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# Age-Related Differences in Implicit Learning of Subtle Third-Order Sequential Structure

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**Age-related implicit learning deficits increase with sequence complexity, suggesting there might be limits to the level of structure that older adults can learn implicitly. To test for such limits, we had 12 younger and 12 older adults complete an alternating serial reaction time task containing subtle structure in which every third trial follows a repeating sequence and intervening trials are determined randomly. Results revealed significant age deficits in learning. However, both groups did learn the subtle regularity without explicit awareness, indicating that older adults remain sensitive to highly complex sequential regularities in their environment, albeit to a lesser degree than younger adults.**

IMPLICIT sequence learning refers to the nonconscious acquisition of a pattern or regularity within a series of stimuli. This type of sequential learning is important for skills such as language acquisition (Kuhl, 2004) and social intuition (Lieberman, 2000), because they involve the learning of predictable patterns from environmental input (i.e., speech and nonverbal social cues) without awareness of what has been learned. Identifying preserved or deficient implicit sequence learning in healthy older adults is therefore relevant to their ability to adapt and respond effectively to regularities in their environment.

Researchers can measure implicit sequence learning by using the original serial reaction time (SRT) task (Nissen & Bullemer, 1987), or a modified version, such as the alternating serial reaction time (ASRT) task (J. H. Howard, Jr. & Howard, 1997). Typically in these tasks, four locations are displayed on a screen. For each trial, a stimulus appears at one location and participants make a corresponding button press, triggering the onset of the next trial. Stimuli that follow a repeating sequence of locations and stimuli that occur in randomly determined locations are presented in separate blocks for the SRT task, and alternate within blocks for the ASRT task. For both tasks, implicit learning is seen as faster reaction times or increased accuracy to pattern versus random trials.

Age-related differences in sequence learning seem to depend on the level of sequential structure that is present to be learned. Studies reporting that implicit sequence learning is unaffected by healthy aging (Frensch & Miner, 1994; D. V. Howard & Howard, 1989) have used sequences with simple structure, in which single elements (zeroth-order structure) or pairs of elements (first-order structure) occur more frequently than others. Thus, in the SRT sequence 423132432, individuals would show learning even if they only learned that elements 2 and 3, or pairs 32 and 24, occur most often. In contrast, studies that use more complex sequences in which the lowest level of regularity to be learned spans three consecutive trials (second-order structure) show implicit learning in both younger and older adults, but with significantly less learning in older adults (Curran, 1997; D. V. Howard et al., 2004; J. H. Howard, Jr., Howard, Dennis, Yankovich, & Vaidya, 2004).

These age-related implicit learning deficits for complex sequential structure may result from age-related slowing of cognitive processing. According to Salthouse's simultaneity theory (Salthouse, 1996), age-related slowing prevents the products of early processing stages from being available in the later stages. Thus, older adults have less information simultaneously activated. Implicit sequence learning involves integrating stimuli over time, by comparing active representations of elements to predictable outcomes. Assuming that implicit learning of associations among elements requires that they be activated simultaneously (Frensch & Miner, 1994), such simultaneity deficits would explain why older adults are impaired at implicit learning of complex high order, but not low order, sequential structure.

In a recent study we identified a possible upper limit on the level of sequential structure that older adults can learn. The study compared younger and older adults on two ASRT tasks that differed in the level of high order sequential structure (D. V. Howard et al., 2004). When the sequence had second-order structure (e.g., 1r2 for the sequence 1r2r3r4r, with r denoting one of the four randomly determined events), both groups learned the regularity, with larger learning effects for younger than for older adults. However, when we made the regularity even more complex by using third-order structure in which the lowest level of regularity spans four consecutive trials (e.g., 1rr2 for the sequence 1rr2rr3rr4rr), only young adults showed significant learning, even after 2,100 repetitions of the sequence. Thus, third-order structure may be the limit at which older adults no longer show sensitivity to regularities within the environment.

