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RESEARCH ARTICLE

Perceptual sequence learning in a serial reaction time task

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Abstract In the serial reaction time task (SRTT), a sequence of visuo-spatial cues instructs subjects to perform a sequence of movements which follow a repeating pattern. Though motor responses are known to support implicit sequence learning in this task, the goal of the present experiments is to determine whether observation of the sequence of cues alone can also yield evidence of implicit sequence learning. This question has been difficult to answer because in previous research, performance improvements which appeared to be due to implicit perceptual sequence learning could also be due to spontaneous increases in explicit knowledge of the sequence. The present experiments use probabilistic sequences to prevent the spontaneous development of explicit awareness. They include a training phase, during which half of the subjects observe and the other half respond, followed by a transfer phase in which everyone responds. Results show that observation alone can support sequence learning, which translates at transfer into equivalent performance as that of a group who made motor responses during training. However, perceptual learning or its expression is sensitive to changes in target colors, and its expression is impaired by concurrent explicit search. Motor-response based learning is not affected by these manipulations. Thus, observation alone can support implicit sequence learning, even of higher order probabilistic sequences. However, perceptual learning can be prevented or concealed by variations of stimuli or task demands.

Keywords Implicit · Explicit · Perceptual learning · Sequence learning · Motor learning

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Introduction

Motor sequence learning is often studied with the serial response time task (SRTT) which was first introduced by Nissen and Bullemer (1987). In it, participants make a motor response by pressing a button which corresponds to a target appearing in one of four locations on a screen. Unbeknownst to the subject, the sequence of targets follows a fixed order which repeats many times. Subjects exhibit sequence learning by being faster and more accurate on blocks of patterned trials as opposed to a block of randomly ordered stimuli. Learning in this task is often considered implicit when it is unaccompanied by conscious awareness of the pattern. Since its inception, the SRTT has become increasingly influential for psychological, cognitive, and clinical studies of motor sequence learning. Despite this widespread use, controversy still surrounds this task, because performance measures may reflect explicit (declarative) knowledge of the sequence which can arise spontaneously, and also because there is disagreement regarding whether performance on this tasks reflects perceptual, in addition to motor, learning (Robertson 2007).

Even though spontaneous explicit awareness of the pattern often develops with training, multiple studies have established that sequence learning on the SRTT task can be implicit (Willingham et al. 1989, 2002; Robertson 2007). It has also become generally accepted that implicit sequence learning on the SRTT can be supported by motor responses and/or motor response locations (Willingham et al. 1989, 1999; Rüsseler and Rösler 2000; Willingham et al. 2000; Deroost and Soetens 2006a). It has proven much more difficult, however, to determine the extent to which perceptual learning contributes to performance on the SRTT task, because observation without motor responding results in increased spontaneous explicit awareness of the pattern (Willingham et al. 1989; Howard et al. 1992).

Many different types of stimuli have been used to direct motor responses in the SRTT including auditory cues (Dennis et al. 2006), color cues (Willingham 1999), letter cues (Rüsseler and Rösler 2000), spatial cues (Nissen and Bullemer 1987), or combinations of these various choices (Robertson and Pascual-Leone 2001). The classic and most often employed version, however, uses spatially oriented targets. For spatial targets, some studies have shown that purely perceptual sequence learning does occur (Howard et al. 1992; Mayr 1996; Remillard 2003) while some studies have shown that it does not (Willingham et al. 1989, 1999; Kelly and Burton 2001). In instances where perceptual learning has been found to occur, it has been unclear whether increases in performance were in fact attributable to perceptual learning, or were reflections of spontaneous increases in explicit awareness or oculomotor sequence learning.

For example, Howard et al. (1992) found that subjects who had simply observed a fixed sequence during a training phase showed as much reaction time difference between patterned and random trials upon responding as those who had made motor responses the entire time. This seemed to suggest that learning on the SRTT could be purely perceptual. However, subjects who only observed the sequence also had more explicit awareness of the pattern, making it unclear whether performance improvements were due to implicit perceptual learning or to increased explicit awareness of the sequence. Evidence in favor of the latter interpretation was reported by Willingham (1999), who first replicated Howard et al. but then removed subjects with greater explicit awareness. No perceptual sequence learning was revealed by the remaining subjects.

For studies in which spontaneous explicit awareness had not developed, oculomotor sequence learning, rather than visuo-spatial sequence learning, appeared to be a likely explanation for performance improvements. For example, in Mayr (1996), two independent sequences were determined by a succession of locations and objects. Subjects made motor responses only to object sequences but they displayed learning for both the location-based and the motor-based object sequences, which seemed to suggest visuo-spatial sequence learning had occurred. However, stimuli were placed far apart along four corners of an imaginary square with a side length of 22 cm, and so eye movements could have led to sequence learning. In Willingham et al. (1989), targets were horizontally separated by no more than 4.7° of the visual field to minimize ocular movements, and subjects responded to the color of a target which appeared in one of the four locations. Subjects displayed sequence learning when the color-based motor responses followed a sequence and the targets had appeared in random locations. In contrast, they failed to reveal sequence learning when the targets followed a spatial sequence but color-based motor responses were randomly determined. This study suggested that without large eye movements, perceptual sequence learning did not occur.

