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Event Timing and Age Deficits in Higher-Order Sequence Learning

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ABSTRACT

Recent studies have reported age deficits in learning sequences that contain subtle sequential regularities [e.g., Curran (1997) *Psychological Research, 60*(1–2), 24; D. V. Howard et al. (2004) *Psychology and Aging, 19*(1), 79; Howard, J. H. Jr, & Howard, D. V. (1997). *Psychololgy and Aging, 12*(4), 634]. This finding is of potential theoretical interest, but the contribution of sequence event timing to this deficit has not been investigated. This study used an alternating serial reaction time task to examine implicit sequence learning in young adults when event timing mimicked that experienced by older adults in previous research. We varied the response-to-stimulus interval directly in Experiment 1 and indirectly by degrading the stimuli to influence response time in Experiment 2. Results indicate that these "aged" young adults learned the higher-order sequence structure implicitly, but they learned less than young controls and more than old adults on some measures of implicit learning in both experiments. In addition, these two different experimental manipulations produced distinct patterns of deficits despite having nearly identical effects on event sequence timing. These findings suggest that event timing alone cannot explain the age deficits observed in high-order implicit sequence learning.

INTRODUCTION

Thoughts and actions typically occur in a temporal sequence. For example, swinging a golf club and producing language involve temporally-structured events. Many studies have investigated how people learn such sequences by using the serial reaction time task in which people respond to each of a series of events by pressing corresponding keys (Nissen & Bullemer, 1987).

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Unbeknownst to the learner, the sequence contains an underlying regularity. Results show that people respond faster with practice and, when the regularity is removed, their reaction time increases demonstrating sequence-specific learning. Furthermore, since people seem to learn without any intention of doing so and often without awareness of what they learned or even that learning occurred (Seger, 1994), it has been argued that the serial reaction time task depends at least in part on implicit or procedural learning rather than on conscious, deliberate declarative learning (Frensch & Ruenger, 2003; Reber, 1993).

A number of studies have investigated how sequence learning changes with age. For simple repeating sequences, healthy older adults show preserved implicit learning compared to young people (Frensch & Miner, 1994; D. V. Howard & Howard, 1989, 1992; Salthouse et al., 1999), but age deficits occur when sequences with subtle regularities are used (Curran, 1997; D. V. Howard et al., 2004; J. H. Howard, Jr & Howard, 1997; J. H. Howard, Jr et al., 2004).

It is possible that age-related differences in sequence timing contribute to the age deficits reported in these latter studies. This follows from the fact that in the serial reaction time task each stimulus succeeds the preceding response by a fixed interval. Since response time becomes slower and more variable with age, the time between successive event onsets is longer and more variable for old than young people. The focus of the present study is healthy aging, but similar arguments apply to other populations that show impaired sequence learning such as Parkinson's and Huntington's disease patients (Helmuth et al., 2000; Willingham et al., 1996), early dementia patients (Negash et al., 2006), schizophrenics (Marvel et al., 2005) and dyslexics (J. H. Howard, Jr, et al., 2006; Vicari et al., 2005).

Previous studies with young adults lend support to this possibility. For example, Stadler showed that introducing unpredictable 2-s pauses between stimuli hindered sequence learning (Stadler, 1993). Several studies have reported that a fixed, but long (1000 ms or greater) response-to-stimulus interval (RSI) leads to less sequence learning than a shorter (500 ms or less) interval (Frensch et al., 1994; Frensch & Miner, 1994; Soetens et al., 2004) and Stadler found impaired learning when the interval varied randomly between 400 and 2000 ms (Stadler, 1995). Dominey was also able to simulate a learning impairment using a recurrent network model with both fixed and variable intervals (Dominey, 1998).

However, Willingham and his colleagues have argued that longer and/or variable response-to-stimulus intervals degrade SRTT performance, but not learning *per se* (Willingham et al., 1997). A group trained with a variable response-to-stimulus interval (50, 450 or 850 ms) appeared impaired while learning a deterministic repeating 12-element sequence, but did as well as a constant-interval control group when transferred to a constant-interval condition. Consistent with this, eliminating the response-to-stimulus interval leads to slower overall responding, but normal sequence learning compared to controls with a fixed interval (Destrebecqz & Cleeremans, 2003).

In the present study we investigate the influence of event timing on sequence learning in an alternating serial response time task (ASRTT) (D. V. Howard et al., 2004; J. H. Howard, Jr & Howard, 1997). We manipulate sequence timing either directly by varying the response-to-stimulus interval or indirectly by degrading the stimuli. Sequences in the ASRTT are probabilistic since alternate events follow a repeating pattern and the others are determined randomly. For example, a person may see the repeating sequence 1432 with interspersed random events: 1r4r3r2r …, where 1–4 are specific locations and “r” is a random one. We have found that although both young and old people respond faster and more accurately to predictable (pattern) than unpredictable (random) events, the difference is smaller for older than younger individuals and this age-related deficit persists even after extended training (D. V. Howard & Howard, 2001; D. V. Howard et al., 2004; J. H. Howard, Jr et al., 2004). Practice also leads to a change in the kind of errors that occur on unpredictable trials since, as they learn, people increasingly make frequent responses to infrequent events (Curran, 1997; D. V. Howard et al., 2004; J. H. Howard, Jr & Howard, 1997; Schvaneveldt & Gomez, 1998). We refer to these as structure-consistent errors, and the increase in the proportion of errors that is structure consistent is greater for young than old learners.

In the present study we investigate whether age-related deficits in sequence learning can be simulated in young people by presenting sequences with timing similar to that experienced by older adults. We accomplish this in Experiment 1 by using a variable response-to-stimulus interval to match the timing encountered by older adults in previous studies. In Experiment 2, we decrease the perceptual contrast of the stimulus display to induce slower and more variable responding in young people. Therefore, in both experiments, young adults encounter a temporal sequence similar to that of older adults. If sequence timing contributes to the age deficits observed in previous research, then these “aged” young people in both experiments should reveal sequence learning deficits as seen in older adults.

EXPERIMENT 1

Method

Participants

Twenty-four college student volunteers participated, 12 in each of two groups (mean age 19.6 years, 14 female). The response-to-stimulus interval was variable for the “aged” young group and constant for the control group.

