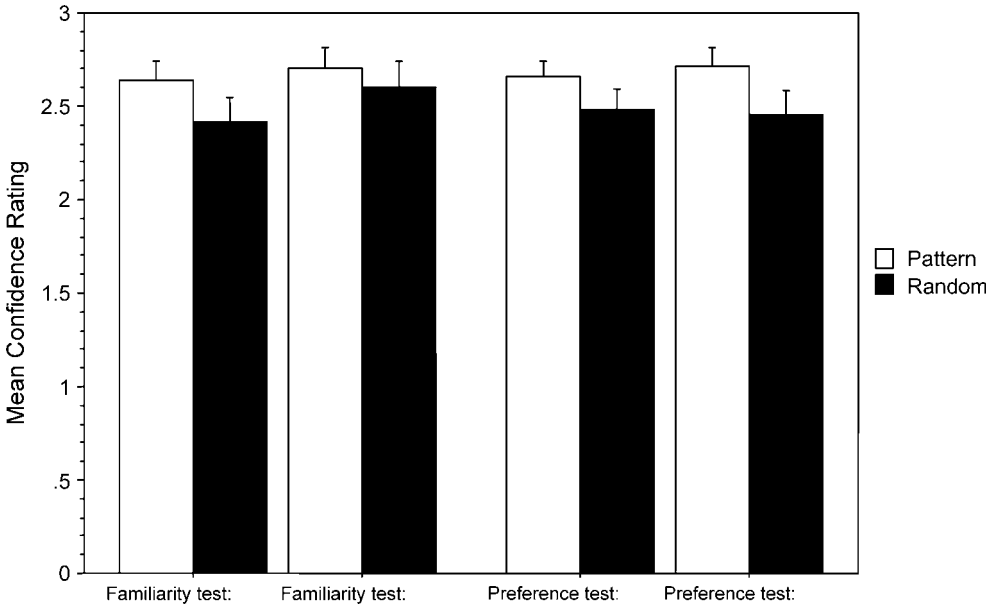

Fig. 5. Mean confidence ratings of young and old groups for pattern and random sequences on Recognition and Preference tests. Filled-in bar represents pattern sequences and open bar represents random sequences. The error bars are ± 1 *SE*.

in that even on the recognition test, people might be able to differentiate on the basis of perceptual fluency in the absence of any ability to describe the pattern (e.g., Seger, 1997). So above chance discrimination would not establish that participants have declarative knowledge. Therefore, the purpose of these tasks was to establish the conditions under which people can apply the pattern knowledge they have gained.

Figure 5 shows the mean confidence ratings of young and old groups for pattern and random sequences on the Recognition and Preference tests. For the Recognition test, a Sequence Type by Age ANOVA revealed no significant effects. For the Preference test, there was a main effect of sequence type, $F(1, 22) = 6.30$, $MSE = 0.089$, but no main effect or interaction with age. Thus, people of both ages show a small but statistically significant preference for pattern sequences, but they do not give significantly higher recognition judgments to pattern than random sequences.

At first glance, the preference results seem to extend the range of implicit learning tasks under which the mere exposure effect has been demonstrated. However, this conclusion must await replication since participants may have been responding to a subtle internal repetition present in the pattern, but not in the random sequences (e.g., for people receiving the 1234 regularity, 1r2r3r4r1r2r3r4r). This is the case for both the Preference and the Recognition tests. Perhaps such a subtle regularity would make pattern sequences more pleasing even in the absence of exposure to them in the earlier ASRT task. In spite of this, and more important for present purposes, neither age group gave significantly higher recognition ratings to pattern than random test sequences. This lack of recognition ability is consistent with the verbal reports in indicating that the sequence knowledge developed in this non-spatial ASRT task is implicit.

