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RESEARCH ARTICLE

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Implicit sequence learning without motor sequencing in young and old adults

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Abstract The ability to detect patterns and organize individual events into complex sequences is a fundamental cognitive skill that is often learned implicitly. The serial response time (SRT) task has been widely used to investigate implicit sequence learning, but it remains unclear whether people learn a perceptual or motor sequence in this task. This study reports three experiments that build on previous research by Goschke and colleagues using an auditory SRT task in which the stimulus-to-response mapping changes on every trial to eliminate spatio-motor sequencing. The current study extends earlier work in three ways. First, healthy young and older adults were tested rather than the neuropsychological patients used in previous research. Second, sequences of different structural complexity were investigated including first- and second-order repeating sequences as well as higher-order probabilistic sequences. Third, the potential role of explicit knowledge was examined using three separate tests of declarative knowledge. Results indicate that young and old adults are able to learn purely perceptual auditory sequences, but that explicit knowledge contributes to learning of repeating sequences by young adults.

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Introduction

Implicit learning refers to the acquisition of information about a complex stimulus environment in the absence of awareness of either what was learned or that learning occurred (Reber 1993). Implicit learning has been investigated using several paradigms including priming, artificial grammar learning, process control, and, most often, the serial response time (SRT) task (Nissen and Bullemer 1987). In this task, stimuli (e.g., asterisks) appear in one of four locations on a computer screen in a repeating sequence, and participants respond to each by pressing a corresponding key. Learning is demonstrated by a reduction in response time (RT) on trials when the positions follow the sequence and by an increase in RT when the repeating pattern is replaced by random trials. This difference in RT between pattern and random trials indicates the extent of learning in that it reflects the performance improvement due to the sequence. Despite the performance difference, participants are often unable to express declarative knowledge of the sequence structure, and in such cases learning is considered to be implicit.

The fact that individuals learn in the SRT task is not debatable, but the question of what they learn is. For example, in the usual task it is possible for people to learn either the perceptual or motor sequence alone or in some combination. A motor theory account of implicit sequence learning focuses on responding and asserts that individuals learn a sequence of manual response movements and this learning is tied to motor-related output areas in the brain, which regulate sequence learning (Goschke et al. 2001). Behavioral studies supporting the motor theory argue that implicit sequence learning does not develop in the absence of motor sequencing (Willingham et al. 1989; Ziessler 1994; Willingham 1999; Ziessler and Nattkemper 2001; Lungu et al. 2004). For example, Willingham et al. (1989) found that only individuals with motor practice demonstrated sequence learning. Responding to the color of stimuli appearing in four locations, one group received a sequence in which the colors were presented randomly, but locations followed a fixed pattern (resulting in a random motor sequence). A second group received a fixed sequence of colors, randomly distributed amongst the four locations (preserving a fixed motor sequence). Only participants in the latter group showed significant sequence learning.

The necessity of sequenced motor responding was further highlighted by Willingham who demonstrated that transfer of sequence knowledge occurred when motor responding was kept constant, but not when perceptual sequencing was invariable (Willingham 1999). Additionally, learning through observation was typically accompanied by explicit awareness of the sequence structure (Howard Jr et al. 1992; Willingham 1999) (but see Heyes and Foster 2002; Dennis et al. 2003b). From these results, Willingham concluded that in order to learn implicitly, people must respond to stimulus locations; and that perceptual sequencing alone could not support implicit learning. Similar conclusions were made by Ziessler and colleagues (Ziessler 1994; Ziessler and Nattkemper 2001) using a modified version of the SRT task where participants had to search a matrix of distractors in which the location of the present stimulus predicted the location of the next stimulus. Results revealed less learning when multiple stimuli mapped to a single response compared to when each stimulus required a distinct response. Ziessler concluded that learning occurred as an effect of the motor responses and that learning was not based on the stimuli sequence.

However, not all evidence supports a motor-based theory of SRT learning. A number of studies support perceptually based learning. A perceptual theory of sequence learning focuses on the stimulus sequence and asserts that learning involves the acquisition of contingencies amongst perceptual stimuli and this learning is reflected in response times (RTs) and motor performance. Evidence for perceptual-based learning in the SRT task comes mainly from observational studies (Heyes and Foster 2002; Dennis et al. 2003b) and dual/independent event sequence learning (Mayr 1996; Goschke et al. 2001; Robertson and Pascual-Leone 2001). Other evidence consistent with a perceptual account is the demonstration of transfer across motor movements (Grafton et al. 1998b) and across hands (Grafton et al. 2002; Japikse et al. 2003).

Despite the explicit awareness shown in previous observational studies (Howard Jr et al. 1992; Willingham 1999), recent studies have shown that people can acquire implicit sequence knowledge by observing either a pattern of finger movements (Heyes and Foster 2002) or a spatial pattern of stimuli (Dennis et al. 2003b). Mayr (1996) also demonstrated implicit sequence learning in the absence of sequenced motor responding. Thus, under certain conditions, sequences of perceptual stimuli can be learned in the absence of both overt motor responding and explicit awareness.

The importance of perceptual factors in sequence learning was further demonstrated by Robertson and Pascual-Leone (2001) who showed that co-varying two features (e.g., color and location), such that on each trial both predicted the next stimulus, resulted in enhanced learning compared to a condition in which only one feature predicted the sequence structure. Results suggest that increased perceptual enhancement of the sequence structure leads to increased learning (via motor performance). Further supporting the role of perceptual stimuli in sequence learning, Pascual-Leone et al. (1996) demonstrated that the application of repetitive transcranial magnetic stimulation (TMS) over the dorsolateral prefrontal cortex (DLPFC) profoundly impaired sequence learning, whereas stimulation over the supplementary motor area (SMA) did not. Results point to the DLPFC as playing a critical role in sequence learning whereas the SMA, while consistently activated in imaging studies (Grafton et al. 1995; Hazeltine et al. 1997; Grafton et al. 1998a; Seidler et al. 2005) does not appear to regulate learning.

However, despite evidence supporting sequence learning in the absence of overt motor responding, no study was able to completely eliminate sequenced motor responding. In all the observational and transfer studies, motor sequencing was the ultimate means by which individuals demonstrated their perceptually learned knowledge. Thus, motor sequencing was never entirely removed from the tasks. The inability to eliminate spatio-motor responding, combined with the mixed evidence presented provides no clear answer for understanding whether purely implicit and perceptual learning can occur in the SRT task.