The present experiments were conducted to see if observation alone could support sequence learning even when eye movements were minimized and when spontaneous increases in explicit awareness did not affect performance measures. Therefore, in both experiments, participants completed a training phase and a transfer phase of an SRTT paradigm in which the same stimulus sequence occurred throughout both phases. Half of the participants responded during both phases, while the other half just observed during the training phase and then responded during transfer.

To minimize oculomotor learning, adjacent locations were horizontally separated by 3.8°, which is comparable to the horizontally separated (4.7°) targets used in the study by Willingham et al. (1989), and corresponds to foveal or near parafoveal space. Second, to prevent the development of spontaneous explicit awareness, probabilistic sequences were used instead of fixed ones. Unlike fixed sequences which rely on repetitions of 6- to 12-unit regularities, probabilistic sequences depend on differing relative frequencies, and learning is shown via faster and more accurate performance on high-versus low frequency sequences. Probabilistic sequences have advantages over fixed sequences in that spontaneous explicit awareness does not readily occur (Howard and Howard 1997; Schvaneveldt and Gomez 1998). Here we used the alternating serial response time (ASRT) task in which predictable Pattern trials alternate with unpredictable Random ones which causes certain "triplets" (a sequence of three trials) to occur at a higher frequency than others. Previous research has shown that participants do not gain explicit knowledge spontaneously in this task, and performance is sensitive to the relative frequencies of triplets, not to the alternating regularity (Howard et al. 2004).

The present experiments also addressed one further concern in observation based studies—the problem of attention to stimuli. For example, Kelly and Burton (2001) found no perceptual learning in an SRTT task, but this negative result was obtained from subjects who had no task to perform during the observation session. Thus, it was unclear whether these subjects were paying attention to the stimuli.

For this reason, in both of the current experiments, all subjects were given tasks which would assure attention to the stimuli during the training phase.

We addressed an additional question relevant to the SRTT literature, namely whether or not perceptual learning is influenced by an explicit mode of learning. Some evidence suggests that explicit knowledge of the sequence can in fact increase perceptual sequence learning. Using stationary letter cues, Rüsseler and Rösler (2000) found that implicit learners showed ERP components in response to motor sequence deviants only, whereas explicit learners showed ERP components when confronted with either motor or perceptual sequence deviants. This additional ERP effect for perceptual deviants occurred only when subjects had successfully acquired explicit sequence knowledge, and not when they were only searching for the pattern (Rüsseler et al. 2003). It was unclear from these experiments, however, whether explicit knowledge improved implicit perceptual learning, or if ERP effects simply reflected the effects of explicit knowledge without having altered implicit perceptual learning. In the first experiment reported here, we explored these questions using a variant of the ASRT in which implicit memory could be measured in both explicit and implicit learners. From these implicit memory measures, implicit learning could be inferred even in subjects who had learned in an explicit mode.

Experiment 1

In Experiment 1, we asked whether perceptual sequence learning could occur by observation alone during a training phase and be reflected in performance measures in a transfer phase. Additionally, we asked whether perceptual learning was influenced by the absence or presence of explicit knowledge during the training phase. For the training phase, subjects were assigned to one of two response groups: either they made motor responses during the training phase (the Respond group) or they did not (the Observe group). In the transfer session, all subjects made motor responses. We assumed that by comparing these two groups during transfer, we could determine the extent to which perceptual processing in the absence of motor responding could support implicit sequence learning.

Within these two response groups, subjects were assigned to one of two Instruction groups: Intentional or Incidental. In an earlier study, it was found that cues could facilitate explicit awareness of the sequence in Intentional learners who would have otherwise had much difficulty in gaining explicit knowledge of the pattern (Song et al. 2007). When these color cues were removed, Intentional subjects displayed no explicit knowledge of the pattern in Uncued blocks, even though it was a pattern identical to that of the Cued blocks. Incidental learners showed no explicit awareness in either Cued or Uncued blocks. Since the removal of cues presumably removed explicit awareness, these Uncued blocks assessed implicit memory which was assumed to reflect implicit learning. By placing Uncued blocks at the start of the transfer session, we attempted to assess both whether or not observation alone led to implicit perceptual learning, and also, if an explicit mode of learning influenced perceptual learning.

Materials and methods

Participants

Fifty-six right-handed volunteers (aged 18–22 years) were recruited from Georgetown University to participate in the study for credit or payment. All subjects were naïve to SRTT based tasks and all signed informed consent approved by the Georgetown University IRB. Subjects were randomly assigned to one of four groups representing the combination of two response conditions (Observe or Respond) by two instruction conditions (Intentional and Incidental). A schematic of the study design is presented in Fig. 1. The entire test visit for each subject took approximately 1 h.

