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BRIEF REPORT

Implicit Learning of Higher Order Sequences in Middle Age

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Previous studies have demonstrated age-related deficits in implicit learning of higher order sequences in comparisons of college-age and elderly adults (e.g., J. H. Howard & D. V. Howard, 1997). This study examined whether these age deficits begin in middle age. Results showed a reliable age-related deficit in pattern sensitivity in "older" compared with "younger" middle-aged people, and age reliably predicted sensitivity to the sequence by using both speed and accuracy measures. The results are consistent with an age-related decline in a generic cognitive resource as reflected in T. A. Salthouse's (1996) simultaneity mechanism of cognitive aging.

People have an impressive ability to learn the relationships among objects or events in their environment. Sometimes this knowledge is learned *explicitly* in that individuals make a conscious effort to learn, are aware of having learned, and can describe what they have learned (e.g., the simple R–G–Y repeating sequence of a traffic signal). In other instances, however, learning occurs *implicitly*. In implicit learning, knowledge is acquired without conscious effort to learn, without awareness that learning has occurred, and without the ability to describe the acquired information (Reber, 1993). In such cases, the evidence for learning comes from people's behavior rather than their direct report (e.g., that people can produce and understand grammatical sentences suggests that the rules of syntax are known even if they cannot be described).

The serial reaction time (SRT) task has been used extensively to investigate implicit learning. People respond to stimuli that appear at one of four spatial locations on a screen (Nissen & Bullemer, 1987). Unbeknownst to the participants, the locations occur in a repeating sequence. If after practice the pattern is removed and locations are presented randomly, people respond more slowly, indicating that they had learned the pattern despite being unable to describe it.

A number of studies have shown age constancy in implicit learning with this task. In these studies, elderly people revealed implicit learning equivalent to college-aged (Frensch & Miner, 1994; D. V. Howard & Howard, 1989, 1992) or college- and middle-aged individuals (Salthouse, McGuthry, & Hambrick, 1999). However, other studies have reported age-related deficits in implicit learning when more subtle, higher order patterns (Curran, 1997; D. V. Howard & Howard, 2001; J. H. Howard & Howard, 1997), more complex hand movements (Harrington & Haaland, 1992), or "low ability" elderly were tested (Cherry & Stadler, 1995).

These latter findings indicate that age-related impairments can occur in even very simple implicit-learning tasks. However, because most studies have compared college-age and elderly groups, it is not known when the deficits emerge. In one study, it was shown that implicit learning in a variation of the SRT task is impaired not only in old (over 60) compared with young (20s), but also in old-old (70s) compared to young-old (60s) adults (J. H. Howard & Howard, 1997). This suggests that the deficit in implicit learning can be detected over relatively small age ranges. The question investigated here is whether age-related deficits begin in middle age.

We use the alternating serial reaction time (ASRT) task, in which alternate items follow a predetermined pattern while the others are selected randomly (J. H. Howard & Howard, 1997). For example, a person may see the series 1r4r3r2r . . ., where 1–4 indicates a specific and "r" indicates a random location. Evidence for learning is revealed by faster or more accurate responding on predictable (pattern) than on unpredictable (random) trials. The ASRT task offers two important advantages over the SRT task for the study of aging. First, in SRT, people often become aware of the repeating pattern, making it difficult to attribute age deficits to implicit rather than explicit learning. In contrast, in ASRT people almost never become aware of the sequence structure. Second, in SRT, implicit learning is assessed only when random trials are

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introduced after several practice blocks. In ASRT, accuracy and response time can be compared on pattern and random trials throughout learning.

The ASRT and SRT tasks produce very different sequence structure. In the original SRT, individual locations (zero-order information), pairs of locations (first order), and runs of $n + 1$ locations (nth order) all occur with unequal frequency. Hence, it is difficult to determine which level of the structure is actually learned. In contrast, ASRT sequences have only second- and higher order structure, because all locations and pairs of locations occur equally often.[1] Because learning cannot be based on simple event (zero order) or pair frequency (first order) people must associate events that span at least three trials (second or higher order).