Goschke et al. (2001) recently introduced a method to un-confound the stimulus and response sequences. In their task, four letters (A, B, C and D) were presented horizontally in discrete locations that mapped to one of four response keys on the keyboard. In contrast to previous SRT tasks where each stimulus would appear one at a time, all letters were presented visually on every trial. Immediately following the presentation of the visual stimuli, one of the four letters was spoken through headphones. Participants were instructed to respond by pressing the key below the letter they heard. Again, unlike previous SRT tasks, the arrangement or location of stimuli on the computer screen changed with each trial, thereby changing the associated motor response from one trial to the next. Results showed that normal, healthy participants demonstrated implicit, perceptually based sequence learning in the absence of spatio-motor sequencing.

The current study builds on this earlier research in three ways. First, we aim to extend the results to healthy young and old adults. Goschke's study, while focused on patients with Broca's aphasia, tested five healthy middle-aged adults (mean age = 53). We plan to investigate implicit sequence learning using his technique in a larger group of healthy young as well as healthy older adults. No study examining the motor basis of SRT learning has included older adults, even though research shows that older adults are able to learn implicit motor sequences under a variety of experimental conditions (Howard and Howard Jr 1989; Howard Jr and Howard 1997; Dennis et al. 2003a; Negash et al. 2003; Howard Jr et al. 2004). Inclusion of an older group also makes it more likely that it will be possible to assess sequence learning in the absence of any explicit knowledge in that older people are not as likely as younger to develop explicit awareness (Howard and Howard Jr 1989, 1992).

Second, we include sequences of different complexities. Goschke and colleagues used an eight-element deterministic sequence, containing first-order dependencies (i.e., a sequence in which each individual trial predicts the next trial). Previous SRT studies have shown that both young and older adults can implicitly learn first- (Howard and Howard Jr 1989; Salthouse et al. 1999) and second-order deterministic sequences (Howard and Howard Jr 1992; Curran 1997), as well as probabilistic sequence structures (Howard Jr and Howard 1997; Howard Jr et al. 2004). It is our goal to assess perceptually based sequence learning in each age group, with each sequence structure.

Finally, we investigate the potential role of explicit knowledge in perceptual sequence learning with the inclusion of three tests designed to assess declarative sequence knowledge. As noted, previous studies investigating perceptual-based sequence learning have reported a high degree of explicit awareness associated with learning, and additional explicit knowledge might have gone undetected because previous studies have typically conducted only limited investigations of explicit awareness. Thus, it is prudent to examine the possibility of explicit knowledge more fully.

Table 1 Participant's characteristics (means and standard deviations)

	Group	
	Young	Old
Experiment 1		
Gender		
Male	5	4
Female	7	8
Age (years)***	20.17 ± 1.64	71.75 ± 4.33
Education	13.42 ± 1.24	14.82 ± 2.75
Health (self-rated)[a]	4.42 ± 0.51	4.00 ± 1.13
WAIS-R vocabulary	34.58 ± 10.05	38.58 ± 6.08
WAIS-R digit symbol (coding)***	90.83 ± 17.36	55.42 ± 12.15
Digit span	21.17 ± 3.49	20.92 ± 3.68
Experiment 2		
Gender		
Male	2	5
Female	10	7
Age (years)***	21.04 ± 1.54	73.55 ± 7.26
Education**	14.50 ± 0.80	16.08 ± 2.84
Health (self-rated)[a],*	4.67 ± 0.65	3.92 ±1.08
WAIS-R vocabulary	35.00 ± 6.94	38.25 ± 3.93
WAIS-R digit symbol (coding)**	84.71 ± 12.69	61.58 ± 11.39
Digit span	19.67 ± 2.71	18.92 ± 3.40
Experiment 3		
Gender		
Male	4	6
Female	8	6
AGE (years)***	20.20 ± 1.52	73.45 ± 7.32
Education**	13.67 ± 2.39	17.33 ± 2.77
Health (self-rated)[a],**	4.54 ± 0.50	4.38 ± 0.77
WAIS-R vocabulary	31.71 ± 3.35	35.42 ± 5.57
WAIS-R digit symbol (coding)**	88.43 ± 16.33	58.33 ± 13.26
Digit span	16.86 ± 3.02	17.08 ± 3.50

Mean ± standard deviation

*$P < 0.05$

**$P < 0.01$

***$P < 0.001$

[a] Responses range from 1 (poor) to 5 (excellent)

Experiment 1

Methods

Participants Twelve young and 12 older adults were paid to participate (see demographics in Table 1). However, two of these young participants were later found to have full explicit knowledge and so their results are not included in the analyses reported. Young people were undergraduate volunteers who responded to flyers placed on campus and the older adults were volunteers from the community who had responded to a newspaper advertisement. Participants had no previous experience with the SRT task.

Stimuli and design Stimuli consisted of four words, romantic, chronological, popularity and operation, each spoken by a different female voice. These words were chosen from the TIMIT speech database, a corpus of high-quality digital recordings, providing speech data for acoustic-phonetic studies (Garofolo et al. 1993) and used in previous laboratory studies (Dennis et al. 2003a). They were equated on subjective speaker clarity and length of presentation. Words averaged approximately 725 ms and each began with a different phoneme. Long multi-syllable words were chosen in order to provide sufficient presentation length for responding while the stimulus was present as in the usual SRT task. The words differed in their initial syllable to allow maximum distinction between stimuli. Words were presented using the built-in 16 bit digital-to-analog converter on a Macintosh iMac computer, sampled at 44 kHz, low pass filtered by a 22 kHz anti-aliasing filter and presented over Senheizer headphones. Presentation levels were determined separately for each participant by a pre-experimental adjustment procedure in order to achieve a comfortable listening level. Participants performed the experimental task with a high level of overall accuracy (95 and 93% for the old and young, respectively), demonstrating that both groups understood the words.