Design and procedure

All subjects completed a training and transfer session of the alternating serial response time task (ASRT). Those in the Observe condition watched the display during the training session and responded via button press only during the transfer session. Those in the Respond condition responded via button press during both sessions. For all blocks and all conditions, participants saw a filled in circle (target) that appeared in one of four open circles arranged horizontally (3 cm from center to center, 1 cm diameter, the four cues together occupied approximately 3.8° of the visual angle) on a computer screen. Each block began with 5 random trials (for warm-up), followed by 80 experimental trials. These 80 trials consisted of 10 repetitions of an 8-item sequence, in which 4 Pattern trials alternated with four Random trials (e.g. 1r3r4r2r for an imbedded pattern of 1,342 where 1 refers to the left-most position and 4 to the right-most). Each subject received one of the six possible patterns (1r2r3r4r, 1r2r4r3r, 1r3r4r2r, 1r3r2r4r, 1r4r2r3r, 1r4r3r2r) and for a given subject, this same pattern occurred throughout all blocks. There were 15 blocks in the training session, and 20 blocks in the transfer session. These blocks were grouped for purposes of analysis into seven epochs containing five blocks each.

In sessions requiring a motor response, subjects responded by pressing one of four corresponding keys on

	Training Session			Transfer Session			
	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6	Epoch 7
Experiment 1	**Cued**			**Uncued**		**Cued**	
1. Observe-Incidental	Observe & Count Targets			Respond		Respond	
2. Respond-Incidental	Respond			Respond		Respond	
3. Observe-Intentional	Observe & Report Sequence			Respond		Respond	
4. Respond-Intentional	Respond & Report Sequence			Respond		Respond	

Fig. 1 Schematic for Experiment 1. For all subjects, there were two types of epochs: Cued (1, 2, 3, and 6) and Uncued (4 and 5). For all four groups, all three epochs in the training session were Cued epochs in which Pattern trials were marked by grey targets while Random trials were marked by black targets. In the transfer sessionm, however, the first two epochs were Uncued epochs. For Uncued epochs, color cues were removed such that all targets were black. Half of the subjects in each response condition were given Incidental Instructions, and half were given Intentional Instructions. Uncued epochs measure implicit learning for all groups regardless of instruction, whereas Cued epochs measured implicit and/or explicit sequence learning, depending on instruction (Song et al. 2007. Subjects in the Observe–Intentional condition reported the 4-unit pattern after each block in the 1st session. Subjects in the Observe–Incidental condition were given a comparable simple task in which they counted 0–7 red targets which appeared in each block instead of black targets. Subjects in the Respond groups made button press responses throughout both sessions. In addition, Respond–Intentional subjects reported the 4-unit pattern after each block in the 1st session. However, all subjects in all four groups were treated identically during transfer session, and all four groups responded

the computer keyboard using the four fingers of the dominant hand. The response-to-stimulus interval was 120 ms, and the circle remained filled in until participants pressed the correct key, at which time the circle cleared and another target appeared after a delay of 120 ms. By giving end-of-block feedback to focus more on accuracy or on speed, subjects were guided to 92% overall accuracy. For observe sessions, stimuli remained onscreen for 380 ms so as to be similar to the on-time in the Respond condition, and the inter-stimulus interval was 120 ms.

For the training session, all Pattern targets were grey while Random targets were black, such that epochs in the training session were Cued (Epochs 1, 2, 3). In the transfer session, the beginning two epochs (4 and 5) were Uncued in that all targets were black and the last two epochs (6 and 7) were again Cued, with grey targets demarcating Pattern trials and black targets demarcating Random ones.

Half of the subjects in each response condition were given Incidental instructions, and half were given Intentional instructions. Those given Incidental instructions were not alerted to the presence of any regularity and were not instructed to look for one. Those given Intentional instructions were told to learn a repeating 4-unit pattern that occurred on every other trial on the Cued epochs and were told that these patterned trials were marked by grey targets whereas black targets were always randomly positioned. After each block, they were asked to report the 4-unit pattern followed by the trials with grey targets. For Uncued epochs, no subject was alerted to the presence of the regularity although it was identical to the pattern in the Cued epochs.

A previous study demonstrated that subjects given Intentional instructions gained explicit knowledge of the repeating pattern in Cued epochs but were unaware of it during the Uncued epochs (Song et al. 2007). In contrast, those given Incidental instructions did not notice the pattern in the Cued nor Uncued epochs. Thus, explicit knowledge did not affect performance measures on Uncued epochs for any groups regardless of instruction, whereas performance on Cued epochs reflected explicit sequence knowledge, depending on instruction (Song et al. 2007).

To ensure that subjects in the Observe groups were paying attention to the stimuli, the following manipulations were employed during the training session. For subjects in the Observe–Intentional condition, having to explicitly learn and report the 4-unit pattern after each block in the training session ensured that they were observing the stimuli. Subjects were not told that the sequence was identical each time, in order to give them reason to always pay attention to targets. Subjects in the Observe–Incidental condition were given a comparable task in which they counted 0 to 7 red targets which appeared randomly in each block instead of black targets. Accuracy on this detection task was 96.7 ± 4.3% which confirms that subjects were paying attention to the stimuli. Subjects in the Observe–Intentional condition also saw the red targets but were told to ignore them. During the transfer session, all subjects in all four groups were treated identically, and all groups made button press responses.