We designed the current study to probe such limits; we examine whether older adults can learn third-order structure in a simplified task. D. V. Howard and colleagues (2004) used a four-element ASRT task in which participants make responses that correspond to four possible stimulus locations (e.g. 1rr2rr3rr4rr). In contrast, in the current study we used a three-element design that reduces the number of possible stimulus locations and responses to three, but does not alter the third-order structure that spans four trials (e.g., 1rr2rr3rr). If the absence of learning in the four-element task was due solely to the inability to simultaneously activate four successive elements, then older adults also shouldn't learn in the three-element task. However, if older adults can learn third-order structure with the simplified task, then alternative processing differences (e.g., associative binding deficits) must also underlie age deficits in implicit learning of higher order sequential structure.

## Methods

### Participants

Participants were 12 Georgetown University students and 12 healthy older adults who responded to advertisements in the Health Section of the *Washington Post*. Demographics and neuropsychological characterizations for each group are presented in Table 1. Participants received either payments or course credit. The Georgetown University Institutional Review Board approved the experimental procedures, and all participants gave informed consent.

Table 1. Demographics and Neuropsychological Test Results

| Demographics or Test Results | Young ($n$ = 12) | Old ($n$ = 12) | $t$ |
|---|---|---|---|
| Demographics | | | |
| Age | 20.0 ± 1.5 | 71.9 ± 6.0 | −28.9** |
| Education | 13.5 ± 1.3 | 17.7 ± 1.7 | −6.8** |
| Male/female | 3/9 | 5/7 | |
| Neuropsychological tests | | | |
| Mini-Mental State Examination[a] | 29.8 ± 0.4 | 28.8 ± 1.2 | 2.9* |
| WAIS-III Vocabulary[b] | 50.6 ± 8.2 | 54.8 ± 3.6 | *ns* |
| WAIS-III Digit Symbol Coding[c] | 92.3 ± 14.4 | 63.6 ± 14.2 | 4.9** |
| WAIS-III Digit Symbol Pairing[d] | 14.4 ± 3.4 | 10.3 ± 5.3 | 2.3* |
| WAIS-III Digit Symbol Recall[e] | 8.2 ± 1.0 | 7.3 ± 1.0 | 2.3* |
| WAIS-III Digit Span Forward[f] | 14.0 ± 1.8 | 10.7 ± 1.9 | 4.4** |
| WAIS-III Digit Span Backward[f] | 8.8 ± 1.7 | 8.3 ± 2.3 | *ns* |

*Notes*: All scores are given as $M \pm SD$. WAIS-III = Wechsler Adult Intelligence Scale III. Independent sample $t$ tests show group effects (*$p < .05$, **$p < .001$). Neuropsychological tests screened for [a]dementia; and they measured [b]vocabulary, [c]processing speed, [d]cued recall, [e]free recall, and [f] working memory.

### Materials and Procedure

Stimuli for the ASRT task consisted of three black-outlined open circles presented in a row on a 17-in. (43.18-cm) computer monitor. On each trial, one circle filled in with black; the experimenter instructed the participant to press one of three buttons corresponding to the three target locations by using his or her dominant hand. The target remained on the screen until the correct response was made, and 120 ms later the target for the following trial was presented.

Participants completed six sessions of the ASRT task over 2 days of testing. Each session contained 10 blocks of 190 trials consisting of 10 practice trials followed by 20 repetitions of the nine-element-long pattern (subsequently described). Therefore, participants encountered 1,200 repetitions of the pattern over the six sessions.

The repeating pattern in this ASRT task had third-order structure; thus, every third trial was part of a repeating pattern. The two patterns we used in this study were 1rr2rr3rr and 1rr3rr2rr, where numbers refer to the location of the filled-in circle (1 = left, 2 = middle, and 3 = right) and the letter r refers to a random trial in which the target could occur at any of the three locations. (The result of this regularity is that, unlike SRT tasks that use pseudorandom sequences, repetitions such as 1111 can occur here. However, as we explain later in the text, we omitted repetitions from the analyses.) Half of the participants in each age group received one pattern and the remaining half received the other.