The stimulus-to-response mapping was indicated by a four-letter display, one for the first letter of each word. Each letter mapped to one of four keys on the computer

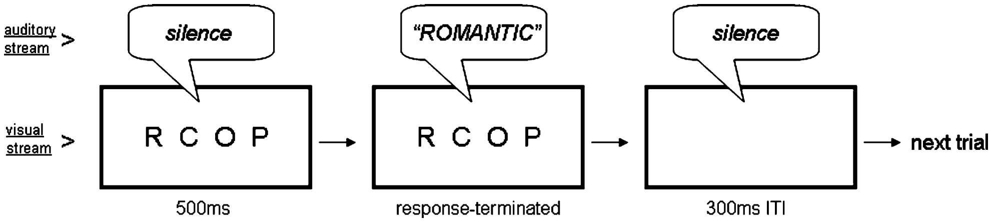

Fig. 1 Study design. Each trial began with the visual presentation of the response mapping (e.g., first letter of each word) for 500 ms. Following, the target word was presented auditorily. The letters remained on the screen until a correct key press was made. If a response was made before the end of the auditory presentation, the presentation (e.g., word) was truncated and screen cleared beginning the 300 ms inter-trial interval (*ITI*)

keyboard, ‘z’, ‘x’, ‘.’, and ‘/’ marked by green tabs. The arrangement of letters was quasi-randomly determined on each trial (the same arrangement not repeated twice in a row), thereby creating a response sequence that was spatially random (see Goschke et al. 2001).

Each participant received one of two first-order deterministic sequences: RCRPOCOP (Ss 1–6 in each group) and PRPCOROC (Ss 7–12 in each group).

Procedure Participants signed an informed consent approved by the Catholic University Institutional Review Board, and filled out biographical and health screening questionnaires before completing the 20-min computer task. People responded with the middle and index fingers of each hand. Participants were not told about underlying sequences, but rather that the purpose of the study was “to investigate how young and old people learn to respond to simple auditory stimuli.” Participants were given an 80-trial practice block to learn word-letter mapping and to become familiar with the task, as well as to verify that the words were easily recognized.

Participants then completed eight blocks where blocks 1–6 and 8 consisted of 80 trials in which the eight-element sequence repeated ten times. Block 7 also consisted of 80 trials, however, the stimuli in this block were randomly determined. On each trial the target word was presented 500 ms after the response mapping was displayed. Letters remained on the screen until a correct response was made and the trial was terminated. If a correct response was made before the completion of the auditory presentation, the presentation of the word was truncated and the trial moved immediately to the inter-trial interval (e.g., a delay of 300 ms). RT was measured from the onset of each auditory presentation until the correct key press (see Fig. 1).

At the end of each block the computer displayed the mean RT and accuracy for the previous two blocks and prompted participants to maintain an accuracy of approximately 92% in order to achieve comparable group error rates. After completing the experimental task, participants were given an end-of-experiment questionnaire consisting of five open-ended questions posed to elicit information about the participants’ strategy as well as assess declarative knowledge. People then completed two blocks of a production task in which they produced their own sequence of words (with remapping in place) by pressing the keys to produce the corresponding word. On the first block participants were told to try to “generate a series of words/trials that resemble the training sequence as much as possible.” In the second block they were told to try to “create a sequence that is different from the one you heard.” Furthermore, participants were instructed not to be ‘systematic’ in their responses for this latter exclusion block. This task was followed by a set of five questions designed to assess participants’ strategy in the production task. A difference in the production of sequence structure under the two instructional conditions has been taken as evidence of participants having control over sequence knowledge and hence as a test of declarative knowledge (Destrebecqz and Cleeremans 2001).

Finally, participants completed a 20 trial recognition task in which they listened to an eight-element sequence on each trial, and indicated whether they thought the sequence had occurred previously on a scale of 1 (certain it did) to 4 (certain it did not). Ten trials were consistent with the sequence structure and ten were foils consistent with the second sequence[1]. Thus, the sequence structure of targets and foils was comparable. Order of trials was randomly determined.

Data analysis For each age group, median RTs for correct trials were calculated for each block for each participant, and a group mean was then calculated by averaging individual means in each block. A preliminary Age Group (young vs. old) × Sequence (1 vs. 2) × Block (1–8) mixed factorial ANOVA on the RTs with Block as the within-subject variable indicated no significant main effect of Sequence, nor any interaction involving Sequence so the data were collapsed across the two sequences.

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[1] The first six participants in each group received a foil sequence that was completely random. This sequence potentially contained repetitions of a stimulus, an event which never occurred in the training sequence and may have been a salient cue to the categorization of the sequence. Participants #7–12 in each group received a foil consistent with that described in the paper. Their data alone were used in recognition analyses.

Results and discussion

Is there sequence learning within each age group? Mean RTs are plotted in Fig. 2a, b, for young and old, respectively. To examine sequence-specific learning the average RT on blocks 6 and 8 (pattern) was compared to the RT on block 7 (random) using a Block × Age Group mixed factorial ANOVA with Block as the within-Ss variable. Results revealed a significant main effect of Age Group, $F(1, 20) = 11.29$, MSE $= 2.22 \times 10^6$, $P = 0.003$, affirming that young responded faster than older adults and a significant main effect of Block, $F(1, 1) = 25.32$, MSE $= 6.03 \times 10^4$, $P < 0.001$, indicating that overall, participants learned the sequence structure. The Block × Age Group interaction did not reach significance, suggesting that sequence learning did not significantly differ between age groups. However, this test may not have sufficient power to detect a group difference (power = 0.217). Most importantly for the present study, separate ANOVAs carried out on the two groups revealed significant main effects of Block for both young, $F(1, 9) = 22.93$, MSE $= 4.34 \times 10^4$, $P = 0.001$, and old, $F(1, 11) = 6.65$, MSE $= 1.85 \times 10^4$, $P = 0.03$, indicating that each group showed sequence specific learning. Thus, although the present data cannot speak to group differences, the results show clearly that both young and old adults learn simple repeating sequences in the absence of motor sequencing.

Was there explicit sequence knowledge? Three measures of explicit knowledge were examined: the End-of-Experiment questionnaire, the Recognition Task, and the Production Task.

Questionnaire As mentioned above, two young adults were able to describe the sequence fully and their data were dropped. Another young adult accurately described one of the eight possible triplets (R–P–C), and a second four of the eight event pairs that actually occurred (e.g., R–C or O–C). In both cases, this fell below the number expected by chance. No older participant described anything that resembled the pattern sequence. Hence, the questionnaire revealed no evidence of explicit knowledge for any of the ten young participants whose learning data were included, nor for any of the 12 older participants.