Although explicit knowledge on this cued variant of the ASRT is deterministic (Pattern trials follow a 4-unit regularity), earlier research indicates that motor performance measures reflect probabilistic learning. That is, performance is not sensitive to the alternating regularity, but rather to the relative frequencies of “triplets” (a sequence of three trials) (Howard et al. 2004). The sequence structure in the ASRT, where predictable Pattern trials alternate with unpredictable Random ones, causes certain triplets of trials to occur at a higher frequency than others. For example, when the pattern is 1r3r2r4r, triplets beginning with 1 and ending with 3 (e.g. 123, 143, 113 etc.) are high frequency whereas those beginning with 3 and ending with 1 (e.g. 321, 341, 311 etc.) are low. Performance improves on the last trial of high-versus low-frequency triplets, regardless of whether this high-frequency triplet ends on a Pattern or Random trial (Howard et al. 2004). Pattern trials are always high frequency, whereas one fourth of Random trials are high frequency by chance, such that 16 high frequency triplets occur 62.5% of the time and 46 low frequency triplets (including 4 repetitions and 8 trills) occur 37.5% of the time. High frequency triplets occur five times more often than any other triplet type. Sequence learning is demonstrated by increasing differences in reaction time and accuracy between high and low frequency triplet sequences (triplet-type-effect) with continued practice. Learning is typically implicit in this task, in that subjects (without specific instruction to guide them otherwise) do not show any awareness of the alternating regularity or of the varying triplet frequencies (Howard et al. 2004). For all results on motor responding reported in the following sections, only high and low frequency triplets are reported. Trills (i.e. 121) and repetitions (i.e. 111) are removed from analysis because they are not counterbalanced across subjects in that they are always low frequency for all subjects. Performance on trills and repetitions could also reflect pre-existing biases, rather than sequence-specific learning (Remillard and Clark 2001).

Tests of explicit awareness. The following end-of-block sequence report task was only given to Intentional subjects. After each Cued block (i.e. in epochs 1, 2, 3, 6 and 7), subjects were asked to verbally report the four-sequence pattern. The four positions corresponded to numbers 1 through 4, and subjects were required to guess after each Cued block. Awareness was said to have been achieved on the block when subjects reported the correct pattern and continued to do so for the remainder of the blocks.

At the end of the ASRT testing, all groups also received the following tests. First, they were given a generation task in which they were asked to generate a typical 16-unit long pattern that occurred. They did so by numerically writing out a typical 16 unit sequence. Thus, if they were able to correctly insert numerically the 4-digit repeating regularity into every other position, then generation was coded as correct. If they were unable to do so, then it was coded as incorrect. Each participant was asked to separately generate a typical 16-unit long pattern that occurred during the Cued epochs and a typical 16-unit long pattern that occurred during the Uncued epochs.

Next, subjects in both instruction groups were given questionnaire interviews which involved increasingly specific questions regarding their knowledge of any regularity in the sequences they had encountered. If they revealed any awareness of the alternating pattern or of triplet frequencies, they were coded as having explicit awareness. They were separately asked questions for Cued and Uncued blocks regarding their knowledge of any regularity in the sequences they had encountered.

Lastly, they were given a card sorting task. For this task, participants were given a stack of 64 index cards, each of which contained three rows of four circles. One circle on each row was filled in with black. Each row represented one trial hence each card denoted three consecutive trials on the ASRT task (a triplet). Participants were told to sort each card into one of two piles labeled “Occurred More Often,” and “Occurred Less Often” based on how often they thought these triplets of trials occurred (Japikse et al. 2001). Participants were specifically asked to sort for Uncued blocks.

Results

Awareness analysis

Incidental groups: No subject in either the Incidental Observe or Respond condition showed or reported any explicit awareness of the correct pattern as measured by generation, questionnaire, or card sort. Results for card sort are summarized in Table 1.

Intentional groups: All Intentional subjects were able to gain explicit awareness of the correct pattern, as measured by end-of-block sequence report. Five subjects reported some recognition of the same pattern in the Uncued epochs as measured by generation, questionnaire and/or the card sorting task, and so these subjects were removed from the analysis. For this criteria, a conservative approach was taken and subjects who even reported a suspicion that the pattern was the same on the Uncued epochs as the Cued epochs were removed from analysis. Thus, $n = 14$ for the Intentional–Observe group, and $n = 9$ for the Intentional–Respond group. For the remaining Intentional subjects, no explicit awareness of the pattern was reported for the Uncued epochs as measured by generation, questionnaire and the card sorting task (Table 1). For these remaining subjects, as assessed by end-of-block sequence report,

Table 1 End of session awareness test for Experiment 1

Group	Card sort (% accurately sorted)
Observe–Incidental	48.6 ± 5.2, $t = -0.98$, $P = 0.35$
Respond–Incidental	51.6 ± 5.1, $t = 1.17$, $P = 0.26$
Observe–Incidental	47.7 ± 5.4, $t = -1.62$, $P = 0.13$
Respond–Incidental	51.3 ± 5.3, $t = -0.71$, $P = 0.50$

explicit awareness of the pattern was reached on average by block 1.0 ± 0.0 of the first epoch for the Observe group, and by block 2.8 ± 1.6 of the first epoch for the Respond group.