The experimenter did not tell participants about the repeating pattern. The experimenter instructed them to respond to each target as quickly as possible with the goal of attaining ~92% accuracy for each block. At the end of each block, participants received feedback designed to maintain their performance at 92% accuracy. For young participants, this feedback displayed their mean reaction time and accuracy for a given block, but old participants were only shown their mean reaction time scores. A statement also prompted participants to "focus more on speed" if their mean accuracy for a given block was above 93% for young and 90% for old, or "focus more on accuracy" if their mean accuracy was below 91% for young and 80% for old. If their mean accuracy for a given block was between 91% and 93% for young and 80% and 90% for older participants, the feedback stated "speed and accuracy are about right." This differential feedback was previously shown to match the age groups on overall accuracy (Negash, 2003); without it, older adults tend to make substantially fewer errors than younger adults, complicating age comparisons.

Participants completed 2 days of testing lasting ~2.5 and ~2 hr, respectively. On the first day, the experimenter gave them a short neuropsychological evaluation and had them fill out biographical and health screen questionnaires. This was followed by three sessions of the ASRT task, lasting ~20 min each. The second day began with three more sessions of the ASRT task, followed by a postexperiment interview and then a card sort task.

We used the postexperiment interview to assess explicit knowledge of the sequence, with questions ranging from general ("Do you have anything to report about the task or stimuli?") to specific ("Did you notice a pattern?" followed by "Can you describe the pattern to me?").

For the card sort task, stimuli consisted of 81 cards, each depicting one of all possible combinations of four consecutive trials (quadruplets) from the ASRT task. Each card had three circles on four rows, with one circle on each row filled in black. The experimenter asked participants to sort the cards into two piles on the basis of whether the quadruplet occurred most often versus least often.

Short breaks (~1 min) were given after each block, with longer breaks between sessions (~10 min). No less than 1 day and no more than 5 days elapsed between Sessions 3 and 4, except for one young participant whose sessions were separated by 20 days.

### Statistical Analyses

For each participant, we calculated median reaction times on correct trials and mean accuracy scores for each block. We then created a variable of epoch by taking the mean of these scores across groups of five blocks.

Previous studies show that individuals learn the relative frequency of the smallest repeating units of a sequence rather than the alternating structure (D. V. Howard et al., 2004;

Perruchet, Gallego, & Savy, 1990). That is, for sequences with second-order structure, instead of learning the rule (e.g., 1 with any intervening event is followed by 2), they learn that certain sequence chunks occur more frequently (e.g., 112, 122, 132, 142). For third-order sequences, runs of four consecutive trials, or quadruplets, are the smallest repeating unit. There are four possible quadruplet types: high frequency (HF), low frequency (LF), repetitions, and quills. HF quadruplets occur often because the first and fourth elements are part of the repeating pattern. For example, 1232 and 3121 are HF quadruplets for the sequence 1rr2rr3rr. LF quadruplets are not consistent with the repeating pattern (e.g., 1213 and 2231 for the sequence 1rr2rr3rr). Repetition quadruplets refer to runs of four identical elements, such as 1111 or 2222, and quill quadruplets have identical first and fourth elements, such as 1231 or 3213. (We adapted the term *quill* from earlier second-order studies in which triplets with identical first and third elements were called *trills*.)

We use statistical analyses to examine implicit learning of the sequence by using repeated-measures analyses of variance (ANOVAs) with the between-subject variable of group (young, old) and the within-subject variables of quadruplet type (HF, LF) and epoch (1–12). We measure reaction time and accuracy from the last trial of HF and LF quadruplets.