The "aged" young group was also compared to a group of twelve older adults tested on a comparable task in an earlier study (D. V. Howard et al., 2004). Although the older adults in the previous study completed 10 training sessions, only data from the first six are considered here.

Task

Four open circles (.5° each) were displayed horizontally on a computer screen (12° at 56 cm) and four marked keys were used for responding. One circle was filled in on each trial in an alternating sequence of fixed and random locations. Four participants, two in each group, received each of the six unique permutations of the four fixed locations (J. H. Howard, Jr & Howard, 1997). Random events were sampled from a uniform distribution. The present task was identical to the one used in the previous comparison study in all key respects including apparatus, number of events, RSI (for controls), number of trials and blocks per session.

Procedure

On the first day people were read instructions and signed an IRB-approved informed consent form. The sequence regularity was not mentioned. Six 21-block sessions were completed, 1 per day within an 8-day period. Each block had 10 random trials followed by 80 learning trials. Participants responded with the middle and index fingers of both hands. On each trial 1 of the circles darkened until a correct response occurred. Reaction time was measured from target onset to the first response. People received feedback at the end of each block to encourage about 92% accuracy. Each person received 11,340 trials across the experiment.

For the control group each trial followed the prior response by 120 ms. For the "aged" young group the RSI was a Gaussian random variable with mean and standard deviation selected to produce sequences that mimicked the mean and within-subject variability of the inter-stimulus-interval (ISI) experienced by older adults in a previous study (J. H. Howard, Jr & Howard, 1997). We did not attempt to replicate the precise shape of ISI distributions. For six of the "aged" young participants, the Gaussian parameters remained constant (270/147 ms for the mean and standard deviation, respectively), whereas for the other six, they declined across the six sessions (270/147, 239/144, 220/128, 203/112, 189/101, and 183/98 ms, respectively). The latter condition was included to capture the tendency for these parameters to decline as people, including older adults, respond more quickly and consistently with practice. However, since a preliminary analysis revealed no differences between these subgroups, this factor was not considered in the analyses below. The experiment concluded with an interview that probed people's declarative knowledge of the sequence.

Results and Discussion

Learning Measures

Sequence learning in the ASRTT is revealed in three measures: *accuracy trial-type effects*, *reaction time trial-type effects*, and *error consistency*. The first two measures reflect the difference in responding to the predictable pattern versus unpredictable random events. As learning occurs, people become relatively faster and more accurate on pattern compared to random trials thereby displaying an increasing trial-type effect with practice on both measures (J. H. Howard, Jr & Howard, 1997). Median reaction times (RTs) were determined separately for correct pattern and random trials on each block and these were then averaged across blocks to obtain a mean RT for each individual and trial type (pattern or random) on each session. A parallel data reduction was performed to calculate mean accuracy. The trial-type effects are the differences in mean RT and accuracy between the pattern and random trials.

The third measure of learning, error consistency, is determined by computing the proportion of errors on random trials that were consistent with the sequence structure (structure-consistent errors) for each individual on each session.[1] Learning is reflected as an increase in this measure with practice since there is an increasing tendency to make pattern-consistent "anticipation" errors as people acquire implicit knowledge of the underlying sequence regularity (D. V. Howard et al., 2004; Schvaneveldt & Gomez, 1998). Although these three measures often show converging results (e.g., D. V. Howard et al., 2004), there is also some evidence that they may measure somewhat different aspects of learning (Song et al., in press). Nevertheless, we have found age-related implicit learning deficits on all three measures, but most consistently on the accuracy trial-type effect and error consistency (D. V. Howard et al., 2004; J. H. Howard, Jr & Howard, 1997; J. H. Howard, Jr et al., 2004).

Do Interviews Reveal Evidence of Declarative Knowledge?

Although most participants thought that there was some regularity (nine and 10 people in the "aged" young and control groups, respectively), none described the alternating structure of the sequence or revealed any other evidence of declarative knowledge. Several people reported incorrectly that the events tended to repeat frequently and a few described event sequences that had no overlap with what actually occurred. These findings

[1] An alternating sequence results in 16 frequently occurring, structure-consistent runs of three consecutive trials (triplets), and 48 less frequent, structure-inconsistent, triplets. For example, in the sequence 1r4r3r2r..., the structure-consistent triplets 1r4, 4r3, 3r2 and 2r1 occur more often than structure-inconsistent triplets such as 142, 224 or 321.

are consistent with previous ASRTT studies in which we have used a number of objective measures of declarative knowledge (e.g., J. H. Howard, Jr et al., 2004) and indicate that the learning described in the following analyses is implicit.

Did Sequence Timing for the "Aged" Young Match that of Older Adults?

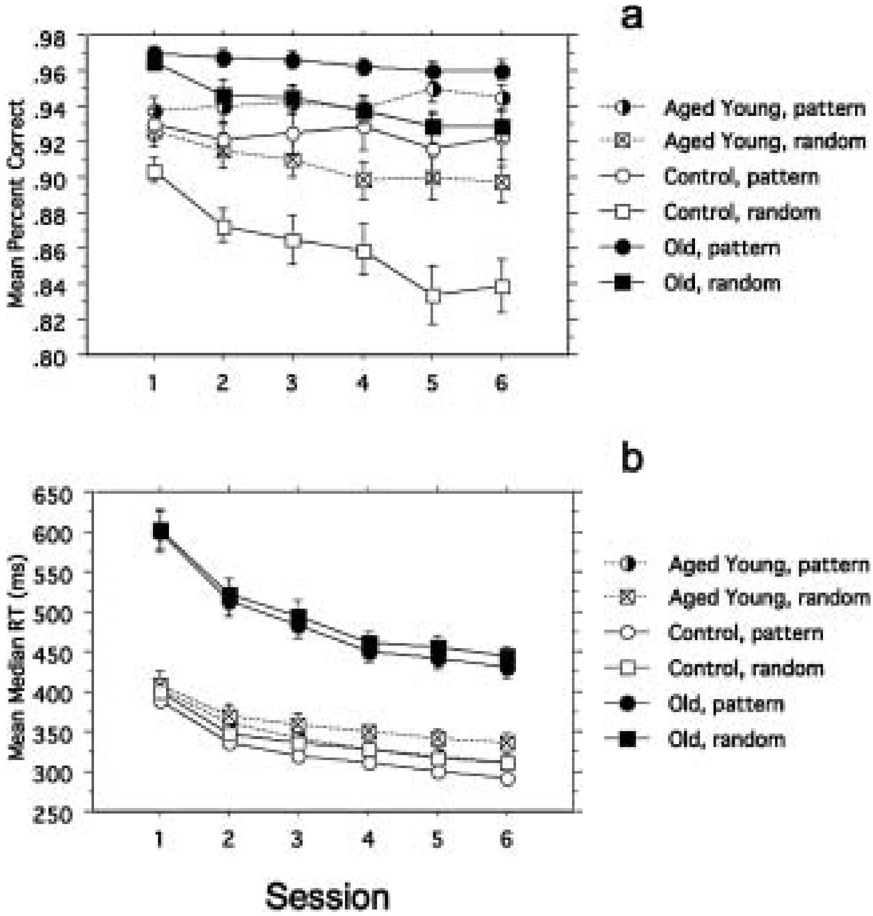
The RSI manipulation was intended to approximate the mean and variance of ISIs experienced by older adults in the "aged" young group. To determine if this actually occurred we calculated the mean and standard deviation of the ISIs within individuals and averaged these values across participants in each group. This revealed a close match in mean ISI between the "aged" young and the older group from the previous comparable experiment described above (mean within-subject ISI of 615 and 600 ms, respectively, $t(22) = .65$); however, ISIs were significantly more variable for the "aged" young than for the old, (mean within-subject ISI standard deviations of 168 and 129 ms, respectively, $t(22) = 4.20$, $p = .0004$). Thus, if variable event timing impairs learning, then the "aged" young here are encountering conditions that are even more challenging than those facing the older adults.