In sum, on Cued epochs, Intentional subjects had explicit knowledge of the regularity but the Incidental subjects did not. On Uncued epochs, no subject included in the final analysis was aware of the regularity present in them.

Performance measures

Means of median reaction times for High and Low frequency triplets for Incidental (Fig. 2a) and Intentional (Fig. 2b) groups are shown for both Observe and Respond conditions. Figure 3 shows triplet-type-effects (reaction time differences between High and Low frequency triplets) for all four groups across all epochs. We assume that

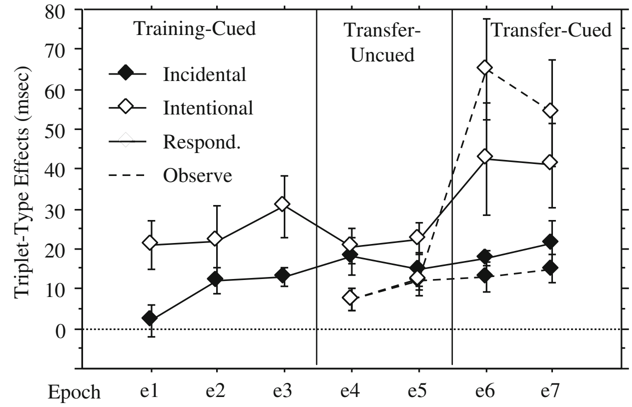

Fig. 3 Sequence learning measures for Experiment 1. Reaction Time Triplet-type-effects (RT for Low minus RT for High frequency triplets) are plotted for all groups. Incidental subjects are plotted with *filled diamonds* and Intentional subjects are plotted with *unfilled diamonds*. Observe groups are plotted with *dashed lines* whereas Respond groups are plotted with *solid lines*. The Intentional and Incidental Observe groups cannot be seen separately for epochs 4 and 5 because these measures overlap completely

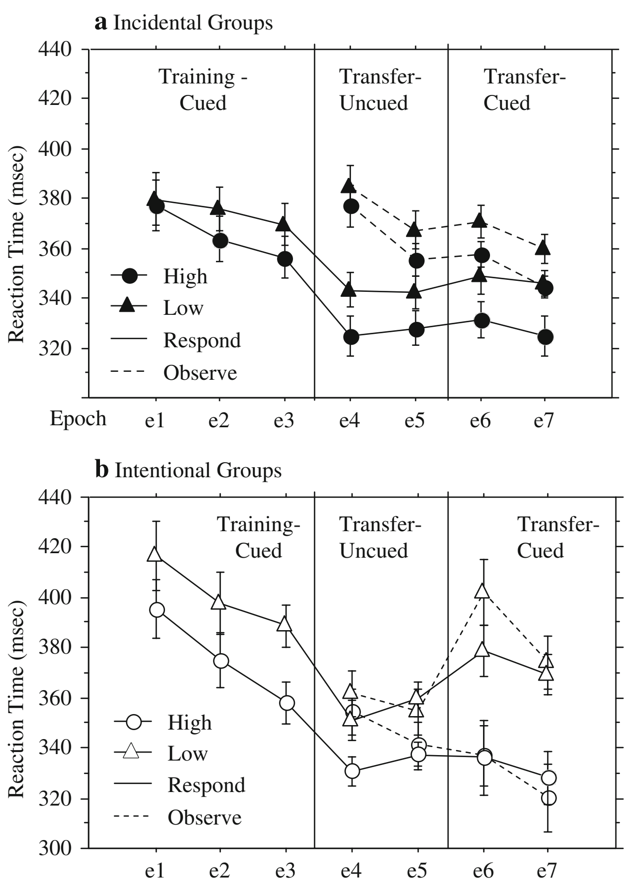

Fig. 2 Reaction Time measures for Experiment 1. Mean of Median Reaction Times for Incidental subjects are plotted in **a** (Incidental Observe and Respond) split by High (*closed triangles*) and Low (*closed circles*) frequency triplets and for Intentional subjects in **b** (Intentional Observe and Respond) split by High (*open triangles*) and Low (*open circles*) frequency triplets. Observe groups are plotted with dashed lines whereas Respond groups are plotted with solid lines. Analyses of the Uncued epochs revealed that those who responded for the training session showed more sequence learning than those who observed only

performance measures for Cued epochs (1, 2, 3, 6 and 7) reflect explicit knowledge for Intentional but not Incidental subjects. In contrast, Epochs 4 and 5, the first two epochs of the 2nd session, are Uncued epochs, and in all four groups, triplet-type-effects seen in these epochs measure implicit learning.

Training session. Since only the Respond groups made motor responses in the Training session, only the Respond–Intentional and Respond–Incidental groups could be analyzed here. These blocks were all cued, and so, this training session would reveal the effects of explicit knowledge on performance measures. For reaction time, a triplet-type (High or Low) by instruction (Intentional vs. Incidental) by epoch (1, 2, 3) ANOVA, revealed a significant main effect of triplet-type, $F(1, 21) = 37.12$, MSE = 250.68, $P < 0.0001$, a trend for a triplet-type by epoch interaction, $F(2, 42) = 3.07$, MSE = 94.21, $P < 0.06$ which reflect that high-frequency triplet trials become faster than low-frequency ones with practice, and a triplet-type by Instruction interaction, $F(1, 21) = 7.91$, MSE = 250.68, $P < 0.02$, which showed that Intentional instructions enabled people to use explicit knowledge to increase measures of sequence learning for reaction time in Cued epochs.