Recognition task People demonstrate explicit sequence knowledge on the recognition measure if they are able to rate pattern sequences as more familiar than foil sequences. Both groups were in the direction of producing higher recognition ratings for target than foil sequences (Destrebecqz and Cleeremans 2001). This difference was marginally significant for the young, $t(4) = 2.71$, $P = 0.054$, but not older adults, $t(5) = 1.06$, $P = 0.34$. Hence, the young adults showed some evidence of declarative knowledge of the sequence structure on this measure.

Production task The Production data were analyzed by assessing the frequency with which each participant produced pattern-consistent and pattern-inconsistent pairs under inclusion and exclusion instructions. Pattern-consistent pairs were those that occurred within the sequence, whereas pattern-inconsistent pairs were those that never occurred during sequence blocks, and could only have occurred during the single random block. Pattern-inconsistent pairs were further broken down into repetitions (e.g., R–R or C–C) and other inconsistent pairs since previous work has shown that repetitions may evoke pre-existing response tendencies such as perceptual or motor priming (Remillard and Clark 2001; Howard et al. 2004). The production of more pattern-consistent pairs in the inclusion than the exclusion block reflects control over sequence knowledge and hence explicit sequence knowledge.

Figure 3 shows the mean proportion of pattern-consistent pairs for both the young and old groups. Since there were eight unique word pairs in the eight-element sequence and 16 possible pairs in all, one would expect a 0.50 proportion of consistent pairs by chance. Single-sample *t* tests carried out on the four conditions plotted in Fig. 3 revealed that only the young Inclusion condition exceeded chance, $t(9) = 3.53$, $P = 0.006$. These data were also submitted to an Age Group × Instruction mixed factorial ANOVA with Instruction as a within subject variable. The main effect of Instruction, $F(1,20) = 3.50$, MSE $= 0.007$, $P = 0.075$, and the Instruction by Age Group interaction, $F(1,20) = 3.35$, MSE $= 0.007$, $P = 0.082$ reached marginal significance. To investigate the possibility of explicit knowledge further, separate one-way repeated measure ANOVAs were carried out on each group. This revealed a significant

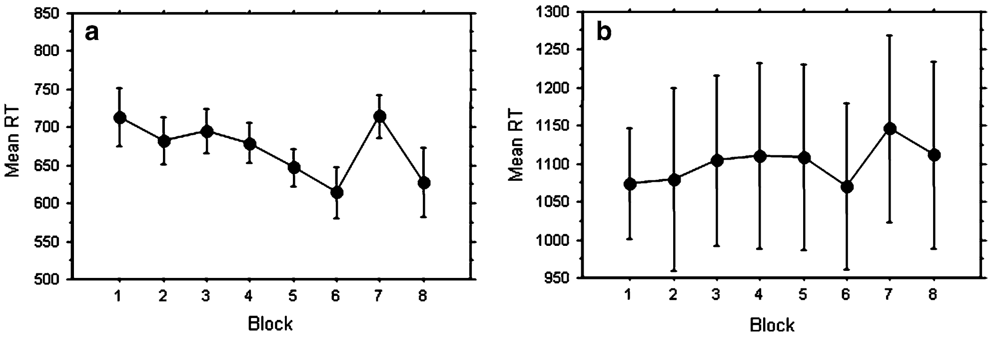


Fig. 2 Overall performance across blocks on response time (*RT*) from the young group (**a**) and old group (**b**). *Error bars* represent one standard error

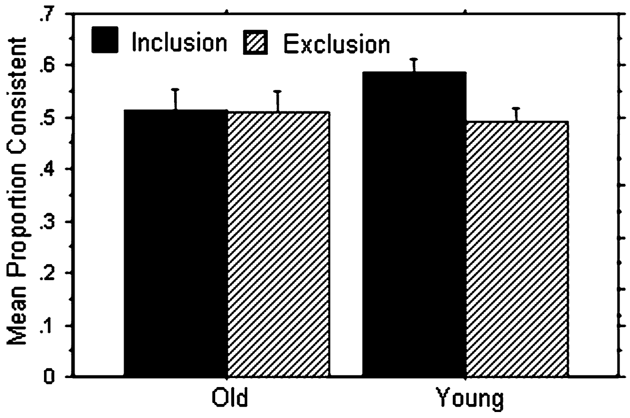


Fig. 3 Mean production rate of pattern-consistent pairs under inclusion and exclusion instructions for the young and old groups. *Error bars* represent one standard error

Instruction effect for the young group, $F(1,9) = 13.60$, MSE $= 0.003$, $P = 0.005$, but not for the old group. This supports the conclusion that young people had explicit knowledge of the sequence structure and that this enabled them to control the production of consistent pairs in the production task (Destrebecqz and Cleeremans 2001). Furthermore, it is not likely that this pattern reflects the use of some “degenerate” response strategy on the exclusion block by young people (such as repeating the same key press). Such a strategy would lead to a substantial increase in the proportion of repetitions produced and/or a decrease in the proportion of consistent pairs produced compared to the inclusion block. In neither case, did these proportions differ from the levels expected by chance.

Experiment 2

Experiment 1 replicates and extends Goschke’s findings by demonstrating that both younger and older adults are able to learn a first-order auditory sequence in the absence of a spatio-motor response sequence. However, while the older adults appeared to learn implicitly, young adults displayed some explicit knowledge. Experiment 2 aims to extend the range of structure under which perceptually based learning occurs by examining perceptual sequence learning of a more complex, second-order deterministic sequence in young and old adults. By doing so, we also aim to prevent explicit learning in the younger group.

Method

Participants Twelve young and 12 older experimentally naïve adults were paid to participate. See Table 1 for participant demographics.

Stimuli and design All materials and stimuli were identical to those used in Experiment 1 except that second-order deterministic sequence structures were used: RCROCPORPCOP and CPCRPORCOPRO. These differ from the first-order sequences in that all pair-wise transitions except repetitions occur equally often. Therefore, learning must be based upon relationships amongst the previous two events and the current event.

