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Implicit Learning of Predictive Relationships in Three-Element Visual Sequences by Young and Old Adults

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Knowledge of sequential relationships enables future events to be anticipated and processed efficiently. Research with the serial reaction time task (SRTT) has shown that sequence learning often occurs implicitly without effort or awareness. Here, the authors report 4 experiments that use a triplet-learning task (TLT) to investigate sequence learning in young and older adults. In the TLT, people respond only to the last target event in a series of discrete, 3-event sequences or triplets. Target predictability is manipulated by varying the triplet frequency (joint probability) and/or the statistical relationships (conditional probabilities) among events within the triplets. Results reveal that both groups learned, though older adults showed less learning of both joint and conditional probabilities. Young people used the statistical information in both cues, but older adults relied primarily on information in the 2nd cue alone. The authors conclude that the TLT complements and extends the SRTT and other tasks by offering flexibility in the kinds of sequential statistical regularities that may be studied as well as by controlling event timing and eliminating motor response sequencing.

Keywords: implicit sequence learning, aging, implicit learning, serial reaction time task, statistical learning

Serial order plays a central role in many aspects of cognitive function, including problem solving, language, and skill learning. Knowledge of the sequential relationships among events enables us to anticipate and thereby process future events more effectively. Laboratory studies of sequence learning have shown that this information is often acquired implicitly in that learning occurs automatically, without effort or even conscious awareness that learning has occurred (e.g., Reber, 1989). Evidence for this kind of *procedural* learning is found in performance improvements with practice, such as faster and/or more accurate responding to predictable than unpredictable events rather than in conscious, *declarative* knowledge of the relationships that were learned. Research has shown that procedural learning is distinct from declarative learning in its behavioral characteristics as well as in its neural bases (Forkstam & Petersson, 2005; Poldrack & Foerde, 2008; Robertson, 2007; Squire, 2004). In the present study, we introduce a new implicit sequence task and illustrate its utility for investigating procedural learning in healthy old adults as well as in young adults.

A number of tasks have been developed to study sequence learning in the laboratory. The most widely used is the serial reaction time task (SRTT; Nissen & Bullemer, 1987), in which people make a motor response to each of a series of events, such as light onsets. In the original version, sequential regularity was introduced by surreptitiously repeating the event sequence. With practice, people come to respond more quickly on blocks of trials with predictable, repeating events than on blocks with random events, thereby demonstrating learning. Variations on this task include introducing random probe events within the repeating sequence to obtain a continuous measure of learning (e.g., Cleeremans & McClelland, 1991) or using more subtle statistical relationships among the events (e.g., Gomez, 2002; J. H. Howard & Howard, 1997; Hunt & Aslin, 2001; Remillard & Clark, 2001; Schvaneveldt & Gomez, 1998). For example, we have used an alternating SRTT (ASRTT) in which people are presented with a repeating four-element sequence on alternate trials and random events on the other trials. In this ASRTT, people come to respond

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faster to events that complete high-frequency triplets than to those that complete less frequent triplets, thus showing sensitivity to the triplet structure (D. V. Howard et al., 2004).

Other sequence learning studies have used the statistical learning task (SLT) introduced by Saffran and colleagues (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996). In the SLT, people are presented with a structured sequence of sounds (e.g., Creel, Newport, & Aslin, 2004) or images (e.g., Fiser & Aslin, 2002), typically while performing another primary task. The focus of this work has been on understanding how people learn to parse the continuous stream of events into object- or word-level units on the basis of the statistical properties of the sequence. Studies have shown that after exposure to the sequence, 8-month-old infants (Saffran et al., 1996), college students (Aslin et al., 1998), and older adults (Badaly, Bennett, Howard, & Howard, 2006) are able to distinguish objects or “words” that conform to the statistical regularity from those that do not. As in the SRTT, learning occurs incidentally; however, in contrast to the SRTT, the SLT depends on subsequent explicit judgments of grammaticality or familiarity to assess what people learned, rather than on the trial-by-trial, performance-based measures, such as reaction time (RT) used in the SRTT (e.g., Aslin et al., 1998; Saffran et al., 1996).

Other research that used the SLT has shown that people not only learn the relative frequency with which events co-occur (i.e., their joint probabilities) but also the predictive relationships among them (i.e., their transitional or conditional probabilities; Aslin et al., 1998). Conditional and joint probabilities represent distinct properties of a sequence and require different calculations (cf. Hunt & Aslin, 2001). For example, if the pair AB occurs twice in an eight-pair sequence, its joint probability, P(A, B), is .25 (2 normalized by the total number of pairs, 8, P[A, B] = *F*[AB]/*F*[XY], where X and Y represent any event). In contrast, the conditional probability of B given A, P(B|A), is determined by normalizing the frequency of AB by the frequency of Event A, P(B|A) = *F*(AB)/*F*(A). Thus, the conditional probability is influenced by how often A occurs as well as by how often the pair AB occurs. Previous studies have shown that people can learn both the conditional and joint probability statistics simultaneously in the SLT task. Conditional and joint probabilities are not easily varied independently in the repeating sequences used with the SRTT, but one study that did manipulate these probabilities separately reported evidence that people can learn both statistics simultaneously in the SRTT task as well (Hunt & Aslin, 2001).

In the present study, we introduce a new implicit sequence-learning task that has similarities to the SRTT and the SLT while offering some advantages over each. In the triplet-learning task (TLT), people are presented with a series of discrete, structured three-event sequences or triplets consisting of two *cue* events followed by a *target* event, C_1, C_2, T. As in the SRTT, each event is a light onset at a particular location on the screen. However, unlike the SRTT, people are asked to simply observe the cue event and to respond to only the third, *target* event on each trial. We introduce statistical dependencies among the three events by manipulating the relative frequency with which the triplets occur across trials. Therefore, the third or target event is more or less predictable from the cues.

In the TLT, conditional probability refers to the probability that a particular target occurs given the first, the second, or both of the cues. In contrast, the joint probability is simply the probability that a particular triplet occurs during learning. We can then examine the relationship between these probabilities and the speed and accuracy of responding both within and across individuals.

The TLT offers several advantages over both the SRTT and SLT. For example, unlike the SLT, in the TLT, a response occurs on every trial, thereby providing an on-line, performance-based measure of learning rather than relying on the learner’s explicit judgments in a subsequent test. In contrast, although learning can be assessed continuously in the SRTT by introducing random probe events, the SRTT has a strong motor sequencing component that makes it difficult to dissociate motor from perceptual learning (Lungu, Wachter, Liu, Willingham, & Ashe, 2004). In addition, because each event in the SRTT typically follows the preceding *response* by a fixed interval, timing of the event sequence will vary across individuals and groups (J. H. Howard, Howard, Dennis, & Yankovich, 2007). This may be problematic for older adults or other populations characterized by slower and/or more variable response times. In contrast, in the TLT, event timing within a triplet is fixed and so does not vary across individuals and groups.

The primary objective of the present study is to demonstrate that people are able to learn the joint (Experiments 1–3) and conditional probabilities (Experiment 3) in the TLT. A secondary goal is to demonstrate the utility of this task for investigating implicit sequence learning in special populations by using healthy older adults as an example. With regard to healthy aging, previous research has shown that although high-ability older adults learn simple regularities as well as young adults (e.g., Frensch & Miner, 1994; D. V. Howard & Howard, 1989, 1992), age deficits often occur with more subtle regularities (e.g., Curran, 1997; D. V. Howard et al., 2004; J. H. Howard & Howard, 1997). Despite this, surprisingly little is known about why age deficits occur under these conditions. In the present study we demonstrate that the TLT can provide insights into the nature of sequence learning in this illustrative special population.

Experiment 1a

The primary goal of Experiment 1a is to demonstrate that young and older adults are able to learn triplet frequency or joint probability in the TLT. We also ask whether this learning parallels that observed in previous studies of the ASRTT with comparable statistical structure.

Method

Participants. Eighteen young (mean age = 20.0 years) and 18 old (mean age = 72.4 years) volunteers participated. The young volunteers were college students recruited from introductory psychology classes at The Catholic University of America (Washington, DC) and the old volunteers were community-dwelling adults who responded to advertisements placed in the Health section of *The Washington Post*. None of the participants had been in a similar study. Undergraduates were given course credit for participating, whereas the older adults received payment. As can be seen in Table 1, the age groups were well matched in gender distribution, self-rated health, digit span, and vocabulary; however, as is typical, they differed on digit coding—a measure of processing speed. The data from one older participant were excluded because

Table 1
Mean Values (With Standard Deviations in Parentheses) of Participant Characteristics

Variable	Experiment 1a		Experiment 1b	Experiment 2		Experiment 3	
	Young	Old	Old	Young	Old	Young	Old
Gender	15 women, 3 men	13 women, 5 men	4 women, 8 men	13 women, 5 men	12 women, 6 men	12 women, 4 men[a]	12 women, 6 men
Age	20.00 (2.33)	72.41 (4.72)***	72.42 (5.88)***	18.89 (1.28)	70.44 (5.14)***	19.50 (1.09)	72.44 (6.23)***
Education	13.56 (1.76)	16.47 (2.60)**	17.58 (2.23)***	12.89 (1.37)	15.83 (2.98)**	13.43 (1.22)	16.11 (2.80)*
Self-rated health[b]	4.44 (0.51)	4.38 (0.50)	4.08 (0.79)	4.28 (0.56)	4.44 (0.51)	4.43 (0.65)	4.33 (0.97)
WAIS digit coding	92.00 (13.89)	63.71 (21.91)***	70.00 (13.59)**	90.89 (10.32)	57.56 (21.50)***	87.15 (15.88)	58.67 (18.94)***
WAIS vocabulary	33.61 (8.54)	32.41 (10.47)	39.92 (7.55)*	30.50 (7.88)	36.35 (6.78)*	34.15 (7.33)	32.44 (9.20)
WMS–III digit span	18.67 (3.97)	16.77 (5.15)	17.92 (4.10)	17.06 (3.69)	17.88 (3.04)	18.62 (3.86)	16.85 (4.10)

Note. WAIS = Wechsler Adult Intelligence Scale—Third Edition (Wechsler, 1997a); WMS–III = Wechsler Memory Scale—Third Edition (Wechsler, 1997b).
[a] Gender was not recorded for two participants. [b] (1 = *poor*, 5 = *excellent*).
* $p < .05$. ** $p < .001$. *** $p < .0001$.

of a technical error during testing, so there were 17 older adults in the analysis.

Design. The design was a 2 × 2 × 6 (Age Group × Triplet Frequency × Session) mixed factorial, with age group (young vs. old) varied between-subjects, and triplet frequency (high vs. low) and session (1–6) varied within-subjects.

Stimuli. An Apple iMac computer with a 15-in. (38.1-cm) monitor was used to display four open circles (0.5° each) horizontally in the center of the screen. The entire display subtended 12° of visual angle at the 56-cm viewing distance. An event occurred when one of the open circles filled in with either red or green. A "triplet" of three events, two red "cues," and a green "target" was displayed on each trial. Participants observed the first two cue events without responding and pressed a corresponding key to the third, target event. Each trial began with the first red *cue* event that remained visible for 120 ms followed 150 ms later by the second red *cue* that also remained on for 120 ms. The green *target* event appeared 150 ms later and remained in view until a correct response occurred. RT was recorded from the presentation of the target to the initial response, regardless of accuracy. Following a correct response, the circles were cleared for 650 ms when the next trial began. Because the duration of the target event was determined by the participant's response time, the intertrial interval varied somewhat across people. Four labeled keys on the iMac keyboard were used for responding with the middle and index finger of each hand ("z", "x", ".", and "/" corresponding to the four events in left-to-right order, respectively).