It has been shown previously that people remain unaware of the alternating structure even after extended practice (D. V. Howard & Howard, 2001; J. H. Howard & Howard, 1997). Our detailed, trial-by-trial analysis of errors and reaction times (RTs) suggested that, without being aware of doing so, people learn the relative frequencies of three consecutive events or triplets. For example, in 1r4r3r2r . . ., the triplets 114, 124, 134, and 144 occur more often than 141 or 331.

J. H. Howard and Howard (1997) and Curran (1997) have argued that age-related deficits in higher order sequence learning follow from Salthouse's (1996) "simultaneity mechanism" of cognitive aging, a consequence of generalized, age-related slowing. Because such slowing results in fewer trials being available for simultaneous processing in older people, higher order sequence learning is impaired. The finding that lengthening the response-to-stimulus interval leads to impaired performance in the young is consistent with this argument (Frensch & Miner, 1994; Willingham, Greenberg, & Thomas, 1997).

According to this hypothesis, the ASRT task should reveal an age-related decline in implicit learning across the life span, because slowing is known to occur throughout adulthood (Salthouse, 1996). In this study, we investigated whether age-related deficits in implicit sequence learning occur in middle age.

Method

Participants

Students and faculty from the Industrial College of the Armed Forces of the National Defense University were recruited for the experiment. Data were acquired from 45 people, ranging from 34.06 to 52.62 years old with a mean of 45.34 years.

Task and Materials

Four open circles were displayed horizontally on a computer screen. Each circle was .5° of visual angle at a viewing distance of 56 cm. The entire display subtended approximately 12° of visual angle. Four labeled keys were used for responding.

Target locations were determined by a repeating eight-element pattern in which fixed and randomly chosen locations alternated. Each participant received one of the six unique permutations of the fixed locations (i.e., 1234, 1243, 1324, 1342, 1423, 1432, numbered left to right).

Procedure

The experiment was carried out over 2 days. On the first day, participants signed an approved informed consent and completed health screening and biographical questionnaires. They were then seated at the computer with the middle and index fingers of their two hands on the response keys, and the task was described as a study of simple motor RT. The regularity in the target sequence was not mentioned.

People then completed three 21-block sessions. Each block had 10 random practice trials followed by 80 learning trials (10 repetitions of an 8-element alternating pattern). A trial began when one of the four circles filled in. This remained visible until the correct key was pressed and the circle was cleared. The next trial began 120 ms later. Reaction time was measured from target onset to the first response. As in J. H. Howard and Howard (1997), feedback was displayed at the end of each block that encouraged people to maintain approximately 92% accuracy. Five-minute breaks occurred between sessions.

On the second day, participants were given the Wechsler Adult Intelligence Scale—Revised (WAIS–R; Wechsler, 1981) Digit-Symbol Substitution and Vocabulary tests before 3 additional 21-block sessions. The experiment concluded with an interview in which people were asked a series of increasingly specific questions about their knowledge of the sequence, ranging from "Do you have anything to report regarding the task?" to "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 procedure used here was similar to that of J. H. Howard and Howard (1997), but with three testing sessions per day rather than one.

Results and Discussion

Are Participants Explicitly Aware of the Sequence Structure?

We examined the postexperimental interviews for evidence of explicit knowledge. Thirty-eight of the 45 participants answered "no" when asked "Did you notice any regularity in the way the stimulus was moving on the screen?" For the 7 who said they did, we counted the number of common triplets in their reported and actual sequences to evaluate overlap. Only 1 person described a sequence with greater than chance similarity to the one that actually occurred, and a close examination of his learning and retention data revealed nothing unusual. On this basis, we conclude that the pattern sensitivity revealed in the following analyses reflects implicit knowledge.

Did Participants Learn the Second-Order Patterns?

Median RTs were determined separately for correct pattern and random trials for each block. These were then averaged to obtain a mean RT for each individual and trial type on each session. A similar data reduction was performed on the percent correct (PC) measure. A statistical criterion of .05 was used in all tests.