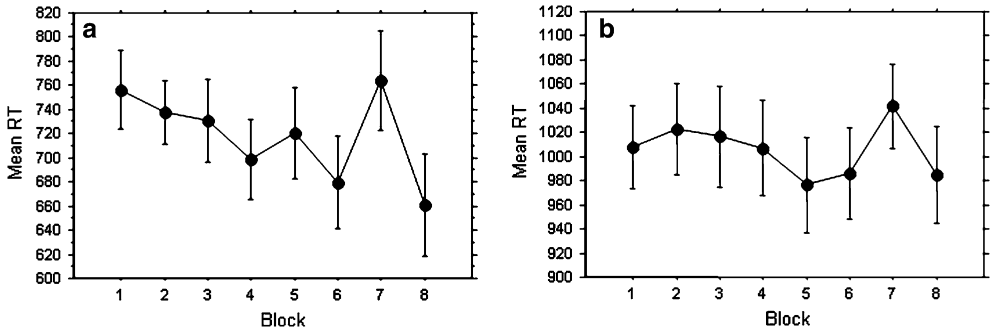
Procedure The procedure was identical to Experiment 1 except that the computer task took 35 min. This portion of the Experiment lasted approximately 1 h and 15 min. It was followed by a second experimental task unrelated to this study.

Data analysis As in Experiment 1, both groups demonstrated high accuracy, 95% for the young and 97% for the old, and since preliminary analyses revealed no differences between the two sequences, data were combined for analysis.

Results and discussion

Is there sequence learning in each age group? Mean RTs for each block, for both the young and old groups are plotted in Fig. 4a, b, respectively. As in Experiment 1, an ANOVA indicated significant main effects of Age Group, $F(1,\ 22) = 30.68$, MSE $= 1.05 \times 10^6$, $P < .001$, and Block, $F(1,\ 1) = 53.16$, MSE $= 6.80 \times 10^4$, $P < 0.001$, and the Block × Age Group interaction did not reach significance. Importantly, independent analyses again revealed a significant main effect for Block for the young, $F(1,\ 11) = 26.89$, MSE $= 5.29 \times 10^4$, $P < 0.001$, and old, $F(1,\ 11) = 32.56$, MSE $= 1.93 \times 10^4$, $P < 0.001$, groups indicating that each group learned the second-order sequence structure.

Fig. 4 Overall performance across blocks on *RT* from the young group (**a**) and old group (**b**). *Error bars* represent one standard error



Was there explicit sequence knowledge?

Questionnaire No individual guessed the correct length or composition of the sequence. Only 3 young adults (and no older adults) revealed partial declarative knowledge of the sequence structure. A review of the preceding RT analysis excluding (both individually and as a group), these participants' data did not change the trend or significance of the results. Therefore, no individual was removed in the analysis and no one was regarded as expressing full declarative knowledge.

Recognition task The mean recognition ratings (with standard deviations) for target than foil sequences were 2.79 (0.40) vs. 2.44 (0.51) for the young group and 2.38 (0.27) vs. 2.48 (0.47) for the old group. This target vs. foil difference was not significant for the either the young, $t(11) = 2.71$, $P = 0.054$, or the older adults, $t(11) = 0.779$, $P = 0.45$. Thus, learning was considered implicit on the recognition measure.

Production task As in Experiment 1, the Production data were analyzed by assessing the differences in pattern-consistent and pattern-inconsistent runs produced by each participant under inclusion and exclusion instructions. Because all pairs occurred with equal probability in the current sequence structure, the lowest level of information distinguishing between pattern-consistent and inconsistent structure would be a triplet, or three consecutive events.

Figure 5 shows the mean proportion of pattern-consistent triplets for both the young and old groups[2]. Since there were 12 unique triplets in the 12-element repeating sequence and 64 possible triplets overall, one would expect a 0.188 proportion of consistent triplets by chance. Single-sample *t* tests carried out on the four conditions plotted in Fig. 5 revealed that only the young Inclusion condition exceeded chance, $t(10) = 4.04$, $P = 0.002$. These data were also submitted to an Age Group × Instruction mixed factorial ANOVA with Instruction as a within subject variable. The main effect of Instruction, $F(1,20) = 17.28$, MSE $= 0.128$, $P < 0.001$, and the Instruction by Age Group interaction, $F(1,20) = 9.62$, MSE $= 0.071$, $P = 0.006$ reached significance. To investigate the possibility of explicit knowledge further, separate one-way repeated measure ANOVAs were carried out on the two groups. These revealed a significant Instruction effect for the young group, $F(1,10) = 48.31$, MSE $= 0.194$, $P < 0.001$, and no effect for the old group. Similar to Experiment 1, this supports the conclusion that young people had explicit knowledge of the sequence structure and that this enabled them to control the production of consistent pairs in the production task.

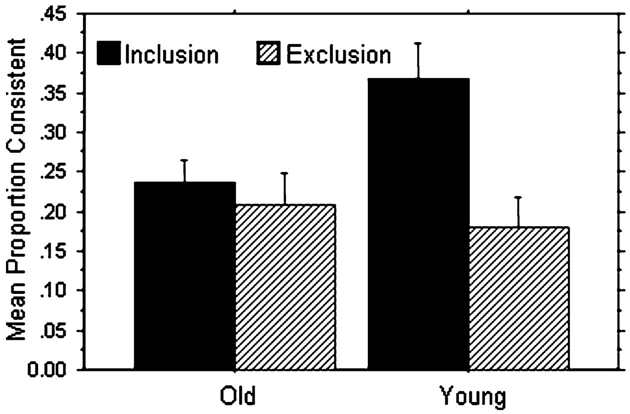


Fig. 5 Mean production rate of pattern-consistent triplets under inclusion and exclusion instructions for the young and old groups. *Error bars* represent one standard error

To investigate the possible use of "degenerate" response strategies, pattern-inconsistent triplets were further broken down into two categories: repetitions, those triplets with two or more events occurring in a row, (e.g., R–R–C or R–R–R) and other inconsistent triplets. Analyses of these data found that while young adults produced significantly less repetition than would be expected by chance on the inclusion block, $t(10) = 10.82$, $P < 0.001$, they did not differ from chance in repetition production during the exclusion block. Additionally, the proportion of consistent triplets did not drop below chance for the exclusion block. These results suggest that young adults learned that repetitions did not occur during training and used this knowledge to aid performance on the production task. Older adults did not differ from chance on any production measure.

As in Experiment 1, the explicit measures reveal that young people most likely gained some explicit knowledge of the second-order sequence structure—again primarily that repetitions do not occur in the sequence structure. In contrast, older adults showed no evidence of explicit knowledge.