All 64 possible triplets were presented. Of these, each of 16 *high-frequency* triplets occurred with a probability of .050000, whereas each of the remaining 48 *low-frequency* triplets occurred with a probability of .004167. Thus, high-frequency triplets were presented on 80% of the trials (16 × .050000), whereas low-frequency triplets were presented on 20% of the trials (48 × .004167), a difference that mirrors the triplet structure in the ASRTT described previously (J. H. Howard & Howard, 1997). The 16 high-frequency triplets were selected so that the first cue event predicted the third target event and, hence, the response for that trial. The second cue was unrelated to the response. Thus, in this experiment, the triplets contained second-order information because the target was predicted by the first cue, again mimicking the ASRTT task. To illustrate, for a given participant, the 16 high-frequency triplets might consist of AXB, BXC, CXD, DXA, where A, B, C, D denote the four lights, and X is any of the four (i.e., AXB means AAB, ABB, ACB, or ADB). So for this person, an initial cue of A predicts target B, B predicts C, and so forth. Note that people can learn that the target is predicted either from the first cue alone or from the pair of cues (i.e., AA, AB, AC, and AD predict B). These predictive relationships have been referred to as "lag-2" and "second-order," respectively, in the sequence learning literature (Remillard & Clark, 2001). The specific cue-target mapping was counterbalanced across participants such that the six unique combinations possible in an alternating continuous sequence were used equally often (J. H. Howard & Howard, 1997). We sampled triplets randomly on each trial using a random number generator, and a postexperimental tally of the resulting triplet distribution revealed that the high-frequency triplets occurred on exactly 80% of all trials as intended.

Given this distribution, the joint probability of the triplets is perfectly correlated with the conditional probability of the target given the first cue, $P(T|C_1)$, as well as the conditional probability of the target given the cue pair, $P(T|C_1, C_2)$. Thus, we are not trying to distinguish between learning of these two types of statistical relationships in this experiment. Note, however, the conditional probability of the target given the second cue, $P(T|C_2)$, is not predictive.

Procedure. People were seated at the computer and read instructions before providing institutional-review-board-approved informed consent. They were told that they would see three colored circles on each trial, two red and one green, and that "It is not necessary for you to be 100% accurate, but please try to keep your mistakes to a minimum (for example no more than 1 error in every 10 trials)." Thus, the instructions encouraged responding, with 90% overall accuracy. Nothing was said about the relative frequency of the triplets or about the predictive relationships among the events.

The experiment was structured into six sessions each consisting of 20, 50-trial blocks, for a total of 6,000 trials per person. People completed two sessions per day over 3 days, with an average of 2.67 days between visits. People were given a break between sessions, and they were encouraged to take a short break after each block. The overall time required for each day (two sessions) varied but was typically about 60 min.

At the end of the final day, explicit knowledge was probed in two ways. First, participants were given a recognition block in which they observed each of the 64 possible triplets displayed as black—rather than colored—circles, without responding. They were instructed to judge whether each triplet had occurred frequently or infrequently during the experiment by responding "2" or "1," respectively. Because recognition data were lost from 4 younger adults, the recognition analysis was based on 14 young and 17 old participants.

Second, the experiment concluded with an interview as an additional probe of people's declarative knowledge of the sequence by asking four increasingly specific questions: (1) What strategy did you use to improve your speed and accuracy in the experiment? (2) Did you notice any relationship between either of the first two lights and the third light? (3) Did all the lights turn on equally often, or did some lights come on more often than others? And (4) In fact, there was a relationship between the first two lights and the third. What do you think it was for the first light? What about the second Light?

Results and Discussion

To determine whether people learn statistical dependencies in the TLT, we compared performance on trials with the 16 high-frequency triplets to those with the 48 low-frequency triplets. We further partitioned the 48 low-frequency triplets to examine *repetitions* (4 triplets: AAA, BBB, etc.) and *trills* (12 triplets: ABA, CDC, etc.). Repetitions and trills were always low frequency for all people in the present study, and previous research has shown that people often show preexisting response tendencies when responding to them (D. V. Howard et al., 2004; Soetens, Melis, & Notebaert, 2004). Consistent with this, an analysis of data from the initial session revealed that both groups responded significantly more slowly to repetitions and trills than to the remaining triplets. Thus, as in earlier work (D. V. Howard et al., 2004), these triplets were excluded from the analyses reported below.

Median RTs were determined separately for correct responses by triplet type for every participant on each block. Overall accuracy was 94%, so few trials were omitted. These data were then averaged across blocks to obtain a single mean RT for each individual and triplet type on each of the six sessions. A similar procedure was used to determine the mean accuracy for each participant on each triplet type. A statistical criterion of .05 was used in all significance tests, and two-tailed tests were used throughout.

Do young adults learn triplet frequency? Mean RTs are plotted for both age groups for high versus low-frequency triplets across sessions in the upper panel of Figure 1, and the mean accuracies are shown in the lower panel. Data from the young group were analyzed with a Triplet (high vs. low frequency) × Session (1–6) repeated measures analysis of variance (ANOVA). The analysis of RT produced significant main effects of Session, $F(5, 85) = 9.48$, $MSE = 4{,}262$, $p < .0001$, $r_{\text{effect}} = .60$, and Triplet, $F(1, 17) = 104.31$, $MSE = 379$, $p < .0001$, $r_{\text{effect}} = .93$, as well as a significant Triplet × Session interaction, $F(5, 85) = 9.45$, $MSE = 96.22$, $p < .0001$, $r_{\text{effect}} = .60$. This indicates that the young people showed triplet frequency learning as well as general skill learning. Skill learning is reflected in the overall faster responding with practice (from a mean of 491 ms on the first session to 400 ms on the final session), whereas triplet frequency learning is revealed in the relatively faster responding to the high- than low-frequency triplets (means of 417 and 444 ms, respectively). Finally, although the significant Triplet × Session interaction indicates that this separation increased with practice, the difference in RT between high- and low-frequency triplets was significant on the first Session (mean RTs of 483 and 499 ms, respectively), $F(1, 17) = 27.74$, $MSE = 86$, $p < .0001$, $r_{\text{effect}} = .79$, suggesting that learning occurred relatively quickly.

A two-way ANOVA on the accuracy data for the young group yielded the same pattern, with significant main effects of Session, $F(5, 85) = 9.10$, $MSE = 0.003$, $p < .0001$, $r_{\text{effect}} = .59$, and Triplet, $F(1, 17) = 6.19$, $MSE = 0.014$, $p = .0235$, $r_{\text{effect}} = .53$, as well as a Triplet × Session interaction, $F(5, 85) = 5.16$, $MSE = 96.22$, $p = .0004$, $r_{\text{effect}} = .48$. The Session effect reflects an overall decrease in accuracy from a mean of .95 in the first session to .88 in the final session. As is evident in Figure 1, this occurs primarily because accuracy declines with practice for low-frequency triplets. This effect is typical of probabilistic sequence learning tasks in which "implicit anticipation" errors increase as the predictive relationships among events are learned (J. H. Howard & Howard, 1997; Jimenez, Mendez, & Cleeremans, 1996; Schvaneveldt & Gomez, 1998). For example, if the triplet 112 occurs frequently and 113 infrequently, as people learn they will become increasingly likely to respond "2" for triplets beginning with "1" or "11." On low-frequency trials, such as 113, this will produce an error. The relatively modest decrease in accuracy over sessions for the high-frequency triplets likely reflects the influence of the feedback we provided to encourage responding at 92% correct. Thus, both the RT and accuracy data indicate that young adults learn triplet frequency in the TLT and that they use this knowledge to respond relatively more quickly and accurately to the predictable than to the unpredictable targets.

Do old adults learn triplet frequency? A parallel analysis was carried out on the data for the old group shown in Figure 1. The RT ANOVA revealed significant main effects of Session, $F(5, 80) = 13.44$, $MSE = 2{,}797$, $p < .0001$, $r_{\text{effect}} = .68$, and Triplet, $F(1, 16) = 92.10$, $MSE = 215$, $p < .0001$, $r_{\text{effect}} = .98$; however, the Triplet × Session interaction, $F(5, 80) = 0.54$, $MSE = 274$, $p = .7477$, $r_{\text{effect}} = .20$, was not significant. The Session effect reflects overall skill learning as described above. The Triplet effect indicates that the older adults also learned triplet frequency because they responded faster to high- than to low-frequency triplets (mean overall RTs of 593 and 618 ms, respectively). Further, this difference was significant in the initial session (mean RTs of 650 and 662 ms for the high- and low-frequency triplets, respectively), $F(1, 16) = 11.79$, $MSE = 102$, $p < .0034$, $r_{\text{effect}} = .65$, indicating that, like young adults, the older adults became sensitive to triplet frequency early in practice. However, the absence of a significant interaction reveals that they revealed little additional triplet learning with practice beyond that point.

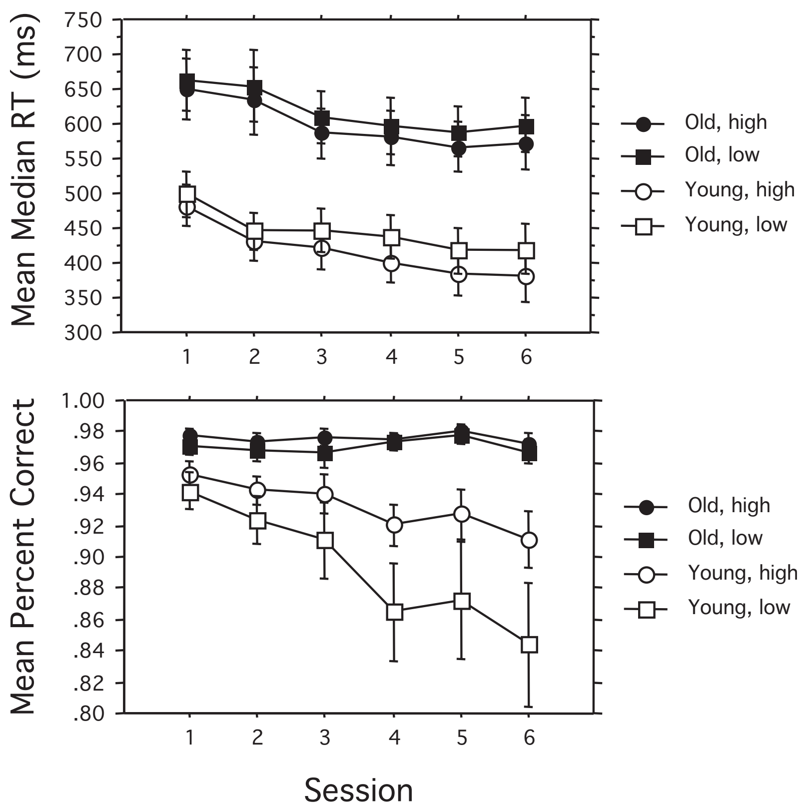

Figure 1. Mean of median reaction time (RT; upper curve) and mean accuracy (lower curve) over sessions by high- and low-frequency triplets and age group for Experiment 1a. Error bars represent the standard error of the mean.

The accuracy data shown in Figure 1 indicate that the older participants were highly accurate for both the low- and high-frequency triplets across all sessions. This reluctance to make errors is common in older adults, but it leaves little room to observe differences in accuracy for the high and low triplets. Despite this, the ANOVA revealed a significant main effect of Triplet, $F(1, 16) = 5.165$, $MSE = 0.0003$, $p = .0372$, $r_{\text{effect}} = .45$, indicating that the old adults were more accurate on high- than low-frequency trials (means of .98 and .97, respectively). However, neither the main effect of Session, $F(5, 80) = 1.27$, $MSE = 0.0003$, $r_{\text{effect}} = .28$, nor the Triplet × Session interaction, $F(5, 80) < 1.0$, $MSE = 0.0001$, $r_{\text{effect}} = .18$, was significant, indicating that this difference was constant across sessions.