Our analyses do not include repetitions or quills for two reasons. First, these quadruplet types have been shown to reflect preexisting response biases rather than, or in addition to, sequence learning, with repetitions yielding fast and accurate responses as a result of perceptual or motor priming (Cleeremans & McClelland, 1991; Remillard & Clark, 2001) and quills producing slow and less accurate responses as a result of negative recency or inhibition of return (Boyer, Destrebecqz, & Cleeremans, 2005). Second, repetitions and quills are not counterbalanced across subjects in that they are infrequent for all participants and therefore do not necessarily reflect learning (D. V. Howard et al., 2004). In contrast, HF and LF quadruplets are counterbalanced across subjects because quadruplets that are HF for one pattern are LF for the other (e.g., 1rr2 is HF for the sequence 1rr2rr3rr but LF for the sequence 1rr3rr2rr).

Because of this counterbalancing, any significant HF versus LF difference must be due to learning that occurred during the experiment. Therefore, we consider both main effects of quadruplet type and Quadruplet Type × Epoch interactions to indicate learning of the regularity. Similarly, we consider the presence of either a Group × Quadruplet Type interaction or a Group × Quadruplet Type × Epoch interaction to indicate age deficits in learning. This approach to measuring learning is comparable with that used in the standard SRT task, in which learning is indexed by reaction time differences between pattern and random blocks (e.g., Nissen & Bullemer, 1987), and age deficits in learning are assessed by means of Age Group × Block Type interactions (e.g., Cherry & Stadler, 1995; D. V. Howard & Howard, 1989).

## Results

### Demographics and Neuropsychological Data

Demographic information and neuropsychological test results are presented for younger and older adults in Table 1. All participants scored within the age-expected range for the neuropsychological measures, with age deficits observed for measures of processing speed and memory but not for vocabulary. Mini-Mental State Examination scores were $\geq 28$, except for one older adult who scored 26.

### Implicit Learning Analysis

To assess potential group differences in implicit sequence learning, we conducted Group (young, old) × Quadruplet Type (HF, LF) × Epoch (1–12) mixed design ANOVAs separately for reaction time and accuracy measures.

For reaction time, there was a significant main effect of group, $F(1, 22) = 30.3$, $p < .001$, partial $\eta^2 = 0.58$, with slower responses for older versus younger adults (73.1 ms). Significant effects of epoch, $F(11, 242) = 35.3$, $p < .001$, partial $\eta^2 = 0.61$, and Group × Epoch, $F(11, 242) = 2.6$, $p < .01$, partial $\eta^2 = 0.10$, showed that overall reaction time decreased more across epochs for older than for younger adults. What is more important is that significant sequence learning was revealed by quadruplet type, $F(1, 22) = 21.9$, $p < .001$, partial $\eta^2 = 0.49$, and Quadruplet Type × Epoch, $F(11, 242) = 2.8$, $p < .01$, partial $\eta^2 = 0.11$, effects, which showed faster responses to HF versus LF quadruplets, a difference that increased across trials (see Figure 1). The Group × Quadruplet Type interaction, $p = .60$, partial $\eta^2 = 0.01$, observed power = .07, and Group × Quadruplet Type × Epoch interaction, $p = .66$, partial $\eta^2 = 0.03$, observed power = .43, were not significant, indicating that we did not detect group differences in sequence learning on reaction time. This lack of a significant age deficit in learning on the reaction time measure could be due to a lack of power. In fact, paired *t* tests provide some evidence that older adults are showing less sensitivity to the pattern in that there was not a significant quadruplet type difference until Epoch 7, $t(1, 11) = -2.6$, $p < .03$, compared with Epoch 5 for younger adults, $t(1, 11) = -2.8$, $p < .02$.

Separate Quadruplet Type × Epoch ANOVAs confirmed that both groups learned the sequence on the reaction time measure, with younger adults having a significant quadruplet type effect (3 ms), $F(1, 11) = 28.5$, $p < .001$, partial $\eta^2 = 0.72$, and older adults having a quadruplet type effect (2.4 ms), $F(1, 11) = 5.5$, $p < .04$, partial $\eta^2 = 0.33$, and Quadruplet Type × Epoch effect, $F(11, 121) = 2.0$, $p < .04$, partial $\eta^2 = 0.15$.