DISCUSSION

Conclusions

The results support several conclusions. First, we found that people of both ages were able to learn the non-spatial sequence. When the age groups were examined separately, both showed

significant trial type effects on the accuracy and response time measures as well as a significant trial type by session interaction on accuracy, signaling increasing sensitivity to the pattern over sessions. These findings are in keeping with those we have obtained with the learning of spatial sequences (e.g., Howard & Howard, 1997), and they suggest that adapting to subtle repeating sequential regularities in the environment continues at least through the decade of the 1970s.

Second, this evidence of learning occurred despite the fact that no one was able to describe the pattern. Nor were people able to discriminate significantly between sequences conforming to the regularity and those not conforming, on recognition judgments. Thus, we conclude that the sequence learning occurring here calls on implicit, rather than explicit, learning systems.

Third, there were age deficits in implicit learning. The trial type effect (pattern vs. random trials) was significantly greater for the younger than the older people on the accuracy measure. Younger people revealed sequence learning after fewer sessions than did older ones on both the accuracy and the response times measures. In addition, when people did make errors on random trials, the errors of the young people were more likely to be pattern consistent than those of the old, and this age difference increased with practice.

Fourth, our main goal was to determine whether age-related deficits in implicit sequence learning are due to a generalized learning deficit or to a covert and/or overt visuo-spatial attention deficit that accompanies normal aging. By presenting stimuli non-spatially, we were able to minimize the need for covert visuo-spatial attentional processing and overt use of eye movements to learn the sequence. We observed age deficits even after removing these spatial attributes of the task. This suggests that age deficits in implicit learning of complex sequences cannot be solely due to covert and overt visuo-spatial deficits, but reflect a more general deficit in the ability to detect and adapt to co-variations in the environment.

Limitations

The present study leaves two questions unanswered. First, while we were able to remove the spatial nature of the stimuli, and thus rule out covert and overt visuo-spatial deficits as mechanisms underlying the age deficits, a spatial component still remained in the responses. Willingham (1998) has proposed that when sequences are learned implicitly, they could be learned in terms of response locations, which are coded in egocentric space, a spatial frame that codes the location of objects relative to part of the body. According to this view, then, it is possible that the age deficits we observed are due to a spatial deficit, in this case in learning response locations.

Second, although our evidence suggests that there is a general age-related deficit in sensitivity to covariations in the environment, the mechanisms underlying this deficit have yet to be specified fully. Prior work has suggested that Salthouse's ''simultaneity mechanism'' of cognitive aging underlies this deficit (Salthouse, 1996). According to this view, as a result of cognitive slowing, older people have less information available simultaneously for processing, and hence a reduced working memory capacity compared to younger people (Howard & Howard, 1997, 2001). Consequently, older people have more difficulty than young in learning sequences based on statistical relationships among non-adjacent events (Curran, 1997; Howard & Howard, 1997). Another explanation arises from the difficulties older people have with feature binding, the process responsible for associating two or more items or features in memory (e.g., Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000). According to this view, since sequence learning entails binding information across time, age deficits in sequence learning may reflect a more general binding impairment. This binding explanation may be considered one example of recent theories which attribute many aspects of cognitive aging to a general age-related deficit in context processing (Braver et al., 2001; Li, 2002). Additional work is required to distinguish and/or integrate the simultaneity, binding and context deficit views of age-related sequence learning impairment.

In conclusion, although we have emphasized the negative, that is, that normal aging brings declines in the efficiency of implicit sequence learning, practically speaking, it is important to restate the positive. Despite the fact that the

regularity we used here was very subtle, with predictable events being embedded in an equal number of unpredictable events, elderly participants showed reliable sensitivity to the pattern. This suggests that implicit sequence learning mechanisms continue to operate in old age, even when the people showing such sensitivity are convinced that they have learned nothing. Therefore, rehabilitation and education programs calling upon implicit learning mechanisms are likely to be particularly effective for aging individuals.

ACKNOWLEDGEMENTS

Selamawit Negash, Interdisciplinary Program in Neuroscience, Georgetown University; Darlene V. Howard, Department of Psychology, Georgetown University; Karin C. Japikse, Interdisciplinary Program in Neuroscience, Georgetown University; James H. Howard, Jr., Department of Psychology, The Catholic University of America.