Does Sequence Timing Influence Overall Performance?

Figure 1a plots the mean accuracy for both groups over sessions and Figure 1b shows the comparable mean RTs. The data from a comparison group of older adults (D. V. Howard et al., 2004) are also shown in this figure, though they are not included in ANOVAs or discussed until a later section. These figures suggest that the "aged" young group responded more slowly and more accurately overall than the control group—a pattern reminiscent of that observed for older people in previous studies (J. H. Howard, Jr et al., 2004).[2] This was tested statistically in separate Group ("aged" young vs control) by Session by Trial-type ANOVAs with repeated measures on the latter two factors. The main effect of Group was significant for accuracy, $F(1, 22) = 5.66$, $MSE = .013$, $p = .0265$, but only marginally significant for RT, $F(1, 22) = 3.01$, $MSE = 9736.36$, $p = .0967$. Thus, the "aged"

[2] The mean RT and accuracy data shown in Figure 1 suggest a speed-accuracy tradeoff in that groups with faster responding have higher error rates. Analysis of the individual data revealed a significant positive correlation between overall mean RT and accuracy, $r(36) = .670$, $p < .0001$, consistent with this observation. However, additional analysis found no evidence of a speed-accuracy tradeoff in the *learning* data. Specifically, overall RT was negatively correlated with each of the three learning measures, reaching statistical significance for the accuracy trial type effect, $r(36) = -.627$, $p < .0001$. This indicates that the fastest responders showed the greatest learning, a result consistent with our previous findings with this task (J. H. Howard, Jr & Howard, 1997) and inconsistent with a speed-accuracy tradeoff effect on implicit learning. Since group differences in learning are the primary the focus of this study, a speed-accuracy tradeoff in the overall performance data does not explain the learning effects we report in later sections.

FIGURE 1. Mean percent correct (upper Figure 1a) and mean of median RTs (lower Figure 1b) across sessions for pattern and random trials for each of the three groups in Experiment 1.



young people resemble older adults in their overall performance in that they respond more accurately and marginally more slowly than controls.

Does Timing Influence Implicit Sequence Learning?

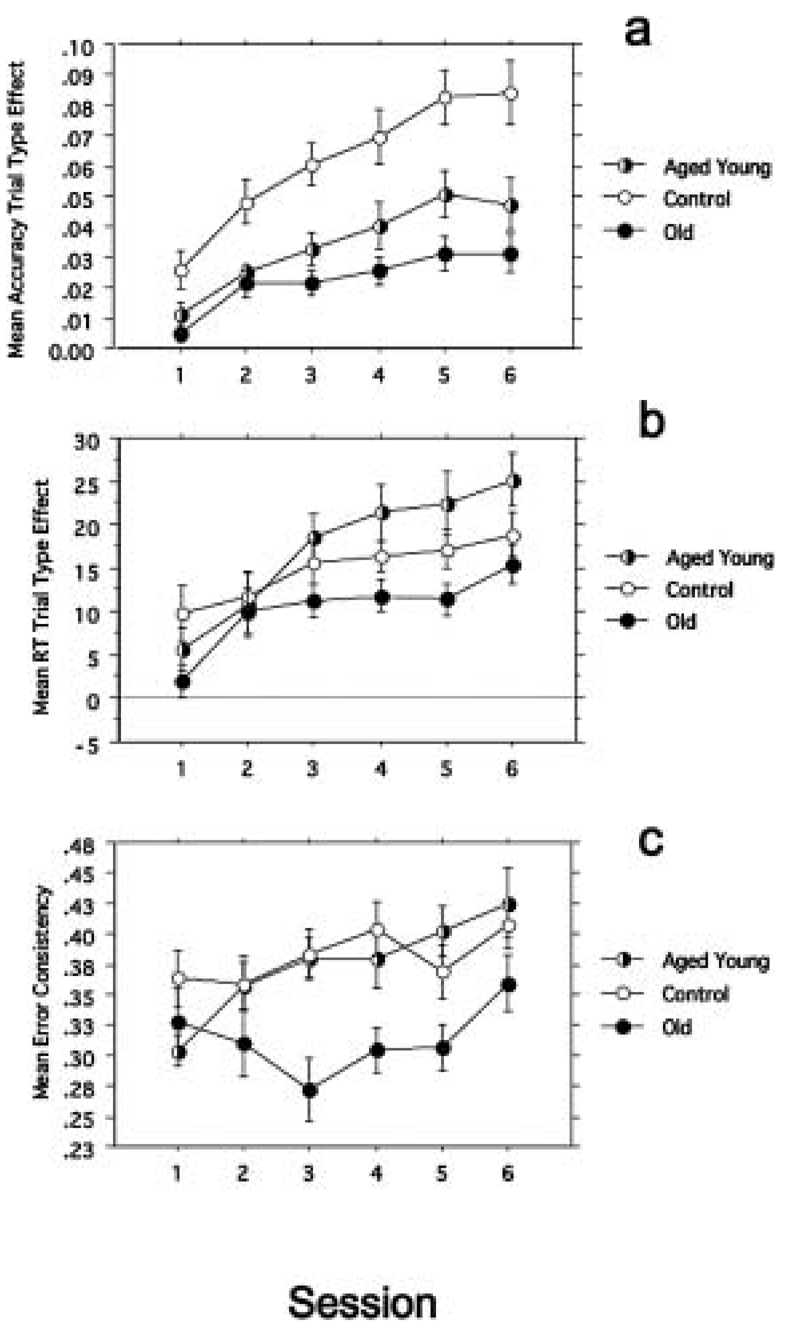
More important for the present study than overall speed and accuracy is the influence of event timing on sensitivity to the sequence structure – that is, on sequence learning. As described above, implicit learning is revealed in positive trial-type effects for accuracy and RT (i.e., relatively faster and more accurate responding to pattern than random trials) as well as in the error consistency measure (i.e., the tendency for errors on the random trials to be pattern consistent) (J. H. Howard, Jr & Howard, 1997).