Thus, like young adults, the older adults show evidence of triplet frequency learning in the TLT. This was seen in the faster responding to high- than low-frequency triplets as well as in a very small, but significant, accuracy advantage for the high- over the low-frequency triplets. The latter occurred in spite of an overall ceiling effect in the accuracy data for the older group.

Are there group differences in learning? The data plotted in Figure 1 suggest that young people may learn more than old people because they display a larger advantage in both RT and accuracy for the high- over the low-frequency triplets. This is consistent with the age-related deficits reported in earlier studies that have investigated learning of second-order relationships in variations of the SRTT (Curran, 1997; J. H. Howard & Howard, 1997).

Omnibus ANOVAs were carried out to compare the two groups in overall RT and accuracy as well as to investigate possible interactions of group with triplet frequency learning. Because we have already demonstrated significant learning for both groups, here we focus only on main effects and interactions involving Group.

The three-way ANOVA on RT produced a significant main effect of Group, $F(1, 33) = 12.57$, $MSE = 263{,}389$, $p = .0012$, $r_{\text{effect}} = .53$, as well as a significant Group × Triplet interaction, $F(1, 33) = 4.70$, $MSE = 299$, $p = .0374$, $r_{\text{effect}} = .35$, and a marginally significant Group × Triplet × Session interaction, $F(5, 165) = 2.00$, $MSE = 182$, $p = .0808$, $r_{\text{effect}} = .24$. This indicates that the older group was significantly slower than the younger group (mean RTs of 608 and 431 ms, respectively) and that the young people had greater triplet frequency learning than the old people (mean RT advantage for the high- over low-frequency triplets of 27 and 20 ms, for the young and old, respectively), with a trend for this group difference to increase with practice.

The analysis of accuracy revealed a similar pattern. The old adults were significantly more accurate overall than the young adults (mean accuracy of .973 vs. .913, respectively), as revealed in a main effect of Group, $F(1, 33) = 9.45$, $MSE = 0.041$, $p = .0042$, $r_{\text{effect}} = .47$, and they showed significantly less learning than the young adults, as seen in a significant Group × Triplet interaction, $F(1, 33) = 7.32$, $MSE = 0.031$, $p = .0107$, $r_{\text{effect}} =$

.34, and a Group × Triplet × Session interaction, $F(5, 165) = 4.74$, $MSE = 0.001$, $p = .0004$, $r_{effect} = .36$.

These omnibus analyses suggest that older adults learned less about triplet frequency than did younger adults. However, the substantial differences between the two groups in overall RT and accuracy complicate this comparison. Therefore, we developed a within-subjects measure of learning that does not depend on absolute performance level. This involved a within-subjects regression analysis to determine the extent to which triplet frequency is related to the RT for individual triplets for each person. Because the within-subjects regression does not depend on the absolute performance level, we were able to compare the relative influence of triplet frequency on RT across individuals with very different performance.

Linear regression was used to construct a model of the relationship between the actual triplet probabilities and mean RT for the 48 triplets, excluding repetitions and trills, across correct trials on the final three testing sessions for each person. The final three sessions were used to capture triplet frequency effects after learning had occurred. The empirical joint probability of each triplet, C_1C_2T, was determined for every participant by dividing the actual frequency of each triplet by the total number of trials in the final three sessions (3,000 trials per individual). Theoretically, these distributions are identical across participants (i.e., as described in the *Method* section). However, because the triplets were sampled randomly on each trial, their frequency varied somewhat from person to person. The resulting correlation coefficient for each person indicates the extent to which their RT to each triplet is predicted by the triplet's probability and, thus, provides a within-subjects measure of triplet frequency learning for each individual.

The mean correlation coefficients for each group are shown in Figure 2. These means were significantly different than zero for both the young group ($M = -0.347$), $t(17) = 11.95$, $p < .0001$, and the old group ($M = -0.155$), $t(16) = 5.97$, $p < .0001$, indicating that response time was inversely related to triplet frequency. This is consistent with the learning data reported above in indicating that both groups were sensitive to triplet frequency. In addition, the correlation was significantly greater for the young group than the old group, $t(33) = 4.910$, $p < .0001$, $r_{effect} = .76$, supporting the conclusion that the old learned less than the young—that is, that the relationship between triplet probability and RT was weaker for the older adults.

Examination of the individual data revealed that all 18 young adults had a negative correlation between triplet probability and RT, $p < .0001$ by Sign Test, with the correlations for 14 individuals showing a significant correlation—$r(46) > .28$, $p < .05$—$p = .0309$ by Sign Test. Similarly, 15 of the 17 older adults had a negative correlation, $p = .0023$ by Sign Test, although only 3 of the 15 individuals had correlations that reached statistical significance at the .05 level, $p = .0127$ by Sign Test. The 2 older adults with a nonnegative correlation were close to zero ($r = .045$ and .086, respectively). Thus, the individual correlations are consistent with the group data in suggesting that both young and old adults learn triplet frequency in the TLT, but the relationship between joint probability and RT is weaker for the older people. This confirms the conclusions reported above but, in this case, using a learning measure that is not sensitive to the absolute performance level.

Was triplet frequency learning implicit? Consistent with previous studies that used the ASRTT, postexperimental interviews revealed no evidence of declarative knowledge. No one mentioned that the first cue predicted the target or that some triplets occurred more often than others. More importantly, analysis of the mean explicit judgments of triplet frequency shown in Figure 3 revealed that both age groups rated the high- and low-frequency triplets as occurring equally often. This was shown in one-way repeated measures ANOVAs carried out on the recognition data for the young and old groups separately.

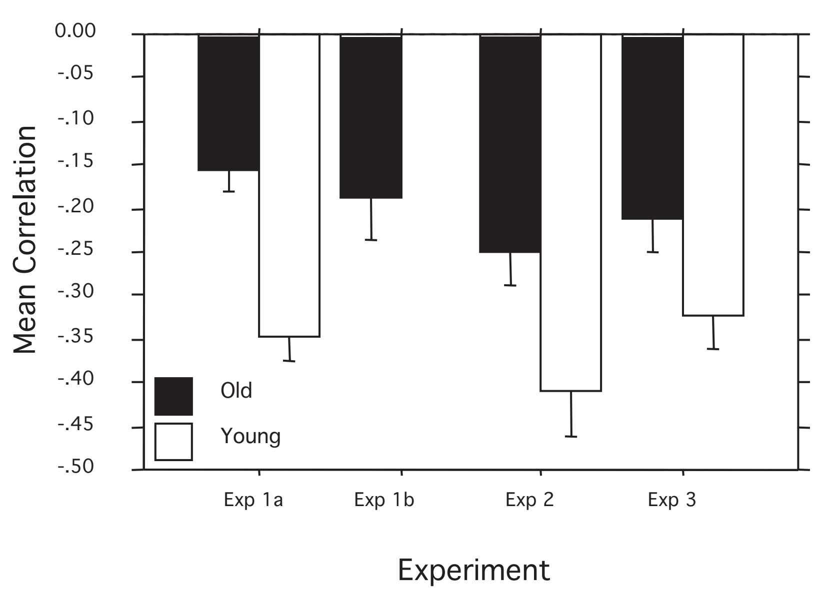

Figure 2. Mean correlation between triplet joint probability, $P(C_1C_2T)$, and mean of median reaction time over Sessions 4–6 collapsed across individuals in each age group for each experiment. Error bars represent the standard error of the mean.

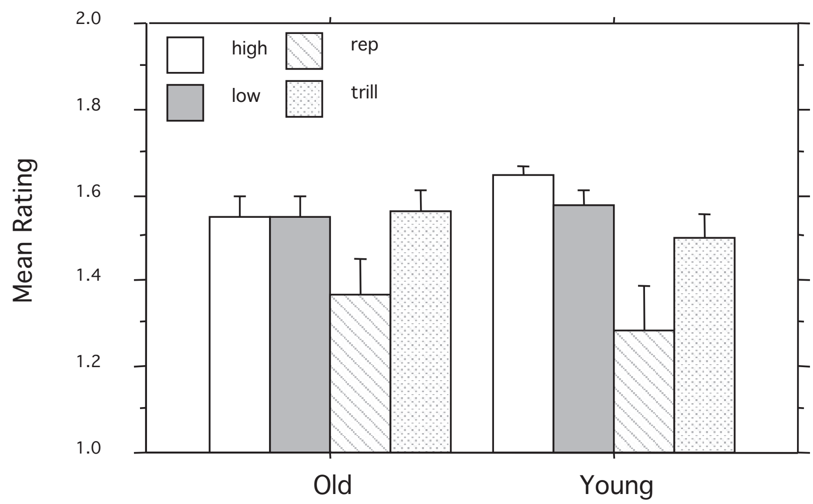

Figure 3. Mean recognition ratings by triplet type and age group for Experiment 1a. Error bars represent the standard error of the mean.

The ANOVA for the young group revealed a significant main effect of Triplet Type (high-frequency, low-frequency, repetitions, and trills), $F(3, 39) = 6.59$, $MSE = 0.051$, $p = .0010$, $r_{\text{effect}} = .58$. Post hoc analysis showed that repetitions were rated as occurring significantly less often than any of the three other triplet types, with no significant differences among the high- and low-frequency triplets or trills. Most importantly, the recognition difference in ratings for the high- and low-frequency triplets (means of 1.64 and 1.57, respectively), .067, fell well within the 95% confidence interval for equivalence (−.023, .158). Thus, the young group appeared to be aware that triplets with three identical events are rare but not that the high-frequency triplets occurred more often than the low.

To investigate whether this reflects an averaging or group phenomenon, we also examined the individual recognition judgments for high- and low-frequency triplets for each young person. The rating difference ranged from −.250 (low judged more frequent than high) to .344 (high more frequent than low), with the observed difference falling within the 95% confidence interval around zero for every young participant. Thus, for the young adults, no individual assigned significantly higher frequency ratings to high- than low-frequency triplets.

The identical pattern was obtained for the old adults. There was a significant effect of Triplet Type, $F(3, 48) = 3.75$, $MSE = 0.039$, $p = .0168$, $r_{\text{effect}} = .44$, that post hoc analyses showed to reflect lower ratings for the repetitions than the other triplet types. The old adults did not distinguish the high- and low-frequency triplets (mean rating difference of −.003; 95% confidence interval = −.146, .140)—an effect observed in the individual as well as the group data (rating difference ranged from −.250 to .219, with all differences within the 95% confidence interval around zero).

Thus, people in both groups seem aware that triplets with three identical events are rare, thus demonstrating that they understood the task instructions. Most importantly, neither group was able to distinguish between high- and low-frequency triplets despite the fact that the high-frequency triplets occurred 4 times more often than the low-frequency triplets. Because the trills and repetitions were omitted from the learning analyses, the triplet frequency learning demonstrated here was implicit.

Experiment 1b

Although the above results suggest that there is an age-related deficit in triplet frequency learning, it is possible that the nearly perfect accuracy of the older adults simply left less room to show triplet differences on both measures, thereby creating the appearance of a learning deficit. To examine whether older adults would show greater learning with more error-prone responding, we tested an additional group of older adults using the same task as Experiment 1a but with end-of-block feedback that encouraged an error rate matching that of younger adults.

Method

Participants. Twelve old volunteers were recruited from the same population as Experiment 1a (see Table 1).

Design. The design was the same as Experiment 1a.

Stimuli. The apparatus and stimuli were the same as Experiment 1a.

Procedure. The procedure was the same as Experiment 1a, except that we added end-of-block feedback to encourage responding with an overall accuracy similar to that of young adults in Experiment 1a. At the end of each block, the prompt "Please respond more quickly" was displayed if accuracy was above 94%, whereas "Please respond more slowly" was displayed if accuracy fell below 90%. We have used this technique in previous sequence learning studies to encourage similar accuracy across groups (Bennett, Howard, & Howard, 2007; D. V. Howard et al., 2004). Although based on accuracy, the verbal prompts only mentioned speed.