This research was supported by grant R37 AG15450 from the National Institute on Aging and by NIA Predoctoral Fellowship F31AG05919. We want to thank Kathleen Durkin, Kristin Valentino, and Steve Klinge for their assistance in data collection. The data from this experiment were included in a poster presentation at the Cognitive Aging Conference in Atlanta, Georgia, April, 2000.

REFERENCES

Bornstein, R.F. (1989). Exposure and affect: Overview and meta-analysis of research, 1968–1987. *Psychological Bulletin*, *106*, 265–289.

Braver, T.S., Barch, D.M., Keys, B.A., Carter, C.S., Cohen, J.D., Kaye, J.A., et al. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General*, *130*, 746–763.

Carter, J.E., Obler, L., Woodward, S., & Albert, M.L. (1983). The effect of increasing age on the latency for saccadic eye movements. *Journal of Gerontology*, *38*, 318–320.

Christensen, K.J., Moye, J., Armson, R.R., & Kern, T.M. (1992). Health screening and random recruitment for cognitive aging research. *Psychology and Aging*, *7*, 204–208.

Cleeremans, A., Destrebecqz, A., & Boyer, M. (1998). Implicit learning: News from the front. *Trends in Cognitive Sciences*, *2*, 406–416.

Crassini, B., Brown, B., & Bowman, K. (1988). Age-related changes in contrast sensitivity in central and peripheral retina. *Perception*, *17*, 315–332.

Curran, T. (1997). Effects of aging on implicit sequence learning: Accounting for sequence structure and explicit knowledge. *Psychological Research*, *60*, 24–41.

Curran, T. (1998). Implicit sequence learning from a cognitive neuroscience perspective: What, how, and where? In M.A. Stadler & P.A. Frensch (Eds.), *Handbook of implicit learning* (pp. 365–400). Thousand Oaks, CA, USA: Sage Publications.

Dennis, N.A., Howard, J.H., Jr., & Howard, D.V. (submitted). Age deficits in learning sequences of spoken words. *Journal of Gerontology B: Psychological Sciences.*

Feeney, J.J., Howard, J.H., Jr., & Howard, D.V. (2002). Implicit learning of higher-order sequences in middle-age. *Psychology and Aging*.

Folstein, M.F., Folstein, S.E., & McHugh, P.R. (1975). ''Mini-Mental State'': A practical method for grading the mental state of patients for the clinician. *Journal of Psychiatric Research*, *12*, 189–198.

Frensch, P.A., & Miner, C.S. (1994). Effects of presentation rate and individual differences in short-term memory capacity on an indirect measure of serial learning. *Memory & Cognition*, *22*, 95–110.

Gomez-Beldarrain, M., Garcia-Monco, J.C., Rubio, B., & Pascual-Leone, A. (1998). Effect of focal cerebellar lesions on procedural learning in the serial reaction time task. *Experimental Brain Research*, *120*, 25–30.

Gomez Beldarrain, M., Grafman, J., Pascual-Leone, A., & Garcia-Monco, J.C. (1999). Procedural learning is impaired in patients with prefrontal lesions. *Neurology*, *52*, 1853–1860.

Goschke, T., Friederici, A.D., Kotz, S.A., & vanKampen, A. (2001). Procedural learning in Broca's aphasia: Dissociation between the implicit acquisition of spatio-motor and phoneme sequences. *Journal of Cognitive Neuroscience*, *13*, 370–388.

Greenwood, P.M., & Parasuraman, R. (1994). Attentional disengagement deficit in nondemented elderly over 75 years of age. *Aging & Cognition*, *1*, 188–202.

Helmuth, L.L., Mayr, U., & Daum, I. (2000). Sequence learning in Parkinson's disease: A comparison of spatial-attention and number-response sequences. *Neuropsychologia*, *38*, 1443–1451.

Howard, D.V., & Howard, J.H., Jr. (1989). Age differences in learning serial patterns: Direct versus indirect measures. *Psychology and Aging*, *4*, 357–364.