Figure 1 appears to reveal trial-type effects in both accuracy and RT for both the "aged" young and control groups suggesting that both groups learned. This can be seen more clearly in Figure 2a,b where the trial-type effect is plotted by session for accuracy and RT, respectively. A three-way ANOVA on the accuracy data revealed a significant main effect of Trial-type, $F(1, 22) = 150.17$, $MSE = .001$, $p < .0001$, confirming that, overall, pattern trials were more accurate than random, and a significant Session by Trial-type interaction, $F(5, 110) = 23.10$, $MSE = .0002$, $p < .0001$, indicating that this difference increased with practice. The RT analysis was consistent with this – people were faster on pattern than on random trials [main effect of Trial-type, $F(1, 22) = 85.58$, $MSE = 219.63$, $p < .0001$], and this difference increased with practice [Session by Trial-type interaction, $F(5, 110) = 23.78$, $MSE = 15.26$, $p < .0001$]. Separate two-way ANOVAs on each young group revealed significant main effects of Trial-type and Trial-type by Session interactions, indicating that both groups showed significant sequence learning on both measures. This result is consistent with previous findings that both older and younger adults learn the subtle sequence regularity in the ASRTT.

As mentioned above, earlier research has shown an age-related implicit learning deficit in the ASRTT. Figure 1 suggests that our attempt to "age" young people by giving them a longer and more variable ISI was only partially successful in affecting sequence learning. While the "aged" young group showed a significantly smaller trial-type effect than the control group on accuracy thereby resembling older adults [significant Trial-type by Group interaction, $F(1, 22) = 12.17$, $MSE = .0002$, $p = .0021$], they actually had a greater trial-type effect than controls on RT [significant Group by Session by Trial-type interaction, $F(5, 110) = 3.39$, $MSE = 15.26$, $p = .0069$]. The Group × Session interaction was not significant for RT, but the significant three-way interaction in the latter case indicates that the group difference emerged with practice on the RT measure as may be seen in Figure 2b. The three-way interaction did not reach significance for accuracy. Thus, these findings indicate that the "aged" young show an age-like deficit compared to a young control group on the accuracy trial-type effect, but not on the RT trial-type effect.

To examine the third measure of implicit learning, error consistency, we calculated the relative frequency of structure-consistent errors on random trials for each person and session where we defined consistency in terms of the triplet-structure of the sequences as in earlier work (e.g., D. V. Howard et al., 2004). Figure 2c plots error consistency across sessions. These data suggest, and a Group by Session ANOVA confirms, that the two young groups do not differ on this measure. Errors on random trials become increasingly structure-consistent with practice for the "aged" young and controls [only the main effect of Session was significant, $F(5, 110) = 5.30$, $MSE = .004$, $p = .0002$]. In addition, the observed proportions were significantly greater than the .25 level expected by chance for both young groups on all

FIGURE 2. Mean learning scores for each of the three learning measures (1a, Accuracy Trial Type Effect; 1b, RT Trial Type Effect; 1c, Proportion of structure-consistent errors) and groups across the six sessions of Experiment 1.



sessions. This indicates that both groups of young people became sensitive to the sequence structure early (within the 1680 trials of the first session) and this sensitivity increased with practice. Thus, unlike older adults in earlier studies (D. V. Howard et al., 2004; J. H. Howard, Jr & Howard, 1997; J. H. Howard, Jr et al., 2004), the "aged" young group did not differ from young controls on this measure.

To summarize, these comparisons indicate that young people who experience a longer and more variable ISI show less implicit sequence learning than young controls on only one of the three learning measures, the accuracy trial-type effect. They were quite unlike the older adults on the other two measures revealing no difference in error consistency and actually showing greater learning on the RT trial-type measure. In the following section, we compare the "aged" young to an older group directly.

Do the "Aged" Young Adults Resemble Older Adults?

We compared the experimental group to a group of older adults from a comparable ASRTT experiment from the previous study (D. V. Howard et al., 2004). These comparison data are shown in the filled symbols in Figures 1 and 2. Group × Session by Trial-type repeated measures ANOVAs revealed that the "aged" young responded less accurately (main effect of Group, $F(1, 22) = 8.16$, $MSE = .007$, $p = .0092$), and more quickly than the older adults (main effect of Group, $F(1, 22) = 52.96$, $MSE = 26357$, $p < .0001$). More importantly, the "aged" young also show greater learning than the old adults on all three measures. They had significantly larger trial-type effects than the old in both accuracy and RT (significant Group by Trial-type interactions, $F(1, 22) = 4.72$, $MSE = .001$, $p = .0408$ and $F(1, 22) = 4.79$, $MSE = 183$, $p = .0396$, respectively). The three-way interaction was also significant for RT, $F(5, 110) = 3.40$, $MSE = 15$, $p = .0068$, but not for accuracy. The same pattern was seen in the error consistency data shown in Figure 2c. A two-way ANOVA indicated that the "aged" young revealed significantly greater error consistency than the older adults (significant main effect of Group, $F(1, 22) = 13.09$, $MSE = .010$, $p = .0015$) and this difference increased with practice (significant Group by Session interaction, $F(5, 110) = 2.52$, $MSE = .005$, $p = .0339$).