Results and Discussion

The modified feedback succeeded in matching the old and young adults in overall mean accuracy across all trials in the initial session (94% vs. 95% for the old and young adults, respectively, a difference that fell well within the 95% confidence interval around zero: −.045, .019). In addition, these older adults responded substantially faster than the older group in Experiment 1a (mean overall Session 1 RT of 520 vs. 694 ms, respectively, a difference of 174 ms), $t(27) = 2.733$, $p = .0109$, $r_{\text{effect}} = .47$, and even matched the young statistically in first-session RT (520 vs. 509 ms, respectively; 95% confidence interval = −85, 107). Thus, we achieved our objective of matching old adults to young adults in overall performance.

Do old people who are performance-matched to young learn triplet frequency? The RT and accuracy data from the matched old group are plotted with those of the young group from Experiment 1a in Figure 4. A two-way ANOVA on the RT data for the matched old group yielded a significant main effect of Session, $F(5, 55) = 3.74$, $MSE = 2{,}878$, $p = .0055$, $r_{\text{effect}} = .50$, but neither the main effect of Triplet, $F(1, 11) = 1.00$, $MSE = 662$, $p = .3399$, $r_{\text{effect}} = .29$, nor the Triplet × Session interaction, $F(5, 55) = 1.12$, $MSE = 1{,}071$, $p = .3622$, $r_{\text{effect}} = .30$, was significant. In other words, although there is evidence of general skill learning in the Session effect, the RT data yield no evidence of triplet frequency learning.

A comparable ANOVA on the accuracy data revealed no significant main effect of Session, $F(5, 55) = 1.48$, $MSE = 0.007$, $p = .2105$, $r_{\text{effect}} = .35$, Triplet, $F(1, 11) = 0.06$, $MSE = 0.015$, $p = .8187$, $r_{\text{effect}} = .08$, or Triplet × Session interaction, $F(5, 55) = 1.662$, $MSE = 0.006$, $p = .1593$, $r_{\text{effect}} = .36$. This supports the RT analysis in suggesting that the matched older group was not sensitive to triplet frequency. It is clear from Figure 4 that there was substantial across-session variability in accuracy for these older adults.

To determine whether the individual data reveal evidence of triplet frequency learning, we performed a within-subjects regression analysis between the actual triplet probabilities and the corresponding RTs over the final three testing sessions for each participant, identical to the regression analyses described for Experiment 1a. The mean correlation for the matched older adults is shown in Figure 2. Interestingly, despite the large between-subjects differences in RT and accuracy, the mean within-subjects learning scores for matched old adults look remarkably like those for the old adults in Experiment 1a. The mean within-subjects correlation for the matched old adults was significantly greater than zero, $t(11) = 3.80$, $p = .0029$, and it was significantly smaller than the mean correlation for the young group in Experiment 1a ($M = -0.347$), $t(28) = 3.01$, $p = .0055$, $r_{\text{effect}} = .50$. Furthermore, this within-subjects learning measure for the matched old group did not differ significantly from that for the old group in Experiment 1a (−.186 vs. −.155, respectively, a difference of .031; 95% confidence interval = −.074, .136). In addition, 10 of the 12 matched old participants showed a negative relationship between

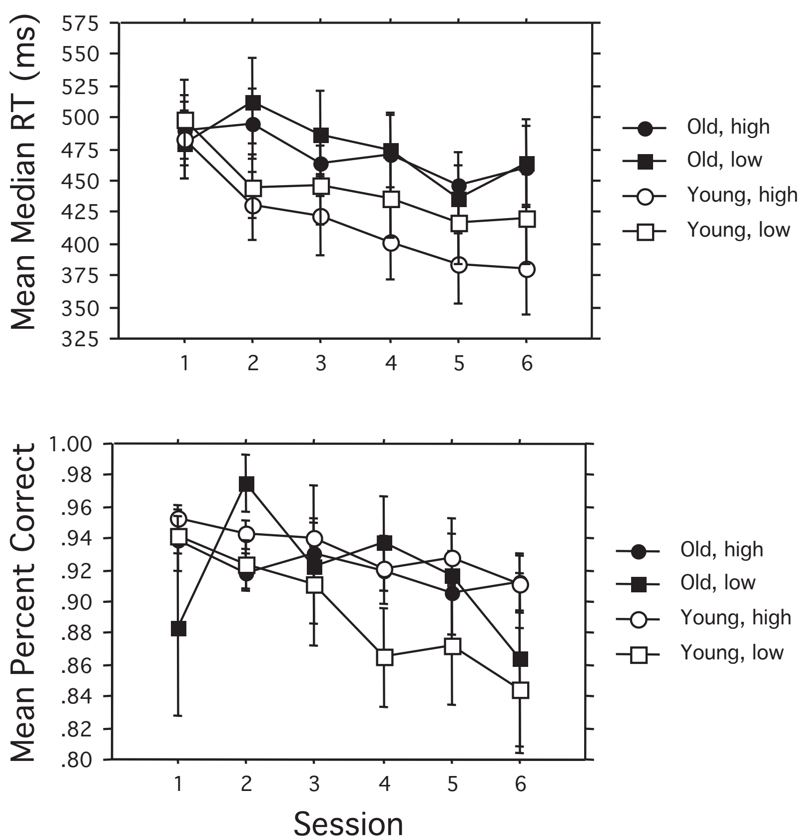

Figure 4. Mean of median reaction time (RT; upper curve) and mean accuracy (lower curve) over sessions by high- and low-frequency triplets comparing the low-accuracy old group from Experiment 1b and the young group from Experiment 1a. Error bars represent the standard error of the mean.

RT and actual triplet frequency, with the 2 nonnegative essentially at zero (.010 and .018), suggesting that more learning occurred than was revealed in the group speed and accuracy analyses. However, the correlation was statistically significant for only 2 of these 10 matched older adults, $p = .1094$ by Sign Test.

Thus, although the individual participant's regression analysis hints at more learning than suggested by the group speed and accuracy measures, it is clear that the older adults had difficulty adopting a more lax response criterion. This may reflect inconsistent or varying response strategies, as the older adults sought to reconcile their strong tendency to maintain high accuracy with the feedback to respond more quickly. In addition, the verbal prompts we added may have led some older people to respond so fast that they were unable to attend or process the cues fully. Regardless of the underlying cause, inducing older adults to match younger adults in speed and accuracy does not lead to greater learning nor does it eliminate the age deficits observed in Experiment 1a.

In addition, despite the very large disparity in overall performance between Experiments 1a and 1b (mean accuracy = .973 and .919, respectively), $t(27) = 2.61$, $p = .0144$, and (mean RT = 608 vs. 473 ms, respectively), $t(27) = 2.51$, $p = .0183$, as reported above, the regression-based learning scores for the older adults did not differ across the two experiments. This suggests that the older people in Experiment 1b were as sensitive to triplet frequency as those in Experiment 1a even while struggling to accommodate the instructions to respond quickly.

Is triplet frequency learning implicit? The postexperimental interview and frequency ratings were consistent with those in Experiment 1a in providing little evidence of declarative knowledge. Repetitions were rated as occurring slightly less often than the other triplet types (mean rating of 1.42 vs. 1.57, 1.56, and 1.55, for trills, high-frequency triplets, and low-frequency triplets, respectively), but these pair-wise differences all fell within the 95% confidence interval. Most importantly, the ratings for high- and low-frequency triplets were nearly identical (mean difference of .01; 95% confidence interval = −.056, .077). The same pattern was seen in the individual ratings. The rating difference ranged from −.219 (low more frequent than high) to .125 (high more frequent than low) for the matched old participants, and the observed difference fell within the 95% confidence interval around zero for every individual.

Experiment 2

The above experiments demonstrated that both young and old adults learn triplet frequency when second-order relationships are varied in the TLT, though old adults showed less learning than young adults. In Experiment 2, we ask whether the same pattern of triplet frequency learning occurs when the high-frequency triplets reflect a first-order predictive relationship rather than a second-order relationship, that is, when the second rather than the first cue predicts the target. In addition, we increased the probability of the high-frequency triplets from .80 to .90 in this experiment.

Previous findings with other sequence-learning paradigms have shown that temporally adjacent dependencies are generally easier to learn than nonadjacent dependencies (Creel et al., 2004; D. V. Howard et al., 2004). Thus, in Experiment 2, we also compare learning across experiments to ask whether greater triplet frequency learning occurs in Experiment 2 than in the previous experiments.

Method

Participants. Eighteen young (mean = 19.0 years) and 18 old (mean = 70.4 years) volunteers were recruited from the same populations as Experiment 1 (see Table 1). One young participant dropped out of the experiment after two sessions, and another was excluded for responding at chance throughout (overall accuracy of 22% vs. 25% chance). Thus, the analyses were carried out on data from 18 old and 16 young adults.

Design. The design was the same as Experiment 1a.

Stimuli. The apparatus and stimuli were the same as Experiment 1a. However, in the 16 high-frequency triplets, the second cue (and not the first) predicted the target. In other words, the triplets contained first-order information in that the target was predicted by the immediately preceding event (i.e., XAB, A predicts B). Thus, for a given participant, the 16 high-frequency triplets might consist of XAB, XBC, XCD, XDA, where A, B, C, D denote the four events, and X is any of the four. The specific cue-target mapping was permuted across individuals such that all combinations occurred in the experiment. We sampled triplets randomly on each trial using a random number generator, resulting in high-frequency triplets on exactly 90% of the trials across participants and sessions.

Procedure. The procedure was the same as Experiment 1a.

Results and Discussion

Figure 5 displays the mean RT (upper panel) and accuracy (lower panel) over sessions for both groups, calculated as in Experiment 1a. Data from the two groups were analyzed in separate Triplet × Session repeated measures ANOVAs.

Do young adults learn? For the young group, the RT analysis produced significant main effects of Session, $F(5, 75) = 3.50$, $MSE = 4{,}239$, $p < .0067$, $r_{\text{effect}} = .95$, and Triplet, $F(1, 15) = 37.02$, $MSE = 5{,}695$, $p < .0001$, $r_{\text{effect}} = .84$, as well as a significant Triplet × Session interaction, $F(5, 75) = 5.99$, $MSE = 1{,}059$, $p < .0001$, $r_{\text{effect}} = .53$. This reveals both general skill learning and triplet frequency learning. Overall RT for the young people improved with practice (from a mean of 427 ms to 373 ms across sessions), and they responded faster to the high- than low-frequency triplets (overall means of 353 and 419 ms, respectively). More importantly, there was greater improvement for the high-frequency triplets (from 412 ms on Session 1 to 319 ms on Session 6) than for the low-frequency triplets (from 441 ms to 427 ms).

The accuracy analysis revealed no main effect of Session, $F(1, 75) = 1.41$, $MSE = 0.020$, $p = .2290$, $r_{\text{effect}} = .29$, but there was a significant main effect of Triplet, $F(1, 15) = 11.09$, $MSE = 0.047$, $p = .0046$, $r_{\text{effect}} = .65$, as well as a significant Triplet × Session interaction, $F(5, 75) = 10.47$, $MSE = 0.003$, $p < .0001$, $r_{\text{effect}} = .64$. Thus, the young adults responded more accurately to high- than low-frequency triplets (means of .91 and .81, respectively) and, as is evident in Figure 5, their accuracy remained stable across sessions for the high-frequency triplets (.89 and .90 on Sessions 1 and 6, respectively) but decreased for the low-frequency triplets (.88 and .72, respectively).