Figures 1A and 1B plot the mean RT and PC by session. These data provide clear evidence of second-order sequence learning

[1] We define second- and higher order structure in terms of the lag or separation between predictive elements in a sequence. For example, in the ASRT task, the event on pattern trial n can be predicted from the events on trial $n - 2$ (second order), $n - 4$ (fourth order), and so forth, alone or in combination. This usage is consistent with that adopted in our previous research (J. H. Howard & Howard, 1997). We note that others have used these terms to refer to the number of consecutive previous trials required to predict a given event (Curran, 1997; Reed & Johnson, 1994). From this perspective, the event on trial n in a second-order sequence can be predicted from a combination of the events on trials $n - 1$ and $n - 2$.

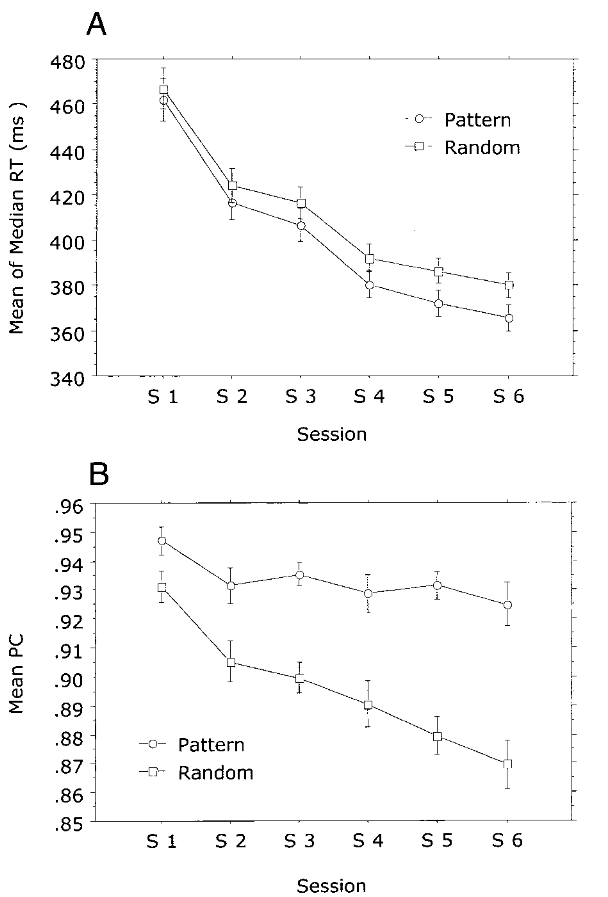

Figure 1. A: Mean of median reaction time (RT) as a function of session (S) and trial type. B: Mean percent correct (PC) as a function of session and trial type. Error bars represent ±1 *SE*.

because pattern and random trials diverged in both speed and accuracy with practice. This was confirmed by two Session (1–6) × Trial Type (pattern vs. random) repeated measures analyses of variance (ANOVAs). For RT there were significant main effects of session, $F(5, 220) = 162.49$, $MSE = 646.74$, and trial type, $F(1, 45) = 127.94$, $MSE = 112.12$, as well as a significant Session × Trial-Type interaction, $F(5, 220) = 23.73$, $MSE = 13.18$. The results were identical for PC with significant main effects of session, $F(5, 220) = 13.33$, $MSE = 0.001$, and trial type, $F(1, 44) = 176.52$, $MSE = 0.001$, and a Session × Trial-Type interaction, $F(5, 220) = 34.17$, $MSE = 0.00014$.

These analyses indicate that overall, participants became faster but less accurate with practice, a pattern that is consistent with our previous findings (J. H. Howard & Howard, 1997). As people become more sensitive to the sequence structure, they make more errors on the unpredictable random trials. In contrast, accuracy on pattern trials declines only slightly, possibly because of the feedback, which encouraged 92% overall accuracy. However it is most important to note that people were increasingly faster and more accurate on pattern than on random trials, indicating that learning occurred across the six sessions.

Is Second-Order Pattern Learning Related to Age?

We addressed this question by comparing two age groups, defined by a median split at 45.19 years. This resulted in younger (6 female, 17 male) and older (5 female, 17 male) groups with mean ages of 41.42 ($SD = 2.98$) and 49.43 ($SD = 2.46$) years, respectively. The two groups differed significantly in age, $t(43) = 9.78$, but not in education (younger = 18.39, older = 18.64 years), self-reported health score (younger = 4.61, older = 4.50), WAIS–R Digit-Symbol Substitution (younger = 60.00, older = 59.96), or WAIS–R Vocabulary (younger = 63.24, older = 62.54).