These analyses demonstrate that the "aged" young people show significantly more implicit learning than a comparison group of older adults on all three measures.

EXPERIMENT 2

The first experiment demonstrated that a longer and more variable ISI leads to less implicit learning on 1 measure in younger adults compared to age-matched controls. This latter result is consistent with earlier findings

(Soetens et al., 2004; Stadler, 1995; Willingham et al., 1997). However, the "aged" young did not differ from controls on two of the learning measures and in a direct comparison they differed from older adults in overall performance as well as on all three measures of sequence learning. Thus, the results of Experiment 1 indicate that differences in event timing may contribute to the age deficits previously seen in the ASRTT (J. H. Howard, Jr & Howard, 1997), but the fact that learning was not impaired on two of the three measures suggests that event timing cannot fully account for them.

However, the first experiment was only partially successful in matching the overall performance of young adults to that of older people. Although the "aged" young group was more accurate and marginally slower than controls, they were significantly faster and less accurate than a comparable old group. In other words, they still looked young when compared to old adults.

In Experiment 2 we manipulated ISI in a different way. Here, we presented young adults with low-contrast events to induce slower and more variable responding and indirectly manipulate event timing. Events were defined by a slight change in the contrast or gray-level of a circle rather than the typical full-contrast change.[3] This experiment differed from Experiment 1 in several additional ways.

First, although the "aged" young in Experiment 1 experienced ISIs that were longer and more variable than usual, there are still potentially important differences between Experiment 1 timing and what older people encounter in the ASRTT. Specifically, since events were extinguished with a correct response, they were displayed for a shorter time than would be typical for older people. Furthermore, under these conditions it is impossible for participants to know precisely when the next event will occur. Previous studies have shown that increased temporal uncertainty can influence overall performance and even make learning more difficult (Sakai et al., 2000). More important for the present study, however, is the possibility that these differences fundamentally alter the ASRTT. A goal of Experiment 2 is to make the ISI longer and more variable while maintaining a fixed RSI and an age-comparable task experience.

Second, there were substantial age differences in overall RT (352 ms vs 492 ms for the "aged" young and old, respectively) and accuracy (.92 vs .95) in the first experiment. In Experiment 2 we adjusted the stimulus contrast in a separate pilot experiment so that the mean RT of young adults matched that of old on the initial session.

Third, in the first experiment it was not possible to distinguish between the effect of sequence timing on learning *per se* and the expression of learning.

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[3] The authors are grateful to Peter Frensch for suggesting this approach.

In other words, it is possible that more learning occurred than was evident in the performance data. Previous studies have shown that a long response-to-stimulus interval (Willingham et al., 1997) or a secondary task (Frensch et al., 1998) can interfere with the ability of people to express what they have learned without impairing learning (see review by Jimenez & Vazquez, 2005). To investigate this we added a seventh session in the second experiment in which events are presented at full contrast.

Finally, in the present experiment we included an explicit recognition test after the final session as an additional probe of declarative knowledge.

Method

Participants

Six college-student volunteers were paid to participate in the "aged" young group (mean age 20.7 years, four females). The first seven of 10 sessions from young and old comparison groups were taken from the same previous experiment as Experiment 1 in which the typical full contrast events were used (D. V. Howard et al., 2004).

Task

The ASRTT was identical to that used in the control group of Experiment 1 except that stimulus events were presented at a reduced contrast in all but the final session. Unlike Experiment 1 in which events differed from non-events by the maximum screen contrast, here they differed only slightly in gray level (38% of the full gray-level scale). Contrast levels were adjusted in a pilot experiment to yield first-session RTs matching those of older adults in our previous studies. The same values were used for all participants.

At the end of training a recognition test was given in which people watched a series of 20 eight-event sequences and rated each on a four-point scale ranging from 1 (certain it had not occurred during training) to 4 (certain it had occurred). Half the sequences were targets that reflected the sequence structure (e.g., 2r4r1r3r) and half were foils generated from a reversed target structure (e.g., 3r1r4r2r). Thus, the targets and foils had the same statistical properties and differed only in their likelihood of occurrence during training. Each presentation began at a random point in the eight-element sequence. As in previous studies (D. V. Howard et al., 2004), people did not respond to each event in the recognition test in order to reduce the likelihood that motor fluency would influence their judgments.

Procedure

The procedure followed that of the control group in Experiment 1 with three exceptions. First, RSI was fixed at 120 ms. Second, there were seven rather than six sessions. The first six sessions used the degraded contrast stimuli, whereas the final session used full-contrast stimuli. Third, an explicit recognition test was administered immediately after the seventh session.

Results and Discussion

Is There Evidence of Declarative Knowledge?

Neither the post-experimental interview nor the recognition test revealed declarative knowledge. No one was able to describe the sequence regularity or realized that it occurred on alternate trials. Consistent with this, in the recognition test people rated the foil (backward sequence) and target sequences as equally familiar (mean ratings of 2.90 and 2.87, respectively, $t(5) = .16$, $p = .88$). This is consistent with our previous work using a number of different measures which has shown that without specific prompting, people do not acquire declarative knowledge in the ASRTT regardless of whether it is measured by this recognition task (Feeney et al., 2002; D. V. Howard & Howard, 2001; D. V. Howard et al., 2004; J. H. Howard, Jr & Howard, 1997; J. H. Howard, Jr et al., 2004), a card sorting task (J. H. Howard, Jr et al., 2006), or an inclusion/exclusion generation task (Dennis et al., 2006). Thus, as in Experiment 1, we conclude that sequence learning was implicit.