For accuracy, a triplet-type (High or Low) by epoch (1–3) by instruction (Intentional vs. Incidental) ANOVA revealed only a main effect of triplet-type, $F(1, 22) = 16.19$, MSE = 0.002, $P < 0.0006$ where high-frequency triplets were more accurate than low-frequency ones. These findings are consistent with Song et al. (2007) in which it was found that explicit awareness affected triplet type effects for reaction time but not for accuracy. Mean accuracy for the groups was 91.8% (Intentional) and 92.5% (Incidental).

Transfer session. Our main questions here were concerned with the transfer of perceptual learning which occurred during training and how it was influenced by explicit modes of learning. Therefore, our analyses focused on the Uncued epochs at the start of the transfer session, and these are reported first below.

Uncued epochs (4–5). A triplet-type (High or Low) by response condition (Observe vs. Respond) by instruction (Intentional vs. Incidental) ANOVA was conducted on Reaction Time for these Uncued epochs. A main effect of response condition, $F(1, 47) = 8.52$, MSE = 2909.23, $P < 0.006$ indicated that the Respond groups were faster than the Observe groups, and a significant main effect of triplet-type, $F(1, 47) = 87.76$, MSE = 116.68, $P < 0.0001$, indicated that High frequency triplets were faster than Low frequency ones reflecting sequence learning. Importantly, a triplet-type by response condition interaction, $F(1, 47) = 8.85$, MSE = 116.69, $P < 0.005$, indicated that the Respond groups showed a larger triplet type effect than the Observe groups, as can be seen in Fig. 3. This indicated that motor responding contributed to sequence learning.

There was no significant triplet-type by instruction interaction, $F(1, 47) = 0.75$, MSE = 116.68, $P = 0.39$, which suggests that explicit knowledge during the training phase had no effect on performance measures of sequence learning in Uncued epochs in the transfer phase. Since explicit awareness was not present in these Uncued epochs, we assume that these blocks reflect underlying implicit-based learning processes even in Intentional learners. This result replicates our previous finding that implicit learning occurred independent of explicit awareness (Song et al. 2007). There was also no triplet-type by instruction by response condition interaction, $F(1, 47) = 0.59$, MSE = 116.68, $P = 0.45$, suggesting that instruction did not alter the relationship between perceptual and motor processes.

Since the Uncued epochs in the transfer session were ten blocks long, to more directly test whether Observe and Respond groups displayed triplet-type differences from the very start of responding, the first two blocks of the transfer session were analyzed separately (Fig. 4). Observe groups showed no significant triplet-type-effect in these initial blocks (Observe–Incidental: $t(13) = -0.11$, $P = 0.91$, Observe–Intentional: $t(13) = 0.63$, $P = 0.54$) whereas Respond groups showed significant triplet-type-effects (Respond–Incidental: $t(13) = 4.13$, $P < 0.001$, Respond–Intentional: $t(8) = 4.63$, $P < 0.002$). Thus, in this first experiment, no evidence for sequence learning by observation alone was found, in that participants who had only observed during training showed no triplet-type effects when they began to respond. In contrast, sequence learning did occur when motor responses were made during training, consistent with the idea that motor responses support sequence learning (Willingham 1999).

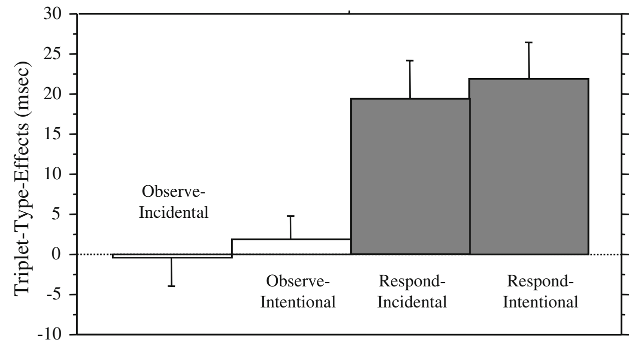

Fig. 4 Sequence learning at start of transfer session for Experiment 1. Those who observed the 1st session showed no significant triplet-type effect in the 1st block of the 2nd session whereas those who responded to the 1st session showed significant triplet-type effects in the 1st block of the 2nd session. There was therefore no evidence for perceptual learning in Experiment 1

Accuracy analyses of Cued epochs 4 and 5 revealed findings similar to those on reaction times reported above. A triplet-type (High or Low) by response condition (Observe vs. Respond) by instruction (Intentional vs. Incidental) ANOVA on accuracy revealed a significant main effect of triplet-type, $F(1, 47) = 66.58$, MSE = 0.001, $P < 0.0001$ as high-frequency triplets were more accurate than low-frequency ones, and a trend for a triplet-type by response condition interaction, $F(1, 47) = 3.80$, MSE = 0.001, $P < 0.06$ reflected the greater sequence learning in Respond groups as compared to Observe groups. Mean accuracy for the four groups in the Uncued epochs ranged from 91.6 to 92.9%.