Figures 2A and 2B show the mean RT and PC, respectively, for the two age groups split by type across sessions. Consistent with more extreme age comparisons, older middle-aged adults are slower than younger middle-aged adults. It is more important to note that the older people are less sensitive to the sequence regularity than the younger people in that they show a smaller difference between pattern and random trials for both RT and PC. These observations were confirmed for RT by a three-way ANOVA. The main effects of age, $F(1, 43) = 11.43$, $MSE = 18429.05$; session, $F(5, 215) = 176.69$, $MSE = 598.68$; and trial type, $F(1, 43) = 145.51$, $MSE = 97.54$, were all significant as

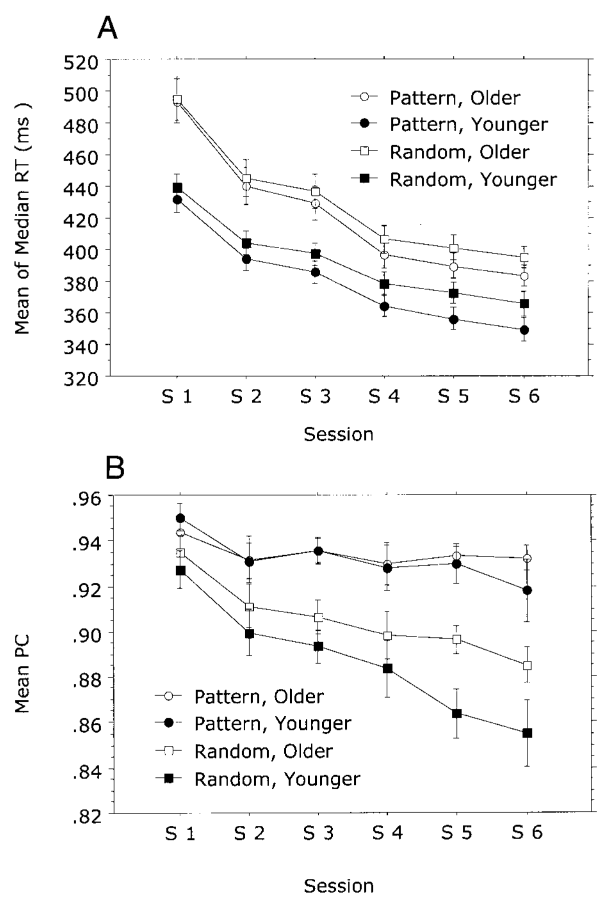

Figure 2. A: Mean of median reaction time (RT) as a function of learning session (S), trial type, and age group. B: Mean percent correct (PC) as a function of session, trial type, and age group. Error bars represent ±1 *SE*.

were the Session × Age, $F(5, 215) = 4.53$, $MSE = 598.68$; Trial-Type × Age, $F(1, 43) = 7.58$, $MSE = 97.54$; and Session × Trial-Type, $F(5, 215) = 23.27$, $MSE = 13.45$, interactions. The three-way interaction did not reach significance.

An identical three-way ANOVA on PC also produced significant main effects of session, $F(5, 215) = 13.19$, $MSE = 0.001$; and trial type, $F(1, 43) = 210.27$, $MSE = 0.001$; as well as Trial-Type × Age, $F(1, 43) = 9.95$, $MSE = 0.001$; and Session × Trial-Type, $F(5, 215) = 36.44$, $MSE = 0.0001$, interactions. Neither the main effect of group nor the three-way interaction were significant.

Hence, these findings reveal age deficits within middle age that mirror our previous results with young and elderly people in some ways, but not in others. As in our earlier work, older middle-aged adults are slower and show smaller trial-type effects on both RT and PC than do younger middle-aged adults. However, unlike our earlier findings, the trend toward slower learning for the older middle-aged adults, evident particularly in the PC data, did not reach statistical significance.

Do Age and Processing Speed Predict Pattern Sensitivity?