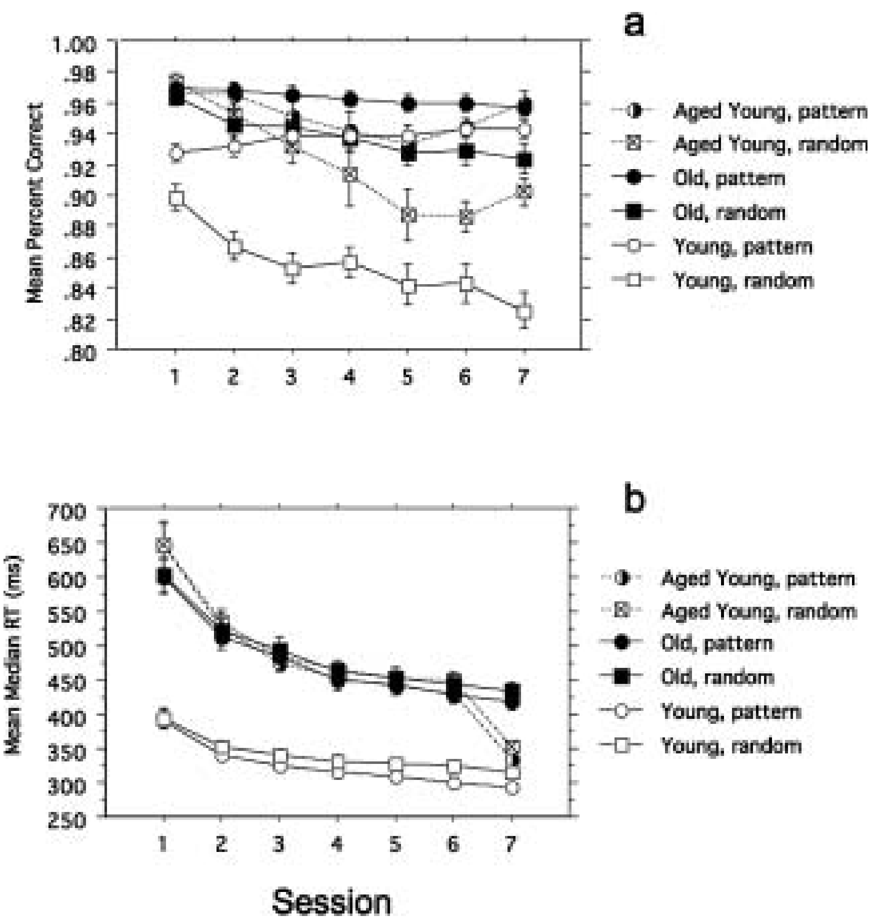
Did Sequence Timing for the "Aged" Young Match that of Older Adults?

A goal of the present experiment was to match the mean and variability of the ISI of "aged" young adults to that of older adults. Since the RSI was fixed, this entails matching the RT distributions. As may be seen in Figure 3b, the "aged" young and old had nearly identical RTs across the initial six sessions (mean overall RTs of 492 and 500 ms, respectively, with no significant main effect or interactions with Group). We also compared the mean within-block RT standard deviations for each individual and session. The "aged" young were significantly more variable than the old in the initial session (mean within subject standard deviations of 208 and 151 ms, respectively; significant Session by Group interaction, $F(10, 135) = 4.75$, $MSE = 263.62$, $p = .0007$), but they were nearly identical in variability across the remaining five sessions (mean within subject standard deviations of 102 and 97 ms, respectively with no significant main effect of Group). Thus, we succeeded in matching the ISIs of the "aged" young adults to those of older adults in both mean and variance.

Do Low-Contrast Events Influence Overall Performance?

The "aged" young not only matched the older adults in their overall RT as shown above, but in their overall accuracy as well. They did not differ significantly from older adults in accuracy (.937 vs .953, respectively, $F(1, 16) = 2.658$, $MSE = .004$, $p = .1225$), and they also resembled older

FIGURE 3. Mean percent correct (upper Figure 3a) and mean of median RTs (lower Figure 3b) across sessions for pattern and random trials for each of the three groups in Experiment 2.



people in responding significantly more slowly (500 vs 338 ms, respectively, $F(1, 16) = 118.73$, $MSE = 10699$, $p < .0001$) and more accurately (.937 vs .898, $F(1, 16) = 12.18$, $MSE = .006$, $p = .0030$) than the young comparison group. Thus, reducing the event contrast leads young adults to resemble older people in their overall performance.

Does Sequence Learning Occur with Low-Contrast Events?

Analysis of the first six sessions for the “aged” young group indicated that significant learning occurred on all three measures. Session by Trial-type ANOVAs on accuracy and RT (Figure 3) revealed significant learning on both measures, $F(1, 5) = 62.50$, $MSE = .0002$, $p = .0005$ and $F(1, 5) = 11.78$, $MSE = 167.27$, $p = .0186$, respectively, as well as significant Trial-type by Session interactions, $F(5, 25) = 12.94$, $MSE = .0001$, $p < .0001$ and $F(5, 25) = 3.92$, $MSE = 27.65$, $p = .0092$, respectively. The main effects of Session were also significant, $F(5, 25) = 7.21$, $MSE = .001$, $p = .0003$ and $F(5, 25) = 36.10$, $MSE = 2037.45$, $p < .0001$, for these measures, respectively. A one-way repeated-measures ANOVA on error consistency (Figure 4c) also showed learning. The main effect of Session, $F(5, 25) = 5.53$, $MSE = .004$, $p = .0015$, was significant indicating that the proportion of structure-consistent errors on random trials increased with practice. Thus, the "aged" young learned the sequence regularity as revealed by all three learning measures.

Is Sequence Learning Impaired in the "Aged" Young?