For accuracy, there was not a significant main effect of group, $p = .33$, partial $\eta^2 = 0.04$, indicating that, as we intended, the feedback provided after every block effectively matched the groups on overall accuracy. The epoch effect, $F(11, 242) = 2.7$, $p < .01$, partial $\eta^2 = 0.11$, showed that accuracy decreased across epochs. This commonly observed result indicates that as participants gradually learn the probabilistic pattern, they make increasingly more errors on trials that do not obey the regularity. Sequence learning was seen as a significant effect of quadruplet type, $F(1, 22) = 24.8$, $p < .001$, partial $\eta^2 = 0.53$, with higher accuracy for HF than for LF quadruplets (1.1 %). Importantly, there were age deficits in the magnitude of learning on this measure with a Group × Quadruplet Type interaction, $F(1, 22) = 4.4$, $p < .05$, partial $\eta^2 = 0.17$, observed power = .52, showing that the quadruplet type effect was significantly larger for younger (1.6 %) than older adults (0.7 %). Even though the three-way interaction was not significant ($p \sim .39$, observed power = .58), paired *t* tests suggest that the onset of learning was earlier for younger adults,

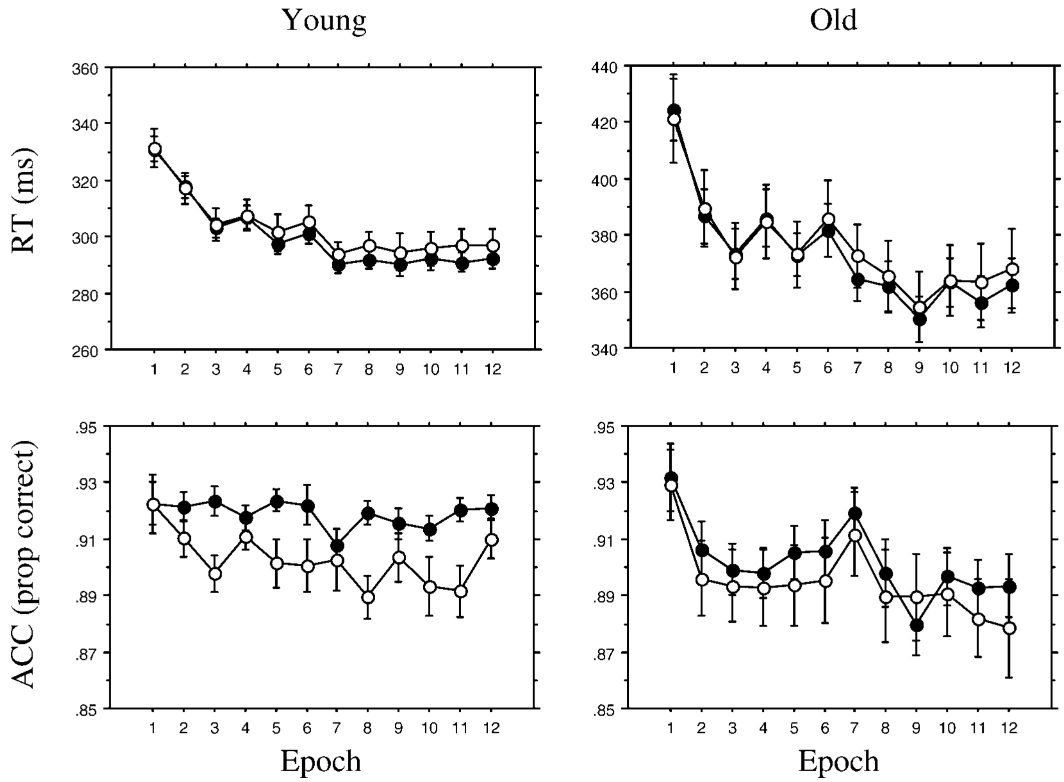


Figure 1. Responses to high frequency (closed circle) versus low frequency (open circle) quadruplets for younger and older adults on mean of median reaction time (ms) and mean accuracy (proportion correct) measures. Note that *y* axes for the reaction time graphs use the same scale (100-ms range with 20-ms increments) but have different intercepts because of group differences in overall reaction time.

who first showed a quadruplet type effect on Epoch 3, $t(1, 11) = -4.3$, $p < .01$, compared with older adults, who did not show a significant difference until Epoch 5, $t(1, 11) = 2.3$, $p < .04$.