To address this question, we calculated two sensitivity measures, RT and PC, by subtracting the corresponding mean performance data on pattern and random trials for each person on the last session. A simple regression with age revealed that sensitivity reliably declined with age for both RT, $F(1, 43) = 6.97$, $MSE = 48.13$, $R^2 = .14$; and PC, $F(1, 43) = 4.08$, $MSE = 0.001$, $R^2 = .09$ (RT = 39.86 − 0.567 × age and PC = 0.13 − 0.002 × age). This is consistent with the group analyses reported above and with our earlier findings with more extreme age groups.

To determine whether these relationships are mediated by processing speed, we performed a hierarchical regression analysis in which individual overall mean RT was entered first, followed by age, for both sensitivity measures. For RT, age remained a significant predictor of sensitivity, $t(42) = -2.14$, whereas for PC, age did not, $t(42) = -0.40$. Hence, although overall speed alone can account for age-related differences in sensitivity on PC, it cannot for RT. This finding is consistent with previous arguments that speed and accuracy may measure different aspects of implicit learning (Schvaneveldt & Gomez, 1998).

Can the Present Findings With Middle-Aged Adults Predict Previous Results With Young and Elderly?

As a test of this, we used the regression equations shown above for RT and PC in our middle-aged sample to predict the comparable measures for young ($M = 21$ years) and elderly individuals ($M = 74$ years), using the same task and level of practice (D. V. Howard & Howard, 1997, Experiment 2a). To evaluate goodness of fit, we correlated these predicted sensitivity measures with those observed in the earlier study. Statistically significant correlations were obtained for both RT ($r = .763$) and PC ($r = .853$). Although this result suggests that the age deficits in middle age are consistent with those between young and elderly adults, it must be interpreted cautiously because of the cross-experiment nature of the comparisons.

General Discussion

The present results extend our previous findings on cognitive aging of implicit sequence learning to middle-aged adults. Over 84% of our participants reported being unaware of any sequence regularity, and no one became aware of the alternating structure of the sequences. Hence, consistent with our previous results, the ASRT task reflects a relatively pure case of implicit learning.

Although all of our middle-aged participants revealed sensitivity to the sequence regularity, the younger middle-aged participants were significantly more sensitive than their older counterparts on both the RT and PC measures. This age deficit was also seen in a simple regression analysis carried out between age and pattern sensitivity that showed a reliable negative relationship for both the RT and PC measures. This occurred despite the limited age range of our sample.

Further, we were able to accurately predict the relative final-session sensitivity of both young and elderly people in our earlier research by extrapolating from the middle-aged individuals tested here.

Although we found clear age deficits in overall sensitivity within middle age, the trend toward age deficits in the rate of learning did not reach statistical significance. This pattern is reminiscent of previous findings with explicit multitrial paired associate learning in the elderly. Some studies have reported overall age-related deficits in paired associate learning, but with equivalent rates of learning in old and young (see Kausler, 1994). Such findings have been interpreted to mean that although elderly people have more difficulty activating their explicit-learning processes, once this is achieved they perform as well as the young. Our findings suggest that this may be true of implicit sequence learning within middle age.

One may ask, what specific cognitive mechanisms underlie this difference in overall pattern sensitivity? Although not designed to address this question specifically, the present results can offer some insights. Most theoretical views of implicit learning describe the underlying process as a kind of covariation learning (Cleeremans, 1993; Reber, 1993) in which people become increasingly sensitive to the co-occurrence of events in their environment simply by being exposed to them. Recent artificial neural network models of implicit learning embody this principle (Cleeremans, 1993). Hoyer and Lincourt (1998) likened this learning process to a "structural sponge," and Claxton (1997) referred to "learning by osmosis." Although descriptions such as these suggest that implicit learning is not resource demanding, it is clear that when the structure to be learned extends over trials as in the sequences used here, the information must be simultaneously available for learning to occur. Some have argued that it is this characteristic that leads to age-related decline in the learning of higher order sequential patterns (Curran, 1997; J. H. Howard & Howard, 1997). Our results are consistent with a declining generic cognitive resource as reflected in Salthouse's simultaneity mechanism of aging, which leads to age-related declines in the ability to learn higher order sequential regularities. The present results suggest that these deficits extend into middle age and that future research should examine implicit learning more broadly across the adult life span.

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