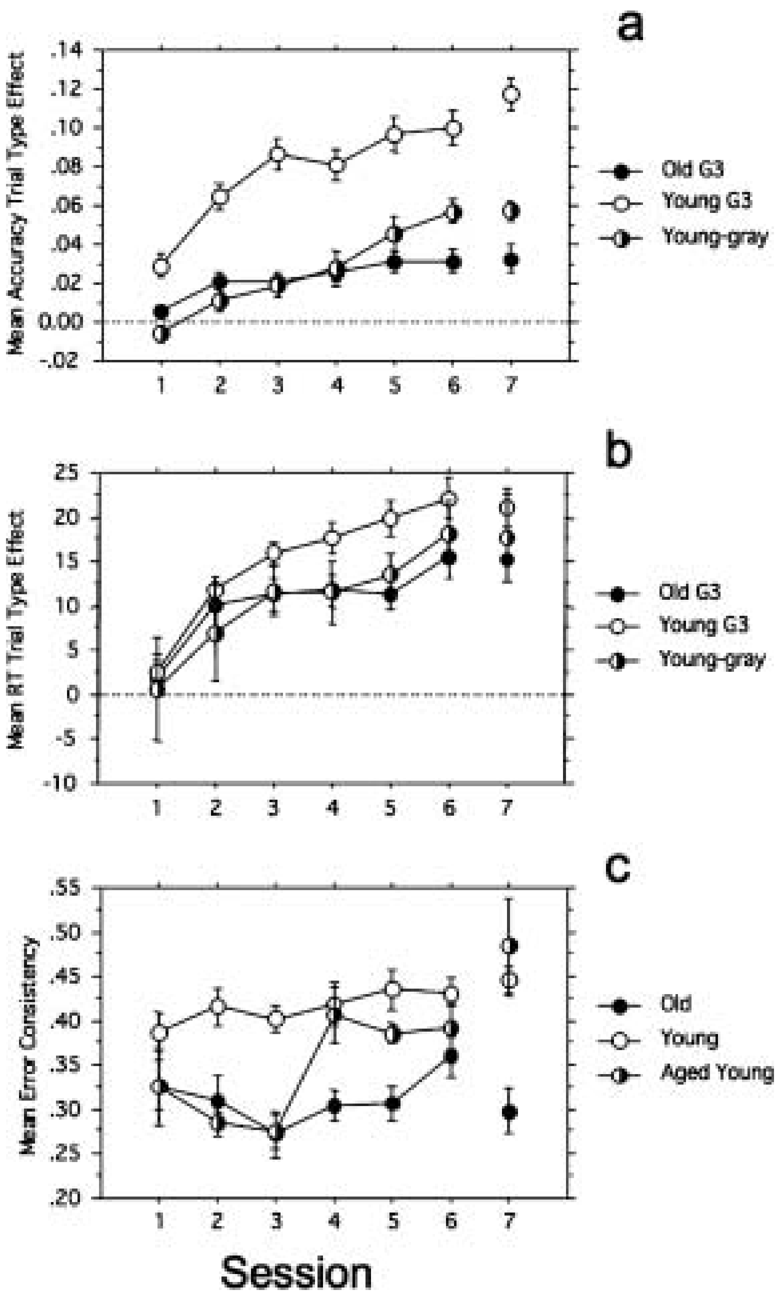
We compare the "aged" young to the young comparison group from our earlier study on the three learning measures in this section, and to the old comparison group in the next.

Group ("aged" young vs young) by Session by Trial-type ANOVAs were performed on the first six sessions of the accuracy and RT data (Figure 3). The Trial-type by Group interaction was significant for accuracy, $F(1, 16) = 30.57$, $MSE = .001$, $p < .0001$, indicating that the "aged" young showed less learning than their high-contrast counterparts as is evident in Figures 3 and 4a. This interaction was not significant for the RT measure, $F(1, 16) = 2.49$, $MSE = 109.23$, $p = .1339$, indicating that the two groups did not differ on the RT trial-type measure (see Figure 4b). These results are consistent with those of Experiment 1 in revealing an implicit learning deficit for the "aged" young group on the accuracy measure, but not on the RT measure.

Figure 4c displays error consistency plotted by session and group. A Group by Session ANOVA on the first six sessions comparing the "aged" young and young control groups revealed significant main effects of Group, $F(1, 16) = 11.96$, $MSE = .010$, $p = .0032$, and Session, $F(5, 80) = 5.35$, $MSE = .004$, $p = .0003$, as well as a significant Group by Session interaction, $F(5, 80) = 2.55$, $MSE = .004$, $p = .0342$. As may be seen in the figure, this reflects the fact that the "aged" young showed less learning on this measure than the comparison young early in learning (through session 3), but nearly equivalent learning thereafter.

The foregoing analyses indicate that reducing the event contrast not only influenced the overall speed and accuracy of the "aged" young adults, but it also led to an overall implicit learning deficit on the accuracy measure as well as a deficit on the error consistency measure, but only early in learning. The latter result indicates that the "aged" young were able to overcome some of the adverse effects of low-contrast stimuli on sequence learning after extensive practice even though their overall RT did not improve.

FIGURE 4. Mean learning scores for each of the three learning measures (1a, Accuracy Trial Type Effect; 1b, RT Trial Type Effect; 1c, Proportion of structure-consistent errors) and groups across the six low-contrast and one high-contrast session of Experiment 2.



Do the "Aged" Young Match the Old Comparison Group in Sequence Learning?

Similar analyses were carried out to compare the "aged" young and the older comparison group. The ANOVA on accuracy revealed significant main effects of Session and Trial-type as well as significant Session × Group and Session × Trial-type interactions, but the most important effect for our present purposes was the significant Session × Trial-type × Group interaction, $F(5, 80) = 4.80$, $MSE = .00009$, $p = .0007$. This indicates that the "aged" young showed more learning than the older adults, but only after extensive practice. *Post hoc* examination of this interaction showed that the group difference in learning reached significance on session 6, $t(16) = 2.64$, $p = .0177$. Thus, on this measure the "aged" young were similar to the old early, but diverged from the older adults later in learning

The RT trial-type data shown in Figure 4b show a different pattern. An ANOVA revealed significant main effects of Session and Trial-type as well as a significant Session × Trial-type interaction, but neither the main effect of Group nor any of the interactions with Group reached significance. Thus, the two groups show equivalent learning on the RT trial-type measure.

The error consistency data (Figure 4c) suggest that "aged" young closely match the old early in training, but differ from them on sessions 4 and 5, similar to the pattern observed on the accuracy trial type measure. However, here, unlike the accuracy trial type measure, the Session × Group interaction was not significant, $F(5, 80) = 1.85$, $MSE = .005$, $p = .1123$. Only the main effect of Session reached significance, $F(5, 80) = 4.35$, $MSE = .005$, $p = .0015$. Thus, the error consistency data mirror the RT in revealing no difference in learning between the old and "aged" young.

Overall, these results suggest that the "aged" young group resembles older adults on two of the three learning measures, the RT trial-type effect and error consistency. In addition, the two groups were quite similar across the first five sessions on the accuracy trial-type measure, but differ on the sixth session. This suggests that the "aged" young adults may be able to overcome an initial learning deficit on this measure after extensive practice. A similar, but statistically non-significant pattern was seen in the error consistency data.

Do Low-Contrast Stimuli Influence Learning or Performance?