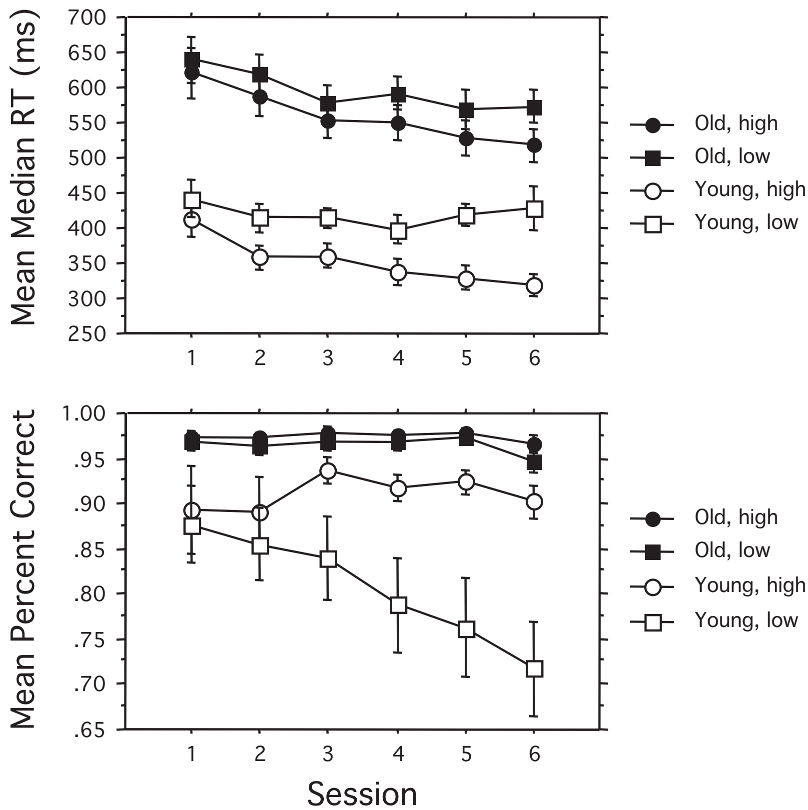

Figure 5. Mean of median reaction time (RT; upper curve) and mean accuracy (lower curve) over sessions by high- and low-frequency triplets and age group for Experiment 2. Error bars represent the standard error of the mean.

These analyses indicate that young adults become sensitive to triplet frequency in the TLT and that they use this knowledge to respond increasingly faster to the predictable than the unpredictable targets with practice. This does not reflect a simple speed/accuracy trade off, as response accuracy does not decline with faster responding for the high-frequency triplets. The converse is also true for the low-frequency triplets—response speed remains relatively stable, whereas accuracy declines with practice.

Do old adults learn? The same analysis was carried out on the data for the old adults. The RT ANOVA revealed significant main effects of Session, $F(5, 85) = 18.38$, $MSE = 2{,}148$, $p < .0001$, $r_{\text{effect}} = .72$, and Triplet, $F(1, 17) = 48.94$, $MSE = 1{,}399$, $p < .0001$, $r_{\text{effect}} = .88$, as well as a significant Triplet × Session interaction, $F(5, 85) = 3.63$, $MSE = 421$, $p = .0051$, $r_{\text{effect}} = .42$. This indicates that the older adults showed both overall skill learning, in that they responded more quickly with practice (from a mean RT of 630 on Session 1 to 545 ms on Session 6), and triplet frequency learning because they responded faster to high- than to low-frequency triplets (mean RTs of 559 and 594 ms, respectively). Practice effects were observed for low- as well as the high-frequency triplets, but the improvement across the six sessions was greater for the high-frequency (103 ms) than low-frequency (67 ms) triplets.

As in Experiment 1a, the older participants were very accurate for both the low- and high-frequency triplets across all sessions. Nevertheless, there was a marginally significant main effect of Session, $F(5, 85) = 2.29$, $MSE = 0.001$, $r_{\text{effect}} = .35$, as well as a significant main effect of Triplet, $F(1, 17) = 9.92$, $MSE = 0.001$, $p = .0058$, $r_{\text{effect}} = .60$, in the analysis of accuracy. The Triplet × Session interaction was not significant, $F(5, 85) = 1.23$, $MSE = 0.0002$, $r_{\text{effect}} = .29$. The Triplet effect reflects slightly more accurate responding to high-frequency (.97) than to low-frequency (.96) triplets, whereas the Session effect reflects a very small decline in accuracy across sessions (from .97 to .96). Although statistically significant and consistent with the RT data, as in Experiment 1a, these small differences must be interpreted with caution given the overall ceiling effect in the older adults' data.

Thus, like young adults, the older adults learn triplet frequency in the TLT. This was seen clearly in the increasingly faster responding to high- than low-frequency triplets with practice. As for young adults, the old group's faster responding to high-frequency triplets did not come at the expense of accuracy; accuracy remained very high for this group across the six sessions despite the improvement in RT.

Are there group differences in learning? Although both the young and old groups show triplet frequency learning, Figure 5 suggests that the older adults show a smaller advantage in both RT and accuracy for the high- over the low-frequency triplets, as in Experiment 1a. This was investigated in omnibus ANOVAs to compare RT and accuracy in the two groups, focusing on the main effect of Group to investigate group differences in overall performance as well as on the Group × Triplet interaction and the Group × Triplet × Session interaction to investigate group differences in triplet frequency learning.

The analysis of RT produced a significant main effect of Group, $F(1, 32) = 37.26$, $MSE = 99{,}710$, $p < .0001$, $r_{\text{effect}} = .73$, as well as a significant Group × Triplet interaction, $F(1, 32) = 7.00$, $MSE = 3{,}413$, $p = .0125$, $r_{\text{effect}} = .42$. The Group × Triplet × Session interaction was not significant, $F(5, 160) = 1.70$, $MSE = 720$, $p = .1369$, $r_{\text{effect}} = .22$. Not surprisingly, this indicates that the older group was significantly slower than the younger group (mean RTs of 577 and 386 ms, respectively) and also that the young people showed greater triplet frequency sensitivity than the old people (mean RT advantage for the high- over low-frequency triplets of 66 and 36 ms, for the young and old people, respectively).

The analysis of accuracy revealed a significant main effect of Group, $F(1, 32) = 18.16$, $MSE = 0.069$, $p = .0002$, $r_{\text{effect}} = .60$, as well as a significant Group × Triplet interaction, $F(1, 32) = 10.20$, $MSE = 0.022$, $p = .0031$, $r_{\text{effect}} = .49$, and a Group × Triplet × Session interaction, $F(5, 160) = 10.49$, $MSE = 0.002$, $p < .0001$, $r_{\text{effect}} = .50$. This indicates that old adults were significantly more accurate overall than the young adults (mean accuracy of .97 vs. .86, respectively), and they showed a significantly smaller accuracy advantage for the high- over the low-frequency triplets (overall difference of .10 and .01 for the young and old adults, respectively).

As in Experiment 1a, we also examined the extent to which triplet frequency or joint probability was related to the RT over the three final sessions using a within-subjects regression analysis. The mean correlation coefficients for both groups are shown in Figure 2. These means were significantly less than zero for both the young group ($M = -0.410$), $t(15) = 7.92$, $p < .0001$, and the old group ($M = -0.251$), $t(17) = 6.62$, $p < .0001$, indicating that RT was inversely related to triplet frequency. This is consistent with the learning analysis reported above in indicating that both groups learned triplet frequency or joint probability. In addition, the correlation was significantly higher for the young group than for the old group, $t(32) = 2.52$, $p = .0171$, $r_{\text{effect}} = .41$, consistent with the conclusion that the old adults learned less than the young adults.

The correlations for individual participants revealed that 15 of the 16 young adults showed a negative correlation between triplet probability and RT, $p = .0005$ by Sign Test, with 13 reaching statistical significance—$r(46) > .28$, $p < .05$—$p = .0213$ by Sign Test. Similarly, 17 of the 18 older adults had a negative correlation, $p < .0001$ by Sign Test, but only 7 reached statistical significance, $p = .4807$ by Sign Test. The 2 individuals with a nonnegative correlation were close to zero ($r = .003$ and .046 for the young and old individuals, respectively).

Thus, the within-subjects regression analysis supports the conclusion that although older adults are able to learn triplet frequency in the TLT, the relationship between joint probability and RT is weaker than it is for younger people.

Was learning implicit? No one indicated in the postexperimental interview that the second cue predicted the target or that the high-frequency triplets occurred more often than the low. More importantly, analysis of peoples' explicit frequency judgments revealed that both younger and older adults rated the high- and low-frequency triplets as occurring equally often. This was shown in separate one-way repeated measures ANOVAs on the frequency judgment data for each group.

For the young group, this analysis revealed a significant main effect of Triplet Type (high-frequency, low-frequency, repetitions, and trills), $F(3, 39) = 5.27$, $MSE = 0.051$, $p = .0038$, $r_{\text{effect}} = .54$. Post hoc analyses showed that repetitions were rated as occurring significantly less often (mean rating = 1.30) than any of the three other triplet types, with no significant differences among the high ($M = 1.61$) and low ($M = 1.54$) frequency triplets or trills ($M = 1.58$). Most importantly, the recognition difference in ratings for the high- and low-frequency triplets (.061) fell within the 95% confidence interval for equivalence (−.004, .125). Further examination of the individual recognition judgments for high- and low-frequency triplets for each person indicated that this is not a result of averaging artifact. The rating difference ranged from −.188 (low judged more frequent than high) to .319 (high more frequent than low), with the observed difference falling within the 95% confidence interval around zero for every young participant. Thus, the young people appeared to be aware that triplets with three identical events were rare, but they were unable to distinguish between the high- and low-frequency items.

The same pattern was obtained for the old adults. There was a significant effect of Triplet Type, $F(3, 51) = 10.66$, $MSE = 0.034$, $p < .0001$, $r_{\text{effect}} = .62$, that post hoc analyses showed to reflect lower ratings for the repetitions (mean rating = 1.28) than the other triplet types (means of 1.53, 1.54, and 1.60 for high-frequency, low-frequency, and trills, respectively). The old adults did not distinguish the high- and low-frequency triplets (mean rating difference of −.012; 95% confidence interval = −.074, .050)—a result observed in the individual as well as the group data (rating difference ranged from −.188 to .306, with all differences within the 95% confidence interval around zero).

Thus, although people in both groups seemed aware that triplets with three identical events are rare, they were unaware of other frequency differences. Most importantly, neither group was able to distinguish between high- and low-frequency triplets in the explicit frequency judgment task. This mirrors the findings of Experiment 1a even though in the present experiment high-frequency triplets occurred 9 times more often than low-frequency triplets. Because the trills and repetitions were omitted from the learning analyses, we conclude that triplet frequency learning was implicit.

Cross-experiment comparisons of triplet frequency learning. The present experiment differed from Experiment 1 in that the predictive relationships within the high-frequency triplets were first- rather than second-order and the high-frequency triplets occurred with higher probability. To investigate whether these changes influenced triplet frequency learning, we performed cross-experiment comparisons of the within-subjects learning measure for both groups.

Although young adults revealed somewhat more learning in Experiment 2 than in Experiment 1a (mean correlation = −.410 vs. −.347, respectively), this difference fell well within the 95% confidence interval for equivalence (difference = .063; 95% confidence interval = −.054, .181). This suggests that young adults are as sensitive to second- as first-order relationships in the TLT and that increasing the probability of high-frequency triplets from .80 to .90 did not lead either to significantly greater learning or to increased declarative knowledge of triplet frequency as shown above.

A very different pattern occurred for the older adults. The old group revealed significantly more learning in Experiment 2 than in Experiment 1a (mean correlation = −.251 vs. −.155, respectively), $t(33) = 2.071$, $p = .0462$, suggesting that for old people, first-order relationships are more easily learned than second-order relationships. This is consistent with previous implicit sequence learning results that used the SRTT (Curran, 1997; J. H. Howard & Howard, 1997). Furthermore, the overall performance was nearly identical for older adults in the present experiment and Experiment 1a for both RT (mean difference = 9.2 ms; 95% confidence interval = −99 ms, 118 ms) and accuracy (mean difference = .007; 95% confidence interval = −.013, .026). The fact that their correlations were significantly higher in Experiment 2 than in Experiment 1a shows that even at very high levels of accuracy, this regression-based learning measure revealed differences due to the structure of the triplet regularities. In contrast, the dramatic differences in RT and accuracy between Experiment 1a and Experiment 1b reported above for old adults did not influence these correlations significantly. This suggests that overall accuracy is having little effect on the regression-based learning measure, whereas triplet structure is having an effect. Thus, although we cannot rule out the possibility that overall accuracy differences contribute to the observed age deficits in learning, these findings strongly suggest there are age deficits in learning.