Although there were age deficits in learning on the accuracy measure, both groups did learn the regularity. Separate Quadruplet Type × Epoch ANOVAs showed a significant quadruplet type effect, $F(1, 11) = 18.7$, $p < .01$, partial $\eta^2 = 0.63$, and a Quadruplet Type × Epoch effect, $F(11, 121) = 2.3$, $p < .02$, partial $\eta^2 = 0.17$, for younger adults, and a quadruplet type effect for older adults, $F(1, 11) = 6.3$; $p < .03$, partial $\eta^2 = 0.36$.

To determine the extent to which individuals showed learning, we conducted Quadruplet type (HF, LF) × Epoch (1–12) ANOVAs for each individual for reaction time and accuracy, using blocks within each epoch to determine error variance. Quadruplet Type × Epoch interactions were not usually significant, most likely because of the low power in these individual ANOVAs. However, the main effect of quadruplet type, $F(1, 4)$, $p < .05$, was significant for all younger and older adults for the accuracy measure, and six younger and one older adult for reaction time. Thus, both age groups were sensitive to the sequential regularity, particularly revealed by the accuracy measure.

### *Implicitness*

After completing the ASRT task, participants were queried about their knowledge of the repeating sequence. Eleven participants (4 young, 7 old) indicated that they did not notice a repeating pattern in the stimuli. Remaining participants reported that they could not use the pattern to improve performance. Most stated that thinking they recognized a regularity led them to slow down or make mistakes. After being informed that the task did contain a repeating sequence, 4 young and 5 old adults attempted to describe the regularity, but no one produced a sequence that was presented during the experiment.

Participants then completed a card sort task in which they were instructed to separate 81 cards depicting all possible combinations of four consecutive trials (quadruplets) into those that occurred more versus less often. A Group × Quadruplet Type (HF, LF) mixed design ANOVA for cards sorted into the "more often" category did not reveal any significant effects. Thus, younger (HF, 14.4 ± 2.8; LF, 15.3 ± 3.2) and older (HF, 15.0 ± 4.9; LF, 15.0 ± 5.1) adults were not aware that HF quadruplets occurred more often than did LF quadruplets. Separate chi-square analyses for each participant confirmed that no individual discriminated between HF and LF quadruplets. In summary, no participant showed explicit knowledge of the pattern during either the interview or the card sort task, despite the fact that both younger and older adults had responded significantly faster and more accurately to HF than to LF quadruplets in the ASRT task.

## Discussion

In this study we aimed to determine if older adults could implicitly learn subtle high order sequential regularities by using a three-element ASRT task with third-order structure.

Results revealed two main findings. First, there were significant age deficits in implicit sequence learning. Second, both groups showed learning of the subtle regularity without explicit awareness.

We observed age-related learning deficits for the accuracy measure, with older adults learning significantly less of the sequential regularity than younger adults as revealed by a smaller difference between HF and LF quadruplets for the older adults. This significant age deficit in learning cannot be due to group differences in overall accuracy, because both groups were ~92% accurate. Instead, group differences in learning must be due to age deficits in sensitivity to the repeating sequence.

The comparable reaction time analysis did not reveal significant group differences in learning, but there was some evidence that older adults required more training than younger adults before showing a quadruplet type effect. The finding that age deficits were less clear for reaction time than accuracy is consistent with earlier work (D. V. Howard et al., 2004; J. H. Howard, Jr. & Howard, 1997) suggesting that reaction time may be less sensitive to age-related decline in sequence learning in the ASRT task compared with accuracy.