Howard, D.V., & Howard, J.H., Jr. (1992). Adult age differences in the rate of learning serial patterns: Evidence from direct and indirect tests. *Psychology and Aging*, *7*, 232–241.

Howard, J.H., Jr., & Howard, D.V. (1997). Age differences in implicit learning of higher order dependencies in serial patterns. *Psychology and Aging*, *12*, 634–656.

Howard, D.V., & Howard, J.H., Jr. (2001). When it does hurt to try: Adult age differences in the effects of instructions on implicit pattern learning. *Psychonomic Bulletin and Review*, *8*, 798–805.

Howard, D.V., Howard, J.H., Jr., Japikse, K., DiYanni, C., Thompson, A., & Somberg, R. (submitted). Sequence learning: Effects of level of structure, adult age, and extended practice. *Journal of Experimental Psychology: Learning*, *Memory*, *and Cognition*.

Jackson, G.M., Jackson, S.R., Harrison, J., Henderson, L., & Kennard, C. (1995). Serial reaction time learning and Parkinson's disease: Evidence for a procedural learning deficit. *Neuropsychologia*, *33*, 577–593.

Jones, D.N., Barnes, J.C., Kirkby, D.L., & Higgins, G.A. (1995). Age-associated impairments in a test of attention: Evidence for involvement of cholinergic systems. *Journal of Neuroscience*, *15*, 7282–7292.

Knopman, D.S., & Nissen, M.J. (1987). Implicit learning in patients with probable Alzheimer's disease. *Neurology*, *37*, 784–788.

Li, S. (2002). Connecting the many levels and facets of cognitive aging. *Current Directions in Psychological Science*, *11*, 38–43.

Madden, D.J., Turkington, T.G., Provenzale, J.M., Hawk, T.C., Hoffman, J.M., & Coleman, R.E. (1997). Selective and divided visual attention: Age-related changes in regional cerebral blood flow measured by H215O PET. *Human Brain Mapping*, *5*, 389–409.

Manza, L., Zizak, D., & Reber, A.S. (1998). Artificial grammar learning and the mere exposure effect: Emotional preference tasks and the implicit learning. In M.A. Stadler & P.A. Frensch (Eds.), *Handbook of implicit learning* (pp. 201–222). Thousand Oaks, CA, USA: Sage Publications.

Mayr, U. (1996). Spatial attention and implicit sequence learning: Evidence for independent learning of spatial and non-spatial sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 350–364.

Nieuwenhuis, S., Ridderinkhof, K.R., deJong, R., Kok, A., & van der Molen, M.W. (2000). Inhibitory inefficiency and failures of intention activation: Age-related decline in the control of saccadic eye movements. *Psychology and Aging*, *15*, 635–647.

Nissen, M.J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, *19*, 1–32.

Nissen, M.J., Willingham, D., & Hartman, M. (1989). Explicit and implicit remembering: When is learning preserved in amnesia? *Neuropsychologia*, *27*, 341–352.

Owsley, C., Burton-Danner, K., & Jackson, G.R. (2000). Aging and spatial localization during feature search. *Gerontology*, *46*, 300–305.

Prull, M.W., Gabrieli, J.D.E., & Bunge, S.A. (2000). Age-related changes in memory: A cognitive neuroscience perspective. In F.I.M. Craik & T.A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum.

Reber, A.S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General*, *118*, 219–235.

Robertson, E.M., Tormos, J.M., Maeda, F., & Pascual-Leone, A. (2001). The role of the dorsolateral prefrontal cortex during sequence learning is specific for spatial information. *Cerebral Cortex*, *11*, 628–635.

Salthouse, T.A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403–428.

Scialfa, C.T., & Joffe, K.M. (1997). Age differences in feature and conjunction search: Implications for theories of visual search and generalized slowing. *Aging, Neuropsychology, and Cognition*, *4*, 227–246.

Willingham, D.B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review*, *105*, 558–584.