Experiment 3

Experiment 2 demonstrated that both age groups can learn a second-order auditory sequence in the absence of motor sequencing. However, as in Experiment 1, young adults demonstrated some evidence of declarative knowledge, limiting any claims of purely implicit learning in this group. In Experiment 3 we promote purely implicit sequence learning by using a higher-order probabilistic sequence structure (Howard Jr and Howard 1997; Remillard and Clark 2001). Previous research has demonstrated little or no declarative learning for second-order sequences using the alternating

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[2] One older and one younger participant were excluded from the Production analysis for failure to follow task instructions. During the exclusion block the older adult repeatedly hit the same key, where the younger adult reported that she continued to respond as they were during the inclusion block.

serial response time (ASRT) task, in which random trials alternate with pattern trials (Howard Jr and Howard 1997; Howard Jr et al. 2004). For example, the sequence 1234 is represented as 1r2r3r4r where the numbers denote a position in the sequence (pattern trial) and the 'r's denote any of those four positions selected at random (random trial). This sequence structure has been called a 'lag-2' sequence (Remillard and Clark 2001) because, unlike the second-order deterministic sequences that employ learning of the previous two sequence events, the random events hold no predictive value. As in a second-order deterministic sequence, there are no pair-wise associations to be learned; to predict the event on any pattern trial, one must have knowledge of what occurred two trials before. Furthermore, in previous research the ASRT task has resulted in no explicit awareness in either young or older adults (e.g., Howard Jr et al. 2004).

Methods

Participants Twelve experimentally naïve young and 12 older adults participated in the study. See Table 1 for participant demographics.

Stimuli and design All materials, stimulus presentation, and timing were identical to those used in Experiment 1 except that only three of the four words were used, *romantic*, *chronological*, and *popularity* and responses were made using three keys, "j", "k", and "l" using the first three fingers of the right hand. Thus, unlike the previous two experiments which were bimanual, the current experiment is unimanual. Each participant received one of two possible lag-2 sequence structures: RrCrPr and RrPrCr, where the letters R, C, and P correspond to each of the three words and the 'r's correspond to one of the three words chosen at random.

Procedure Participants completed two 1-h testing sessions on 2 days separated by no more than one day. Session 1 consisted of a 30-trial practice block followed by 20 blocks in each of which the six-element sequence repeated ten times. Session 2 included 20 blocks of the experimental task followed by the questionnaire, a 60-trial production task, and a recognition task.

Results and discussion

Because of the alternating sequence structure, the most basic information one can learn is the relative frequency of three consecutive events or triplets. The three-element alternating sequence used here results in nine frequently occurring, high-frequency triplets and 18 less frequent, low-frequency triplets. Like previous studies using the alternating sequence (e.g., Howard Jr et al. 2004), we investigated sequence learning by comparing reaction time and accuracy for the two triplet types. High frequency triplets consisted of triplets that end on a pattern trial, as well as those that end on a random trial, but are consistent with the pattern sequence by chance. Low frequency triplets consisted of the remaining triplets, but with repetitions and trills (e.g., R–C–R) excluded as they demonstrate preexisting response tendencies (Remillard and Clark 2001) and they are not counter-balanced across individuals. The data for each triplet type were further broken down into eight, five-block Epochs in order to examine how learning develops with practice.

Do people learn the alternating sequence? This question was examined by two Epoch × Triplet × Age Group mixed factorial ANOVAs.

Accuracy Figures 6a and 7a show the mean accuracy for the young and old groups, respectively. The accuracy analysis revealed significant main effects of Age Group, $F(1,22) = 18.07$, $\mathrm{MSE} = 0.24$, $P < 0.001$, Epoch, $F(7, 154) = 2.34$, $\mathrm{MSE} = 0.003$, $P < 0.05$, and Triplet, $F(1, 1) = 4.80$, $\mathrm{MSE} = 0.003$, $P < 0.05$. Only the interaction of Epoch × Group, $F(7, 154) = 2.34$, $\mathrm{MSE} = 0.003$, $P < 0.05$, reached significance. When examined separately, younger adults show a significant main effect of both Triplet, $F(1, 11) = 5.64$, $\mathrm{MSE} = 0.004$, $P < 0.05$, and Epoch, $F(7, 77) = 2.65$, $\mathrm{MSE} = 0.004$, $P < 0.05$, but no significant interaction. Thus, although young peoples' accuracy was significantly greater for high than low frequency triplets, this triplet-type effect did not increase significantly across sessions, suggesting that sequence learning occurred very early for the young group. In fact, the learning effect appears to decline over time. Older adults, on the other hand, exhibited no significant main effects or interaction, indicating that they did not learn the sequence in the absence of motor sequencing.

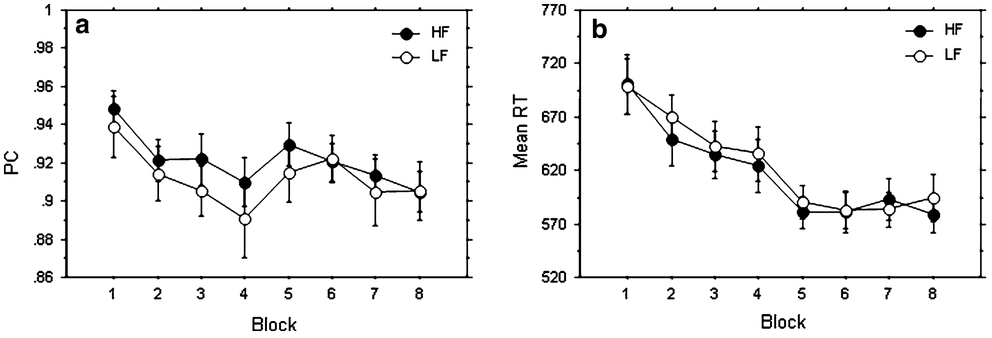

Fig. 6 Performance on accuracy (**a**) and *RT* (**b**) measures across epochs for high frequency (*closed symbols*) and low frequency (*open symbols*) triplets for the young. *Error bars* represent one standard error