Although the present study revealed clear age deficits in learning, it is equally important that both younger and older adults did learn the third-order regularity. That is, both groups showed significant quadruplet type effects for reaction time and accuracy measures. In addition, analyses of individuals showed that every participant of both age groups learned, with each individual having made significantly more errors on LF quadruplets than on HF quadruplets. This reveals a remarkable degree of sensitivity to subtle regularities, because only one third of the trials are predictable and learning this predictable relationship requires picking up a regularity that spans four items.

Results from an earlier study had indicated that second-order structure may be the limit to the level of sequential structure that older adults can learn implicitly, because older adults did not learn third-order regularities using a four-element version of the ASRT task (D. V. Howard et al., 2004). Salthouse's simultaneity theory (Salthouse, 1996) was proposed as one mechanism that may underlie the age-related deficits in implicit sequence learning of higher order structure. According to the theory, cognitive slowing prevents older adults from having multiple representations simultaneously activated. If learning a sequence with third-order structure requires simultaneous activation of predictable pattern elements that occur every fourth trial, then the absence of learning for older adults, as seen in D. V. Howard and colleagues, may reflect their inability to integrate pattern elements across the four trials. However, the simultaneity theory cannot fully explain why older adults are seemingly able to simultaneously activate across four elements in the present three-element task. Thus, other mechanisms, either in place of or in addition to simultaneity, must be responsible for the group differences.

One such explanation for older adults learning in the three- but not four-element ASRT task may be age-related associative binding deficits, which state that older adults are impaired at making associations between multiple stimuli or stimulus features and binding these associations into lasting memory traces (Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Naveh-Benjamin, 2000). Associative binding deficits are generally used to explain older adults' performance declines in explicit, episodic, and source memory tasks, but recent work suggests that similar processes may be involved in implicit learning (Harrison, Duggins, & Friston, in press). In the third-order ASRT task, learning requires forming associations between simultaneously activated runs of four consecutive trials and then binding these associations into memory traces for HF and LF quadruplets. The four-element ASRT task has more than twice as many HF quadruplets to be learned as does the three-element ASRT task (64 vs 27). Thus, the lack of learning for older adults in the four-element task may result from binding deficits that limit the number of associations that can be formed. The smaller number of HF quadruplets in the three-element task may not exceed this binding capacity; hence, older adults were able to learn the regularity.

Associative binding deficits may also affect older adults' ability to bind the associations into distinct memory traces, thereby producing the pattern of age deficits seen for the three-element versus four-element ASRT tasks. In a recent study, researchers simulated associative binding deficits in older adults by using a computational model of impaired neuromodulation (Li, Naveh-Benjamin, & Lindenberger, 2005). They achieved this by reducing the gain parameter, making neural activity for individual stimulus representations less distinct, which leads to increased errors when a person is forming associations between multiple stimulus features. In the ASRT task, impaired neuromodulation may affect older adults' ability to learn third-order structure because associations between elements of HF quadruplets may be erroneously bound with elements of LF quadruplets. The potential for inaccurate binding between elements of HF quadruplets is greater in the four-element task because it has a lower signal-to-noise ratio than the does three-element design (0.25 vs 0.33), which means that proportionally there are more LF quadruplets that can interfere with learning HF quadruplets. Taken together, it is possible that a combination of associative binding and simultaneity deficits are responsible for the age differences observed in higher order implicit sequence learning. Future studies are required to assess binding processes during sequence learning and to systematically examine them as a function of healthy aging in both ASRT study designs.

In summary, older adults were impaired in learning third-order sequential structure in the ASRT task, even when the simplified three-element design was used. Nonetheless, younger and older adults did show implicit learning on both behavioral measures, indicating that both groups are sensitive to complex regularities that span four elements even though neither group had any awareness of what they had learned. This study provides evidence that older adults remain sensitive to subtle sequential regularities in their environment, albeit to a lesser degree than younger adults. However, the upper limit of the level of structure that older adults can implicitly learn is still unclear.

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