Experiment 3

The previous experiments demonstrated that young and old adults learn triplet frequencies (joint probability) implicitly in the TLT. Earlier studies that used the SRTT and SLTs have shown that people also learn the conditional as well as joint probabilities (Aslin et al., 1998; Hunt & Aslin, 2001). Therefore, these studies suggest that in the TLT, people should become sensitive to predictive statistical relationships within triplets as well as to the overall frequency with which the triplet occurs. We have some evidence that within-triplets relationships are important in the TLT in that older adults learned more when high-frequency triplets were characterized by first-order (Experiment 2) rather than second-order (Experiment 1a) relationships. In Experiment 3, we asked whether people are able to learn conditional probabilities in the TLT as well as overall triplet frequency.

To accomplish this, we manipulated the frequency of individual triplets such that the conditional probability of a target given the cue events, $P(T|C_1C_2)$, varied *within* the high-frequency triplets. In other words, some triplets occurred more often than others (high- vs. low-frequency triplets), and within the high-frequency triplets, some cues were more predictive of the target event than others (strong vs. weak conditional probability). Thus, we were able to examine the learning of both joint and conditional probability statistics in the same experiment. We also varied first- and second-order statistics by including both first-order (e.g., XAB) and second-order (e.g., AXB) relationships within the high-frequency triplets.

Method

Participants. Eighteen young (mean = 19.5 years) and 18 old (mean = 72.4 years) volunteers were recruited from the same populations as the previous experiments (see Table 1). The data from 1 old participant were lost because of an equipment failure, and 1 young participant was excluded for chance responding on the final session (26.9% accuracy). The analyses below are based on the remaining 17 individuals in each group.

Design. The design was the same as Experiment 1a.

Stimuli. The apparatus and stimuli were the same as Experiment 1a. However, for half of the 16 high-frequency triplets, the first cue predicted the target, whereas for the other half, the second cue predicted the target. Thus, high-frequency triplets contained either first- or second-order information. For example, for a given individual, the high-frequency triplets might consist of XAB, XBC, CXD, DXA, where A, B, C, D denote the four events, and X is any of the four. As in the earlier experiments, all 16 high-frequency triplets occur with the same probability (i.e., equivalent joint probability); however, unlike the earlier experiments, the conditional probabilities of a target given the pair of cues, $P(T|C_1C_2)$, differ.

The joint and conditional probabilities within the high-frequency triplets are shown for the above example in Table 2. The three left columns list the triplets in which the second cue predicts the target, and the three right columns list triplets for which the first cue is predictive. Because high-frequency triplets occur on 80% of the trials, each will occur with probability .05 as shown in the joint probability columns, $P(C_1C_2T)$. However, we constructed the high-frequency triplets so that for half, the cue-pair strongly predicts the target (cells not in bold), whereas for the remaining half, the cue-pair only weakly predicts the target (bolded cells). We refer to these as *strong* and *weak* conditional probability triplets, respectively. Thus, the conditional probability of the target is high for the strong triplets, $P(T|C_1C_2) = .80$, and low for the weak triplets, $P(T|C_1C_2) = .46$, as shown in the conditional probability columns, $P(T|C_1C_2)$, in the table. The specific cue-target mapping was counterbalanced across individuals such that each event occurred as both first- and second-order predictors, and all four events served as targets. Postexperimental analysis showed that the random sampling resulted in high-frequency triplets on exactly 80% of the trials overall, and the actual conditional prob-

Table 2
High-Frequency Triplets for Experiment 3 With Their Overall Joint Probability and Cue-Pair Conditional Probability

First-order (XAB, XBC)			Second-order (CXD, DXA)		
Triplet	$P(C_1C_2T)$	$P(T\|C_1C_2)$	Triplet	$P(C_1C_2T)$	$P(T\|C_1C_2)$
AAB	.05	.80	**CAD**	.05	.46
BAB	.05	.80	**CBD**	.05	.46
CAB	.05	.46	CCD	.05	.80
DAB	.05	.46	CDD	.05	.80
ABC	.05	.80	**DAA**	.05	.46
BBC	.05	.80	**DBA**	.05	.46
CBC	.05	.46	DCA	.05	.80
DBC	.05	.46	DDA	.05	.80

Note. The high-frequency triplets were constructed so that for half, the cue-pair strongly predicts the target (presented in normal font), whereas for the remaining half, the cue-pair only weakly predicts the target (presented in bold font). We refer to these as *strong* and *weak* conditional probability triplets, respectively.

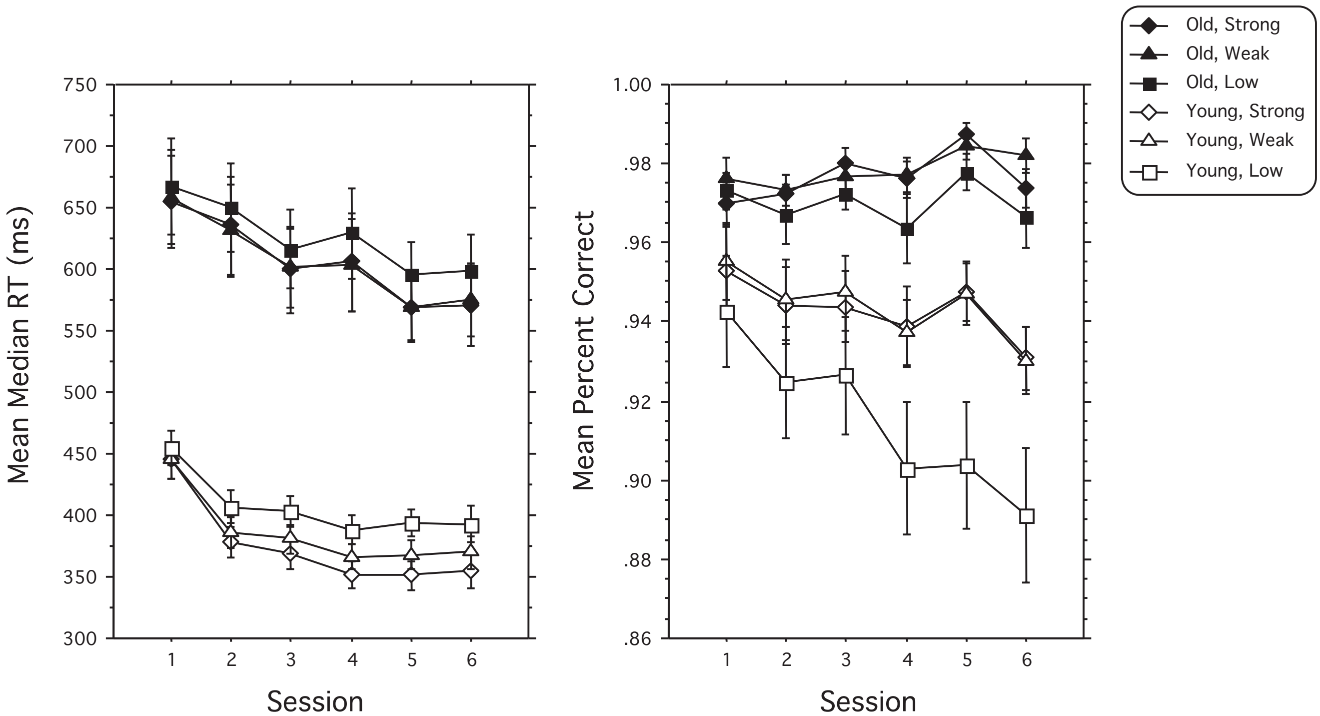

Figure 6. Mean of median reaction time (RT; left curve) and mean accuracy (right curve) over sessions by high- and low-frequency triplets and age group for Experiment 3, with the high-frequency triplets broken down by strong and weak cue-pair conditional probability, $P(T|C_1C_2)$. Error bars represent the standard error of the mean.

abilities across conditions were .4613 for the weak conditional probability pairs and .8012 for the strong pairs.[1] The fact that the conditional probabilities differ for the high-frequency triplets, whereas their joint probabilities do not, enable the effects of joint and conditional probability to be examined separately.

Procedure. The procedure was the same as Experiment 1a.

Results and Discussion

Do young adults learn triplet frequency? The mean RT and accuracy data are shown in Figure 6, with high-frequency triplets partitioned into strong (diamonds) and weak (triangles) conditional probability. Here, we ask whether young people learn triplet frequency (joint probability) by comparing responses to low-frequency (squares in Figure 6) and high-frequency (mean of the diamonds and triangles) triplets. Conditional probability learning is examined in a later section.

A Triplet × Session ANOVA on the RT data for the young group revealed a familiar pattern. Overall skill learning was shown in a significant main effect of Session, $F(5, 80) = 40.43$, $MSE = 743$, $p < .0001$, $r_{\text{effect}} = .85$, with mean RT improving from 449 to 374 ms across the six sessions. Triplet frequency learning was also demonstrated in a significant main effect of Triplet, $F(1, 16) = 63.45$, $MSE = 441$, $p < .0001$, $r_{\text{effect}} = .89$, and a significant Triplet × Session interaction, $F(5, 80) = 6.48$, $MSE = 52$, $p < .0001$, $r_{\text{effect}} = .54$. The overall RT advantage for high- over low-frequency triplets (379 vs. 402 ms, respectively) increased from 11 ms in the first session to 28 ms in the last. The same pattern was seen for accuracy, with significant main effects of Session, $F(5, 80) = 6.22$, $MSE = 0.001$, $p < .0001$, $r_{\text{effect}} = .53$, and Triplet, $F(1, 16) = 14.02$, $MSE = 0.003$, $p = .0018$, $r_{\text{effect}} = .68$, and a significant Session × Triplet interaction, $F(5, 80) = 3.36$, $MSE = 0.0001$, $p = .0083$, $r_{\text{effect}} = .41$. Thus, the present findings replicate the triplet frequency learning findings of the previous experiments for young adults.

Do older adults learn triplet frequency? For the older adults, a Triplet × Session ANOVA on the RT data produced a significant main effect of Session, $F(5, 80) = 11.45$, $MSE = 2{,}927$, $p < .0001$, $r_{\text{effect}} = .65$, indicating that the old adults also show overall skill learning (mean RT improved from 661 to 584 ms with practice). There was also evidence of triplet frequency learning in a significant main effect of Triplet, $F(1, 16) = 63.45$, $MSE = 441$, $p < .0001$, $r_{\text{effect}} = .74$, with older adults responding 21 ms faster to high- than low-frequency triplets overall (mean RTs of 604 and 625 ms, respectively). However, the Triplet × Session interaction, $F(5, 80) = 1.18$, $MSE = 197$, $p = .3261$, $r_{\text{effect}} = .26$, was not significant, perhaps because of the relatively large variability for the older group.

[1] Because $P(T|C_1C_2) = P(C_1C_2T)/P(C_1C_2X)$, where X is any target event, these values are $.05/(2 \times PH + 2 \times PL) = .05/.1083 = .46$ for the weak pairs, and $.05/(PH + 3 \times PL) = .05/.0625 = .80$ for the strong pairs, where PL is the probability of a low-frequency triplet (.00416), and PH is the probability of a high-frequency triplet (.05000).