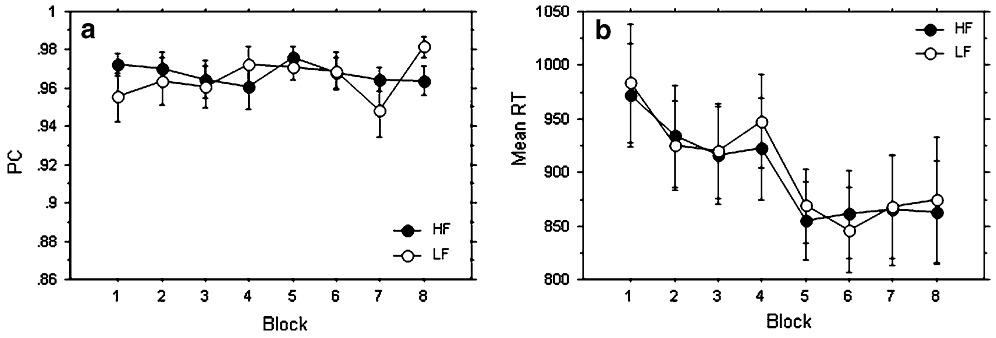

Fig. 7 Performance on accuracy (**a**) and *RT* (**b**) measures across epochs for high frequency (*closed symbols*) and low frequency (*open symbols*) triplets for the old. *Error bars* represent one standard error

Response time Figures 6b and 7b show the mean RT data for the young and old groups, respectively. The RT analysis revealed only significant main effects of Age Group, $F(1, 22) = 35.90$, $\mathrm{MSE} = 7.52 \times 10^6$ and Epoch, $F(7, 154) = 20.58$, $\mathrm{MSE} = 9.20 \times 10^4$, indicating that younger adults do respond faster than old adults, and that RTs for both groups decline across epochs. Again, separate Triplet type × Epoch ANOVAs were performed on each age group.

As with the accuracy data, young people demonstrated a significant main effect of both Triplet type, $F(1, 11) = 5.10$, $\mathrm{MSE} = 2.11 \times 10^3$, $P < 0.05$, and Epoch, $F(7, 77) = 12.78$, $\mathrm{MSE} = 4.48 \times 10^4$, $P < 0.001$. Older adults only demonstrated a significant main effect of Epoch, $F(7, 77) = 8.94$, $\mathrm{MSE} = 4.85 \times 10^4$, $P < 0.001$, indicating merely that their overall RT decreased with practice. Hence, on this RT measure, as with the accuracy measure, only the young group showed evidence of sequence learning. These findings indicate that young adults are sensitive to the lag-2 auditory sequence with random response mapping but that older adults are unable to learn under these conditions.

Was there explicit sequence knowledge?

Questionnaires Some individuals expressed feelings that regularities occurred without being able to verbalize them and no one was able to articulate the alternating structure or identify the correct length of the sequence. Six younger and four older adults speculated on the sequence structure. However, as in previous work with this paradigm, guesses were unrelated to the sequence structure. Hence, learning was implicit as assessed by verbal report.

Recognition task A Sequence Type × Age Group mixed factorial ANOVA (with Sequence Type varying within Ss) revealed no main effects or interaction. Hence, the random sequences were rated as familiar as the target sequences by both young [target = 2.50 (0.43) vs. random = 2.52 (0.45)] and old participants [2.37 (0.59) vs. 2.38 (0.65)]. Therefore, the recognition task revealed no evidence of explicit knowledge.

Production task Figure 8 shows the mean proportion of pattern-consistent triplets for both the young and old groups. As repetitions and trills were excluded from the learning analysis, they were also excluded from the current analysis. When this is done chance for high frequency, consistent triplets is 0.50 since there are nine consistent triplets and 18 possible triplets overall (27 less the 9 repetitions and trills). Single-sample t tests carried out on the four conditions plotted in Fig. 8 revealed that both the young and old Inclusion condition fell significantly below chance, $t(11) = 6.80$, $P < 0.001$ and $t(11) = 2.91$, $P = 0.01$, for young and old, respectively. Results suggest that neither group had conscious knowledge over the sequence structure, as neither was able to produce the sequence at or above chance during the Inclusion block. These data were also submitted to an Age Group × Instruction mixed factorial ANOVA with Instruction as a within subject variable. Only the main effect of Instruction, $F(1,22) = 8.09$, $\mathrm{MSE} = 0.026$, $P = 0.009$ reached significance. Separate one-way repeated measure ANOVAs carried out on the two groups revealed a significant Instruction effect for the old group, $F(1,11) = 9.56$, $\mathrm{MSE} = 0.025$, $P = 0.01$, and no effect for the young group. Oddly, these data suggest that the older group, while unable to express sequence knowledge during learning, had some explicit knowledge that aided their performance during the production task. However, as both inclusion and exclusion production rates of consistent triplets fell below chance, this explanation seems improbable. Follow-up analyses examining the use of "degenerate" response strategies found that neither age group exceeded chance in their production of

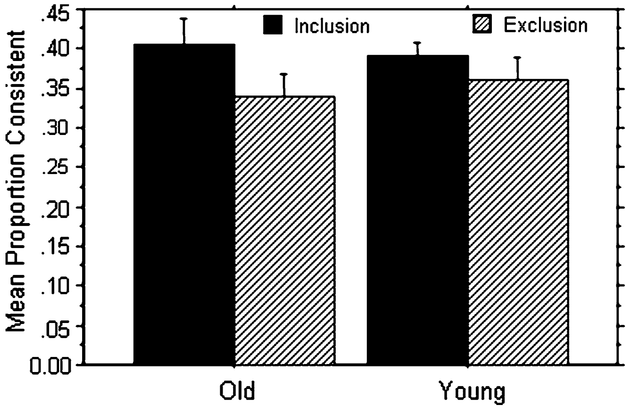

Fig. 8 Mean production rate of pattern-consistent triplets under inclusion and exclusion instructions for the young and old groups. *Error bars* represent one standard error

repetitions during either the Inclusion or Exclusion blocks.

Data from all three explicit learning measures suggest the same conclusion - neither group gained explicit knowledge. Thus, unlike the previous two experiments where young adults demonstrated some level of explicit awareness, all results based upon indirect measures on sequence learning in the present experiment can be regarded as purely implicit for both young and older adults.

General discussion

The experiments presented here investigated people's ability to learn perceptual sequences in the absence of motor sequencing. Taken together, the results indicate that implicit learning can occur in the absence of spatio-motor learning.