As indicated above, low-contrast events may impair people's ability to express what they have learned rather than their ability to learn *per se*. To evaluate this, we compared all three learning measures on the last low-contrast sessions 6–7 in which full-contrast events were introduced. Improved overall performance without a corresponding increase in the three learning measures would point to a true learning impairment.

Session × Trial-type ANOVAs were carried out on sessions 6 and 7 of the "aged" young data shown in Figures 3 and 4. This revealed significant main effects of Session, $F(1, 5) = 28.10$, $MSE = .00005$, $p = .0032$; $F(1, 5) = 203.58$, $MSE = 272.98$, $p < .0001$, and Trial-type, $F(1, 5) = 393.70$, $MSE = .00005$, $p < .0001$; $F(1, 5) = 19.32$, $MSE = 101.21$, $p = .0071$; for accuracy and RT, respectively. More importantly, the Trial-type × Session interaction did not approach significance in either analysis indicating that while people became significantly faster (440 vs 344 ms) and more accurate (.915 vs .931) when shifted to full-contrast events in session 7, this was not accompanied by an increase in either the accuracy (.057 vs .058 in sessions 6 and 7, respectively) or RT (18.31 vs 17.79 ms) trial-type effect.

The error-consistency data in Figure 4c suggest a somewhat different result – the "aged" young people show a substantial increase in their structure-consistent errors when full-contrast events are introduced (.393 vs .484 for sessions 6 and 7, respectively). Despite this, however, the Session effect did not reach significance. Thus, all three measures indicate that the degraded stimuli led to true differences in learning.

GENERAL DISCUSSION

The objective of this study was to investigate the possible role of event sequence timing in the age-related implicit learning deficit observed in the ASRTT and other higher-order sequence learning tasks. The present experiments varied timing in two different ways, both of which achieved the objective of inter-event intervals close to those of older adults in both duration and variability. There were several major findings as summarized below.

First, despite the substantial differences in procedure, both experiments revealed overall performance in the "aged" young that resembled that of older adults. Specifically, the "aged" young were significantly more accurate than young controls in both experiments as well as significantly slower in the second experiment and marginally so in the first. These findings are consistent with previous studies that have manipulated event timing in tasks with repeating sequences (Frensch & Miner, 1994; Willingham et al., 1997) as well as with recent findings using subtle, probabilistic higher-order sequences (Soetens et al., 2004).

Second, although in both experiments the "aged" young appeared older than their peers in overall speed and accuracy, the two experiments produced very different results when they were compared to older adults. In the first experiment, the "aged" young were faster and less accurate than the old whereas in the second, they matched the old on both speed and accuracy. This indicates that while both experimental procedures succeeded in "aging" the overall performance of young adults, the event contrast manipulation of

Experiment 2 did so to a greater degree than the timing manipulation of Experiment 1.

Third, more important for the present study than the changes in overall speed and accuracy are group differences in implicit sequence learning. Both experiments revealed evidence of impaired learning in the "aged" young on some measures, but to different degrees. Impairment was minimal in the first experiment, with the "aged" group showing less learning than young controls on only one of the three learning measures (accuracy, but not RT or error consistency), but significantly greater learning on all three measures than a comparison group of older adults. Thus, directly varying event timing had only a minor influence on implicit sequence learning despite leading to ISIs that matched those of the older group.

The second experiment revealed learning deficits for the "aged" young compared to their peers on two of the three learning measures. Specifically, there was significantly impaired learning on the accuracy trial type measure as well as on the error consistency measure in early sessions. Further, the "aged" young matched the comparison group of older adults on the RT and error consistency measures. Thus, there is evidence of impaired learning in the "aged" young on some measures in both experiments.

Overall, then, the ability of young adults to learn a higher-order probabilistic sequence structure implicitly was disrupted to some degree in both experiments. This occurred despite the very different manipulations used to "age" the young in the two experiments both of which were equally effective in matching the ISI to that of older adults. On the other hand, since the resulting impairment fell short of that previously observed for older learners (Curran, 1997; D. V. Howard et al., 2004; J. H. Howard, Jr & Howard, 1997), we conclude that event timing alone cannot explain the age deficits in sequence learning.

Two aspects of our findings support this conclusion. First, the two experiments did not reveal a consistent pattern of learning impairment despite the fact that both matched the event timing experienced by older adults. If event timing alone led to the deficit then the "aged" young in the two experiments should have shown the same pattern of deficits. Second, there is also evidence in Experiment 2 that the "aged" young are able to overcome this deficit with practice since their sequence learning, but not their overall RT and accuracy, differ more from older adults on the later sessions than the earlier sessions. Thus, the "aged" young differ from the older adults in that previous studies have shown that the age-related implicit learning deficits persist even after almost twice the practice used in the present study (D. V. Howard et al., 2004).

Although event timing does not explain the age deficits in higher-order sequence learning, our experimental manipulations did lead to impaired sequence learning on some measures. How do we account for these effects? One possibility is that the manipulations in both experiments increased task difficulty. For example, the greater working memory load created by longer ISIs in the first experiment may have disrupted the ability to learn the predictive relationships among events in the first experiment (e.g., Frensch & Miner, 1994), whereas the degraded target events led to slower perceptual processing and greater task difficulty in the second (e.g., Lindenberger et al., 2001). While the finding that the “aged” young responded more slowly overall than their age-matched peers in both experiments is consistent with this explanation, the fact that they were also more accurate is not. Nonetheless, this explanation cannot be ruled out on the basis of the present data.

Another possibility is that the changes we introduced to the experimental tasks influenced the strategies adopted by the “aged” young to perform the task. For example, the degraded events used in Experiment 2 would be less likely to “pop out” perceptually than the typical high-contrast events. This in turn might require a visual search to identify the event location after a change is detected. While we are not able to address this possibility in the present study, it does serve to illustrate how changes to the display could influence how the ASRTT is performed.

In conclusion, the present findings have produced implicit sequence learning deficits on some measures in “aged” young adults by introducing task changes that influence event timing. It is possible that these effects were indirect in that the changes we used to vary event timing altered task difficulty or influenced the processes people used to perform the task. Regardless of the specific cause of these effects, the finding that the two experiments revealed distinct patterns of deficits despite nearly identical event sequence timing, and the fact that young people “aged” in these ways still learned more than older adults suggest that event timing alone cannot explain the age deficits observed in high-order implicit sequence learning.

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