Cued epochs (6 and 7). Although our primary questions concerned the Uncued epochs as analyzed above, we also examined the Cued epochs for two purposes. First, we wanted to see how reintroducing cues and explicit awareness affected performance measures in Intentional learners. Second, we wanted to see whether transitioning back to Cued blocks from Uncued blocks led to any changes in performance for Incidental learners, because these Cued blocks reinstituted the perceptual conditions all groups encountered during the training blocks which were Cued.

For Reaction Time, a triplet-type (High or Low) by instruction (Intentional vs. Incidental) by response condition (Observe vs. Respond) ANOVA revealed a significant main effect of triplet-type, $F(1, 47) = 66.01$, MSE = 848.86, $P < 0.0001$, and a triplet-type by Instruction interaction, $F(1, 47) = 16.65$, MSE = 848.85, $P < 0.0001$. This finding along with Fig. 3 indicates that Intentional subjects were able to recall and reinstate their explicit knowledge to affect their performance for reaction time in Cued epochs.

For accuracy in Cued epochs 6 and 7, a triplet-type (High or Low) by instruction (Intentional vs. Incidental) by response condition (Observe or Respond) ANOVA revealed only a main effect of triplet-type, $F(1, 36) = 41.34$, MSE = 0.001, $P < 0.001$, which reflects that high-frequency trials were more accurate than low-frequency ones Mean accuracy for groups ranged between 90.6 and 91.6%.

In addition, we analyzed Reaction Time for Incidental subjects separately to explore whether the stimulus changes which occurred from Uncued to Cued blocks affected sequence learning measures. We compared reaction time triplet-type effects on the last two blocks in Uncued epoch 5 to the first two blocks in Cued epoch 6. We reasoned that if perceptual learning was contextually selective for Cued blocks, then transitioning from Uncued to Cued epochs could have led to a benefit. No such benefit was found in that triplet-type effects from the last two blocks of Uncued epoch 5 did not differ from that of the first two blocks of Cued epoch 6 (Observe–Incidental: $t(13) = -1.03$, $P = 0.32$, Respond–Incidental: $t(13) = -0.50$, $P = 0.62$). Further experiment, however, is necessary to conclusively determine whether transitioning from grey and black targets to all black targets or vice versa can affect performance.

Discussion

In this experiment, no evidence for perceptual sequence learning via observation was found, even when the subjects had full explicit knowledge of the regularity during the training phase. This was demonstrated by the fact that subjects in the Observe groups showed no differences between High and Low frequency triplet types at the beginning of the transfer session. In contrast, Respond subjects showed significant triplet-type effects from the beginning of the transfer session, and showed more sequence learning overall than Observe subjects. This latter finding supports the generally accepted conclusion that motor responding can support sequence learning (Willingham 1999).

In addition, we found that during transfer, Intentional subjects had greater triplet-type effects than Incidental subjects on Cued epochs where they could use their explicit knowledge, but not on Uncued epochs when explicit knowledge was removed. This is consistent with our previous report that explicit knowledge affects performance, but not implicit motor sequence learning itself (Song et al. 2007).

The fact that no evidence for implicit perceptual sequence learning was reflected in our performance measures even for Intentional learners may add insight to the conclusions of Rüsseler who found that perceptual learning did occur and only when subjects had full explicit knowledge. This may be because explicit knowledge is tied to the stimuli but does not increase perceptual learning (Rüsseler and Rösler 2000; Rüsseler et al. 2003). When explicit knowledge is removed from performance measures, as it was in the current study, an explicit awareness may have no effect on perceptual processing. It has been suggested that in the presence of explicit knowledge, motor responses are more stimulus bound (Knee et al. 2007). However, other explanations may account for these findings. The Rüsseler studies used letter cues while the current study used visuospatial targets.

Experiment 2

The results of Experiment 1 seem to suggest that implicit sequence learning did not occur via mere observation of the sequence, even when subjects had full explicit knowledge during training, and hence attention to the sequence had been assured. However, it was also possible that the alternating color cues during the training phase could have disrupted the acquisition of perceptual learning or that the switch from alternating color targets during training to all black targets in transfer could have disrupted the expression of any perceptual learning that occurred during training.

To address these possibilities, in Experiment 2 all targets were black at all times in both training and transfer sessions. As in Experiment 1, **s**ubjects were assigned to one of two response groups, Observe or Respond, based on how they were treated during training. In Experiment 2, all subjects were given Intentional instructions during training in that they were told to search for any patterns and to report any patterns found at the end of each block. We did this to ensure attention to the stimuli. However, based on previous studies (Howard and Howard 2001), we expected that, in the absence of the alternating color cues used in Cued epochs in Experiment 1, no subject would gain explicit knowledge with these vague instructions and this amount of training. Hence, any learning would remain implicit and would occur in the absence of any explicit knowledge of the regularity. The term “implicit” learning has been used to encompass two different concepts. First and most notable is the lack of conscious awareness of learning and a resultant inability to communicate this knowledge. However, some authors also suggest “implicit” learning must also be defined by a lack of intention to learn (Frensch 1998). In this study, we have separated these two concepts such that “Incidental” or “Intentional” instruction refers to the intention to learn the sequence, while “implicit” or “explicit” refers to the consciousness of the resultant sequence learning.