Young adults demonstrated sequence knowledge in the absence of spatio-motor sequencing in all three experiments. However, in Experiments 1 and 2, they also exhibited explicit awareness for both first- and second-order deterministic sequences, limiting claims to pure implicit perceptual learning with these relatively simple sequence structures. In Experiment 3, however, the young adults did learn a probabilistic sequence without explicit awareness. Older adults did not gain explicit knowledge in any of the three experiments on any of the explicit measures, giving an opportunity to examine learning of lower level structure in the absence of awareness. The fact that older adults showed significant learning in Experiments 1 and 2 indicates that first- and second-order deterministic sequences can be learned implicitly, even when learning depends only upon relationships amongst perceptual stimuli. However, older adults showed no learning at all for the second-order probabilistic sequences in Experiment 3. Thus, when the findings from both age groups are considered they support the conclusion that people are able to implicitly learn relationships among perceptual stimuli in the absence of response learning for both relatively simple repeating sequences and higher-order probabilistic sequences.

The fact that young adults showed signs of declarative knowledge when learning deterministic sequences (Experiments 1 and 2) should not be taken as an indication that explicit knowledge is necessary for perceptual sequence learning. Rather, it is most likely that this reflects explicit knowledge typically acquired for simple deterministic sequences even when sequential motor responses are involved. Additionally, sequence specific learning cannot be assessed in the standard SRT tasks until the introduction of a random block, in the present Experiments 1 and 2 this occurs in block 7. Young adults may develop sequence learning early under purely implicit conditions, and explicit learning may develop only with extended practice. Thus, it is possible that had we measured sequence learning after less practice, young adults would have learned lower-level structure in the absence of explicit awareness.

The current set of results parallels that which is seen in the traditional SRT task—with both young and older adults showing significant learning of deterministic sequence structures (Howard and Howard Jr 1989, 1992; Salthouse et al. 1999). However, unlike previous studies where older adults show significant learning of higher-order sequences (Curran 1997; Howard Jr and Howard 1997; Howard Jr et al. 2004), they showed no higher-order learning in Experiment 3 of the current study. Furthermore, the younger adults are showing less learning than has been typical with this alternating regularity (e.g., Howard Jr et al. 2004). There are at least two possible explanations for this departure from earlier findings, and they are not mutually exclusive.

One possible explanation for the complete absence of learning in the old, and the somewhat weak learning in young in Experiment 3 is that motor sequencing does provide some support for sequence learning. That is, although motor learning is not necessary for sequence learning it may augment perceptual learning (and vice versa). Furthermore, this additional motor support may actually be necessary for older adults to learn subtle sequences of the sort used in Experiment 3. Simultaneous activation of elements appears to be necessary for associations to be learned among them (Braver et al. 2001) and so learning higher order structure such as that in Experiment 3 requires activation of at least three elements simultaneously. Older adults' lower processing capacity would make activating all of these items simultaneously more difficult (Salthouse 1996).

A second possible explanation for the reduced learning by young people and the lack of learning by old in Experiment 3 draws on the fact that the remapping used in all three of the present experiments slows responding compared to that in conditions without remapping [e.g., mean RT for older adults of 901 ms in Experiment 3 compared to 806 ms in a comparable task without remapping (Dennis et al. 2003a)]. Because the inter-stimulus interval (ISI) depends on the subject's RT, an increase in RT results in an increase in the inter-event interval (IEI). There is evidence that increasing the IEI decreases learning, or at least the expression of learning (Frensch and Miner 1994; Willingham et al. 1997; Frensch et al. 1998). Thus, according to this explanation, the absence of a predictable motor sequence is not central to the lack of learning; rather it is the slowed stimulus sequence that the remapping procedure produces.

Discrepancies between the current findings and those previous studies that failed to show purely implicit perceptual sequence learning may be due to differences in attentional demands between studies. Unlike studies that did not require responding to sequence-specific trials during training (Willingham et al. 1989; Russeler and Rosler 2000), each stimulus in the current study required a response. Therefore individuals needed to attend to each stimulus, process its meaning, and translate that knowledge into a correct response. Without individual responses in previous studies, it cannot be assumed that individuals were attending to each and every stimulus. In addition, in the current study attention was not divided by instructions to focus on other task components. Thus, participants were able to process the essential sequential information in the to-be-learned context. Therefore, the failure to find learning in previous studies may be due to a lack of stimulus encoding, resulting from attentional deficits.

The current study did not seek to investigate the separate contributions of motor and perceptual learning to overall sequence learning. Nor are the authors claiming that perceptual or motor sequencing alone accounts for learning in the typical SRT task. As noted, the previous work by Willingham and colleagues (Willingham et al. 1989; Willingham 1999) has demonstrated that implicit sequence learning can occur based solely on motor sequencing. In the current study, learning was purely perceptually based. Taken together results indicate that learning can be based on either task component.

When both perceptual and motor sequences co-vary, as is the case in the typical SRT task, implicit learning occurs in both young and older adults for sequences of varying complexities (Howard and Howard Jr 1989; Howard Jr and Howard 1997; Dennis et al. 2003a; Negash et al. 2003; Howard Jr et al. 2004). Furthermore, as previously mentioned, increased contextual support (i.e., co-varying stimuli cues) increases learning in younger adults (Robertson and Pascual-Leone 2001; Shin and Ivry 2002). These researchers suggest that the correlation between the two repeating sequences serves to increase the contextual content. This in turn leads to a greater knowledge base from which individuals can draw during training. Hence, as the current study suggests, while motor cues may be unnecessary for learning simple sequences, learning more complex sequences may require added contextual support. This may be especially relevant in older adults who already experience age-related deficits in contextual processing (e.g., Braver et al. 2001). Adding a motor sequence to the current design may increase learning in both age groups—perhaps leading to significant learning in older adults for complex sequence structures (e.g., Experiment 3).

In summary, the current study supports the argument that implicit sequence learning can be based solely upon learning contingencies amongst perceptual stimuli. The current study also extended the work of Goschke by demonstrating that both young and older adults can learn simple, first- and second-order sequences in the absence of a spatio-motor sequence. Furthermore, older adults learn under completely implicit learning conditions. Lastly, young adults are able to implicitly learn and express sensitivity to higher-order sequence structures in the absence of motor learning. While motor responding, analogous to that seen in previous SRT tasks, was used in the current study, remapping of the stimulus-to-response relationship on every trial eliminated the possibility of motor sequence learning. Thus, learning under response remapping reflects perceptual sequence learning.

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