As in the earlier experiments, older people were very accurate ($M = 97\%$ overall) and remained so with practice. Nevertheless, the ANOVA on these data produced a significant main effect of Session, $F(5, 80) = 2.66$, $MSE = 0.0002$, $p = .0282$, $r_{effect} = .35$. Inspection of the right panel of Figure 6 suggests that this may reflect cross-session variability rather than a systematic trend for accuracy to change with practice. This ANOVA also revealed a significant main effect of Triplet, $F(1, 16) = 5.78$, $MSE = 0.001$, $p = .0286$, $r_{effect} = .52$, with slightly higher accuracy for high- than low-frequency triplets (means of .978 and .970, respectively), which is consistent with triplet frequency learning. As in the case of RT, the Session × Triplet interaction was not significant, $F(5, 80) = 1.663$, $MSE = 0.0001$, $p = .1531$, $r_{effect} = .32$. Thus, when combined with the RT results, these findings provide evidence of triplet frequency learning in older adults.

Are there group differences in learning triplet frequency? As in the previous experiments, this question was investigated in omnibus ANOVAs focusing on the main effect of Group and the Group × Triplet interactions.

The three-way ANOVA on RT produced a significant main effect of Group, $F(1, 32) = 40.70$, $MSE = 125{,}769$, $p < .0001$, $r_{effect} = .75$, but neither the Group × Triplet interaction, $F(1, 32) < 1.00$, $MSE = 784$, $p = .6224$, $r_{effect} = .09$, nor the Group × Triplet × Session interaction, $F(5, 160) < 1.00$, $MSE = 125$, $p = .7987$, $r_{effect} = .12$, was significant. This indicates that whereas the older group was significantly slower than the younger group (mean RTs of 615 and 391 ms, respectively), unlike Experiments 1 and 2, no differences in triplet frequency learning were detected between the two groups.

The analysis of accuracy revealed a significant main effect of Group, $F(1, 32) = 15.37$, $MSE = 0.013$, $p = .0004$, $r_{effect} = .57$, as well as a significant Group × Triplet interaction, $F(1, 32) = 6.40$, $MSE = 0.002$, $p = .0165$, $r_{effect} = .41$, but the three-way interaction was not significant, $F(5, 160) = 1.42$, $MSE = 0.0003$, $p = .2188$, $r_{effect} = .21$. Thus, as expected, the older adults were significantly more accurate than the young (.97 vs. .93, respectively). They also showed a significantly smaller accuracy advantage for the high- over the low-frequency triplets than young (overall difference of .01 and .03, respectively), but this did not change significantly with practice. Thus, the accuracy data offer evidence of a small age deficit in triplet frequency learning, but once again, the very high accuracy of the older group limits the conclusions we can draw from these analyses.

We also compared the two groups by estimating regression-based measures of learning as in the earlier experiments. The resulting mean correlations are displayed in Figure 2 for each group. These were significantly different from zero for both groups—young group (mean correlation = −.32), $t(16) = 8.98$, $p < .0001$, and old group (mean correlation = −.21), $t(16) = 5.63$, $p < .0001$—showing that both groups learned triplet frequency consistent with the analyses reported above. Further, the mean correlation was significantly larger for the young group than the old group, $t(32) = 4.62$, $p = .0393$, $r_{effect} = .36$, indicating that the relationship between triplet probability and RT was stronger for the young adults.

All 34 participants had a negative correlation between triplet probability and RT, but only 10 of the old people and 7 of the young people reached statistical significance, $p = .6291$ by Sign Test, for both groups. Thus, the individual correlations provide little evidence for overall age deficits in triplet frequency learning. This may reflect the fact that conditional probabilities are also varying, leading to greater variability than in the earlier experiments because here individuals may differ in the statistical relationships they learn.

Do young adults learn conditional probability? In the above analyses, we confirmed that people learn triplet frequency when both joint and conditional probabilities are varied. To investigate whether people also learn conditional probabilities, we compared learning for the high-frequency triplets having strong and weak conditional probability. Figure 6 suggests that young people are sensitive to conditional probability because they respond more quickly to the strong than weak triplets with practice.

A Triplet Conditional Probability (TripletCP – strong vs. weak) × Session ANOVA carried out on the RT data for the young group revealed a significant main effect of Session, $F(5, 80) = 52.94$, $MSE = 696$, $p < .0001$, $r_{effect} = .88$. More importantly, there was also a significant main effect of TripletCP, $F(1, 16) = 45.16$, $MSE = 133$, $p < .001$, $r_{effect} = .86$, indicating that young people were faster to triplets with strong than weak conditional probability (375 vs. 386 ms, respectively). Further, the significant TripletCP × Session interaction, $F(5, 80) = 11.55$, $MSE = 26.84$, $p < .001$, $r_{effect} = .65$, indicates that this difference increased with practice from a mean difference of 3 ms on the first session to 15 ms on the sixth session.

The accuracy data were less informative as is evident in Figure 6. The ANOVA for the young group revealed only a significant main effect of Session, $F(5, 80) = 3.34$, $MSE = 0.001$, $p = .0086$, $r_{effect} = .41$, indicating that overall accuracy declined toward the target 90% value across sessions. Neither the main effect of TripletCP, $F(1, 16) = 0.054$, $MSE = 0.0002$, $p = .8198$, $r_{effect} = .06$, nor the TripletCP × Session interaction, $F(5, 80) = 0.221$, $MSE = 0.0002$, $p = .9526$, $r_{effect} = .12$, was significant. Thus, young people learned the conditional probability between the target and the cue pair because with practice they responded more quickly to the triplets having strong conditional probability than to those with weak conditional probability. However, accuracy seems to be insensitive to conditional probability.

These findings suggest that younger adults not only use the information available in the overall joint frequency of the three events on each trial but also the information in the predictive relationships among the three events within the triplets (i.e., the conditional probability of the target given the cues).

Do older adults learn conditional probability? The two-way ANOVA on RT for the older group produced only the expected significant main effect of Session, $F(5, 80) = 14.18$, $MSE = 2{,}771$, $p < .0001$, $r_{effect} = .69$, reflecting the overall skill learning documented above. Neither the main effect of TripletCP, $F(1, 16) = 0.02$, $MSE = 712$, $p = .8790$, $r_{effect} = .04$, nor the TripletCP × Session interaction, $F(5, 80) = 0.98$, $MSE = 103$, $p = .4322$, $r_{effect} = .24$, was significant, reflecting the fact that RT did not differ for triplets with strong and weak conditional probability (606 ms for both).

The ANOVA on accuracy for the older adults produced similar results. There was a significant main effect of Session, $F(5, 80) = 5.59$, $MSE = 0.0001$, $p = .0002$, $r_{effect} = .52$; however, the main effect of TripletCP, $F(1, 16) = 2.10$, $MSE = 0.00007$, $p = .1671$, $r_{effect} = .36$, was not significant. The TripletCP × Session interaction, $F(5, 80) = 3.088$, $MSE = 0.00006$, $p = .0134$, $r_{effect} = .41$,

Table 3
Best Fitting Individual Stepwise Regression Coefficients for Cue-Pair and Single-Cue Conditional Probabilities and Each Participant in Experiment 3

Group	Participant no.	Intercept	$P(T \mid C_1C_2)$	$P(T \mid C_1)$	$P(T \mid C_2)$	R^2
Old	1	568.91			**−107.88**	.0935
Old	2	600.47				
Old	3	737.24				
Old	4	1056.74		**−211.34**		.0295
Old	5	850.08		−187.31	**−192.43**	.2115
Old	6	557.62			**−111.46**	.0722
Old	7	566.95			**−189.46**	.4598
Old	8	906.51				
Old	9	713.30			**−182.06**	.2351
Old	10	622.90				
Old	11	480.90	**−63.11**			.1023
Old	13	465.75	54.38	−52.56	**−82.80**	.1527
Old	14	625.22		**−76.78**		.0316
Old	15	491.88			**−147.67**	.3929
Old	16	645.78			**−193.84**	.2756
Old	17	580.44			**−124.69**	.1764
Old	18	808.37				
Young	1	369.34	**−171.52**	150.47		.1394
Young	2	383.32	**−60.21**			.1239
Young	3	439.66	**−35.56**			.1219
Young	4	489.82		**−109.32**		.0793
Young	5	490.37	8.22	−109.32	**−155.31**	.5967
Young	6	433.27			**−52.47**	.0523
Young	7	459.52		−69.58	**−133.49**	.2527
Young	8	373.25	80.76	**−146.25**	−122.05	.2051
Young	9	517.92			**−212.44**	.2560
Young	10	371.46	**−63.06**			.2689
Young	11	464.94			**−57.62**	.0297
Young	12	387.24		**−78.61**		.1390
Young	13	361.45	**−20.86**			.0906
Young	14	411.76	**94.22**			.2075
Young	15	549.01			**−139.90**	.2236
Young	17	408.20	−55.31		**−62.32**	.3503
Young	18	344.19	**−49.28**			.1719

Note. The coefficients for each predictor variable, split by participant and group, are shown with the strongest predictor (first added) highlighted in bold for each person.

was significant, but Figure 6 suggests that accuracy did not vary systematically with either variable for the older adults.

Are there group differences in conditional probability learning? The above analyses suggest that young adults were sensitive to the within triplet conditional probabilities, whereas older adults were not. Here we compare RTs in the two groups directly in an omnibus ANOVA, examining the main effect of Group and its interaction with TripletCP. We focus on RT because accuracy was insensitive to conditional probability. This revealed a significant main effect of Group, $F(1, 32) = 39.32$, $MSE = 131{,}988$, $p < .001$, $r_{\text{effect}} = .74$, reflecting the ubiquitous age difference in RT, as well as a significant TripletCP × Group interaction, $F(1, 32) = 6.38$, $MSE = 423$, $p = .0167$, $r_{\text{effect}} = .41$, and a TripletCP × Session × Group interaction, $F(5, 160) = 3.25$, $MSE = 65$, $p = .0080$, $r_{\text{effect}} = .34$. Thus, the younger adults show significantly greater overall sensitivity to the within-triplet conditional probability than do older adults.

As in the previous experiments, we also compared the groups using learning scores determined by within-subjects regression analyses. We used three predictor variables, including the single-cue conditional probability for each cue as well as the cue-pair conditional probability. We included the single-cue conditional probabilities, $P(T|C_1)$ and $P(T|C_2)$, to investigate the possibility that there are individual or group differences in learning the predictive information in one or another cue and/or in the pair of cues. We designed the experiment such that the conditional probability for the first cue, $P(T|C_1)$, was greater than that for the second cue, $P(T|C_2)$, for high-frequency triplets with second-order information (right columns of Table 2), whereas $P(T|C_1)$ was less than $P(T|C_2)$ for triplets with first-order information (left columns of Table 2). These values were also independent of the triplet joint probability and cue-pair conditional probability.

We performed a stepwise linear regression for each individual, using the mean RT over the final three sessions for the 48 triplets (excluding repetitions and trills) as the outcome measure, and the three conditional probabilities described above as predictors. At least one predictor variable met an add-in criterion of .25 for all 18 participants in the young group and for 12 of the 18 participants in the old group, $\chi^2(1, N = 36) = 5.86$, $p = .0155$. Table 3 shows the coefficients for each predictor variable split by participant and group, with the strongest predictor (first added) highlighted in bold for each person.

It is clear from Table 3 that the best predictor differed for the young and old participants. Specifically, the cue-pair predictor was best for 7 of the young people (7 of 17 or 41%), whereas this was the case for only 1 or 8% of the 13 older adults whose data were fit by the conditional probability model, $\chi^2(1, N = 30) = 4.50$, $p = .0339$. In contrast, of these 13 older adults, 11 relied on one or the other individual cue, $p = .0225$ by Sign Test, with more depending on the second cue than on the first (9 vs. 2, $p = .0654$ by Sign Test), although this difference was only marginally significant. These findings suggest that older adults rely more on individual cue information, and specifically on the second cue, rather than on the pair of cues.

These results are consistent with the group comparison reported above in suggesting that the young people use the predictive information in the two cues within each triplet better than older adults. In addition, the individual correlations suggest that when this information is used, older adults tend to focus on a single cue and specifically on the second cue. This latter result is consistent with the finding that older adults learned more when the high-frequency triplets had first-order relationships (Experiment 2) than second-order relationships (Experiment 1a).

Is learning implicit? As in the previous experiments, neither the interviews nor the frequency rating data revealed evidence of declarative knowledge. For the young group, a one-way ANOVA on the ratings yielded no main effect of Triplet, $F(3, 51) = 2.16$, $MSE = 0.036$, $p = .1035$, $r_{\text{effect}} = .34$. Thus, the slightly lower rating assigned to the repetitions, 1.44, did not differ from the ratings assigned to the other triplets (1.59, 1.57, 1.53 for the high, low, and trills, respectively). Furthermore, the individual ratings for high- and low-frequency triplets ranged from −.305 (low judged more frequent than high) to .288 (high more frequent than low), with the observed difference falling within the 95% confidence interval around zero for every young participant.

A comparable analysis of frequency ratings by the older adults revealed a significant main effect of Triplet, $F(3, 51) = 4.36$, $MSE = 0.057$, $p = .0083$, $r_{\text{effect}} = .45$. Post hoc analyses showed that repetitions were rated as occurring significantly less often (mean rating = 1.28) than any of the three other triplet types, with no significant differences among the high-frequency ($M = 1.52$) and low-frequency ($M = 1.52$) triplets or trills ($M = 1.50$). Most importantly, the mean frequency ratings for the high- and low-frequency triplets were identical. The difference in rating between high- and low-frequency triplets for individual older old adults ranged from −.311 (low judged more frequent than high) to .305 (high more frequent than low), with the observed difference falling within the 95% confidence interval around zero for every person. Thus, although the old people appeared to be aware that triplets with three identical events were infrequent, they did not distinguish between the high- and low-frequency triplets. Because repetitions as well as trills were omitted from the learning analyses, we conclude that triplet frequency learning was implicit for both groups.

General Discussion

Overall, these findings indicate that the TLT is a useful complement to the SRTT and other tasks for investigating implicit sequence learning. This general conclusion follows from three major findings. First, both young and old adults were able to learn the statistical relationships among events to improve their responding in the TLT and they did so incidentally and implicitly. Second, we were able to distinguish between learning different types of statistical dependencies, including overall triplet frequency (i.e., joint probability) and within-triplet conditional probability. Third, although both groups showed implicit learning, there were differences between the two age groups. Overall, older adults revealed less learning than younger people, consistent with previous studies of subtle relationships in sequence learning with the SRTT, but they also showed a different pattern of learning, with older adults showing greater learning for relationships among adjacent elements (first-order) than nonadjacent elements (second-order). These findings are elaborated below.

Learning in the TLT

Both younger and older adults showed implicit triplet frequency learning in all experiments. People responded more quickly and more accurately to the frequent than the infrequent triplets, and this difference increased with experience in the task. In addition, triplet frequency learning in the TLT occurred regardless of whether the high-frequency triplets contained first- or second-order structure or a combination of the two (Experiments 2, 1 and 3, respectively).

The present findings parallel the results of studies that have used the SRTT and its variants (Forkstam & Petersson, 2005; D. V. Howard et al., 2004; Reed & Johnson, 1994), but they go beyond the earlier results in demonstrating that these types of sequential structure can be learned even when there is no manual motor sequence to be learned. Of course, questions remain concerning the extent to which learning in the TLT may be based on learning anticipatory eye movements (e.g., Albouy et al., 2006; Marcus, Karatekin, & Markiewicz, 2006) as well as the extent to which the TLT and the SRTT are tapping similar underlying systems (but see discussion of preliminary functional magnetic resonance imaging [fMRI] results below). Further research will be needed to address these questions. Nonetheless, the present study provides converging evidence for SRTT studies that have demonstrated nonmotor sequence learning (Dennis, Howard, & Howard, 2006; Goschke, Friederici, Kotz, & van Kampen, 2001; Lungu et al., 2004) but with a very different task.

Learning Is Implicit in the TLT

For each of the above studies, we presented evidence from postexperimental interviews as well as from a triplet-frequency judgment task that people did not acquire declarative knowledge about triplet frequency in the TLT; ratings for high- and low-frequency triplets were not significantly different in either the individual or group data. However, in a recent article, Rouder, Speckman, and Pratte (2007) have argued that traditional statistical techniques are not appropriate for designs in which the predicted outcome is chance performance, as is the case in our frequency judgment task. To address this, they introduced a hierarchical Bayesian model to estimate the probability that each individual is performing at chance. As an added precaution, we applied their model to our data to estimate the probability that each of the 111 individuals in the study were at chance based on the number of correct frequency judgments made for the high- and low-frequency triplets (i.e., excluding the trills and repetitions). The results have confirmed traditional methods that the TLT task is implicit. Specifically, the mean estimated probability of chance performance across all individuals was .971, with 103 participants exceeding the $p > .95$ posterior probability criterion (Rouder et al., 2007), and the 8 who did not (5 old and 3 young participants) had an average probability of .867 (.715 to .933) of chance performance.

Learning Joint Versus Conditional Probabilities

This study also goes beyond most previous SRTT studies in investigating the role of conditional probability in sequence learning. As Perruchet and Pacton (2006) have pointed out, research on how people learn statistical relationships, such as conditional probability, has generally employed tasks other than the SRTT, such as artificial language learning (Perruchet & Pacton, 2006). In contrast to the SRTT, these tasks depend on explicit judgments of grammaticality or familiarity to assess what people learned rather than on on-line, implicit, performance-based measures (e.g., Aslin et al., 1998; Saffran et al., 1996). The TLT introduced in the present study falls somewhere between these approaches in that it relies on on-line, performance-based measures to evaluate statistical learning. As such, the TLT can help to bridge these otherwise separate literatures (Perruchet & Pacton, 2006).

To illustrate, in Experiment 3 we demonstrated that many people learned to exploit the statistical relationships among within-triplet events to improve their responding. This was based on the finding that the conditional probabilities of a target given either single cues and/or the cue pair were significant predictors of response time. Thus, people are able to learn both the joint probability of events (triplet frequencies) as well as their conditional probabilities (within-triplet statistics) in the TLT. These findings are consistent with a previous study reporting that young people can use both types of information simultaneously in an SRTT (Hunt & Aslin, 2001). As in the present study, Hunt and Aslin (2001) also found substantial individual differences in the statistics people used even within their relatively homogeneous student sample. These individual differences may ultimately be useful for investigating the underlying basis of impairments reported for various special populations (Forkstam & Petersson, 2005; J. H. Howard, Howard, Japikse, & Eden, 2006; Negash et al., 2007).

Age Differences in Learning

Although both the older and younger groups showed implicit learning in the TLT, there were also group differences. This was revealed in two major findings. First, there was an overall age deficit in learning triplet frequency in all experiments suggesting that older adults are less sensitive to the joint probability of three-event sequences. This was evident in both overall group analyses and in individual analyses. These findings are consistent with previous studies reporting age-related impairment in learning subtle sequential regularities (Curran, 1997; J. H. Howard & Howard, 1997). However, the present findings go beyond earlier results in showing that age deficits occur even when event timing is identical for the two groups, something that does not occur in the SRTT. In addition, unlike previous SRTT studies that have shown age deficits in sequence learning, in the present study we have shown that age differences in sequence learning are not limited to situations that require learning manual motor sequences.

Second, Experiment 3 demonstrated that compared with younger adults, older adults were also limited in their ability to use the within-triplet statistics or conditional probabilities in the TLT. Whereas young people appeared to use the information in both cues, the older adults relied primarily on information in the second cue alone. This provides converging evidence from a different learning paradigm that age deficits are greater for sequences with higher order structure than for simpler sequences.

There is ample evidence from studies of artificial language learning that regularities among nonadjacent events are more difficult to learn than those among adjacent events and that such learning may only occur under special conditions (Creel et al., 2004; Newport & Aslin, 2004). For example, 18-month-old children and adults were able to learn nonadjacent dependencies (e.g., between A and B in AXB strings) when the variability between adjacent pairs (AX, XB) was high (Gomez, 2002), although younger 12-month-old infants could not (Gomez & Maye, 2005). Because variability is very high for adjacent pairs in the TLT task, particularly in Experiments 1a and 3, the conditions were favorable for learning nonadjacent statistics, as observed for the younger participants. However, our results indicate that older adults are impaired in doing so. This may reflect an age-related associative learning deficit (Mitchell, Johnson, Raye, & D'Esposito, 2000) or a more general age-related working memory limitation (Salthouse, 2004).

There are two limitations in the present study that that may temper our conclusion of an age deficit in the TLT. First, it is possible that the apparent deficit reflects the fact that with their very high accuracy, older adults simply have less room to reveal learning than younger adults. However, as we argued above, we think this is unlikely to be a major factor in the age deficit. This argument rests on the finding that the regression-based measure of learning, which depends on within- rather than across-subjects performance levels, was sensitive to differences in sequence structure even with very high levels of accuracy (old adults in Experiments 1a vs. 2). Further, older adults demonstrated the same amount of learning for comparable structure even when there were substantial differences in overall performance (old adults in Experiments 1a vs. 1b). Thus, overall accuracy seems to have little effect on this learning measure, whereas triplet structure does. In addition, when we provided feedback to push the older adults to make more errors matching the young adults (Experiment 1b), the age deficit persisted even though the feedback led to substantial variability both between and within individuals. In fact, the regression-based measure of learning did not differ across these very different conditions.

Second, our conclusions may also be limited by the event timing we used. Stimuli were always presented with a 120-ms cue duration and 150-ms intercue interval. This presentation rate might have been too fast for the older adults to process the cues fully. On the other hand, the finding that older adults appeared to depend more on the second cue than the first suggests that the individual cues were, in fact, being processed. Nevertheless, this explanation cannot be ruled out, and the age deficit we observed may depend on the event timing we used here. Future studies should investigate the role of event timing in the TLT as well as attempt to equate accuracy by other means, such as by encouraging younger adults to be more accurate.

The TLT as a Complement to the SRTT

The present findings indicate that although the TLT and SRTT are very different, there are a number of similarities between our findings with the TLT and those from previous studies that used the SRTT. For example, both young and old adults show implicit learning of event frequencies and of subtle sequential relationships among events, but the old adults are less efficient in doing so. These similarities suggest that comparable mechanisms may underlie learning in the two tasks. However, additional work is required to investigate this possibility. For example, one could explore transfer of learning across the two tasks or compare the neural systems engaged by using functional neuroimaging or related techniques. Indeed, two preliminary fMRI studies that used the TLT have reported patterns of activation similar to what has been shown for the SRTT (Fletcher et al., 2005) and for another task used to examine frequency-based learning (Amso, Davidson, Johnson, Glover, & Casey, 2005). One study from our lab revealed learning-related caudate activation in young adults (Simon, Barnes, Vaidya, Howard, & Howard, 2008), and another showed striatal and cerebellar activation in typically developing children and children with autism spectrum disorder (Barnes et al., 2008).

Regardless of whether learning in the two tasks engages the same or different mechanisms, the TLT provides another useful tool for investigating implicit sequence learning. Because it is not constrained by a single long sequence, there is considerable flexibility in the kinds of statistical regularities that may be studied using the TLT. In addition, the fact that responses do not occur to every event makes it possible to investigate learning without manual motor sequencing as well as to manipulate timing of the event sequence independently of response speed. In fact, the fixed trial structure of the TLT offers a clear advantage for event-related fMRI over the trial structure of the SRTT. This makes the TLT particularly well suited for use in event-related fMRI or event-related potential studies in which event timing must be controlled.

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