Subjects were also assigned to one of two transfer groups. Half of the Observe and half of the Respond subjects were asked to stop searching for a pattern in the transfer session (Stop-Search), while the other half were asked to continue to look for and report a pattern in the transfer session (Continue-Search). Our goal was to see if continued search for the pattern affected the expression of perceptual or motor based learning. Engaging in intentional search often interferes with expression of implicit learning

	Training Session			Transfer Session		
	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6
Experiment 2	**Uncued**			**Uncued**		
1. Observe Stop-Search	Observe & Guess Sequence			Respond		
2. Respond Stop-Search	Respond & Guess Sequence			Respond		
3. Observe Continue-Search	Observe & Guess Sequence			Respond &Guess Sequence		
4. Respond Continue-Search	Respond & Guess Sequence			Respond & Guess Sequence		

Fig. 5 Schematic for Experiment 2. For all subjects, all epochs were with black targets. All subjects searched for a pattern in the training session, but half of the subjects were instructed to stop searching in the transfer session. Half continued to search in the transfer session

although not its acquisition (Jimenez et al. 2006; Song et al. 2007). In this manner, in addition to asking whether implicit sequence learning could occur via observation alone, we could assess whether intentional search had an effect on the expression of such learning.

Materials and methods

Participants

Forty right-handed volunteers (aged 18–25 years) were recruited from Georgetown University to participate in the study for credit or payment. All subjects were naïve to SRTT based tasks, and all subjects signed informed consent approved by the Georgetown University IRB. Subjects were randomly assigned to one of four groups representing the combination of two training response conditions (Observe or Respond) by two transfer conditions (Stop-Search or Continue-Search). A schematic of the study design is presented in Fig. 5. The entire test visit for each subject took approximately 1 h.

Design and procedure

All subjects completed a training and transfer session of the Alternating Serial Response Time task (ASRT). All stimulus and response parameters were identical to those used in Experiment 1 with the following exceptions. All trials were marked by black targets at all times. Transfer sessions were 15 instead of 20 blocks long. All groups were instructed to look for a pattern in the training session. Hence, Observe groups searched for a pattern but made no motor responses for the training session. Respond groups searched for a pattern and simultaneously made button press responses. In the transfer session, all groups made motor responses. "Stop search" groups, however, were instructed to stop searching for a pattern and instead respond motorically. "Continue search" groups were instructed to continue to search for a pattern in addition to responding motorically (Fig. 5).

Tests of explicit awareness. The following block report task was administered after each block for sessions when subjects were instructed to search for a pattern. Subjects were told they could code the four positions corresponding to numbers 1 through 4 if this was helpful to them, and subjects were required to give their best guess after each block. If in any block, subjects were able to report either the alternating regularity or report that certain triplets of trials occurred with higher frequency, they were coded as having explicit awareness. Unlike the sequence report task used in Experiment 1, in this block report, subjects in Experiment 2 did not know to look for an alternating 4 sequence regularity and hence were allowed to report any patterns they had noticed at all in any manner they chose.

At the end of the ASRT testing, all groups also received the end of session awareness tests administered in Experiment 1. This included the generation test, questionnaire, and card sorting task. These differed from those of Experiment 1 only in that there was no mention of Cued versus Uncued blocks.

Results

Awareness analysis

No subject in any group showed or reported any explicit awareness as measured by end-of-block report, generation, questionnaire, or the card sorting task. For the card sorting task, the results are listed in Table 2. Therefore, even though all groups were searching for a pattern during training, as we had expected based on earlier work with this task, no one found it. Therefore, any learning detected via response time and/or accuracy reflects implicit learning.

Table 2 End of session card sort awareness test for Experiment 2

Group	Card sort (% accurately sorted
Observe Stop-Search	52.6 ± 6.4, $t = 1.13$, $P = 0.23$
Respond Stop-Search	51.1 ± 6.5, $t = 0.53$, $P = 0.61$
Observe Continue-Search	52.6 ± 7.4, $t = 1.11$, $P = 0.29$
Respond Continue-Search	47.1 ± 8.7, $t = -1.07$, $P = 0.31$

Performance measures

Means of median reaction times for High and Low frequency triplets are shown in Fig. 6a for the Stop-Search groups and in Fig. 6b for the Continue-Search groups. Figure 7 shows triplet-type-effects (reaction time on Low minus High frequency triplets) for all four groups across all epochs.

Training session. For the training session, where only the Respond groups yield data, a triplet-type (High or Low) by epoch (1–3) by transfer condition (Stop-Search vs. Continue-Search) ANOVA on reaction time revealed significant main effects of epoch, $F(2, 38) = 9.41$, MSE = 308.38, $P < 0.005$, and triplet-type, $F(1, 19) = 28.09$, MSE = 146.43, $P < 0.001$, and a triplet-type by epoch interaction, $F(2, 38) = 4.59$, MSE = 56.82, $P < 0.02$, indicative of general skill and sequence-specific learning in the training session for Respond groups.

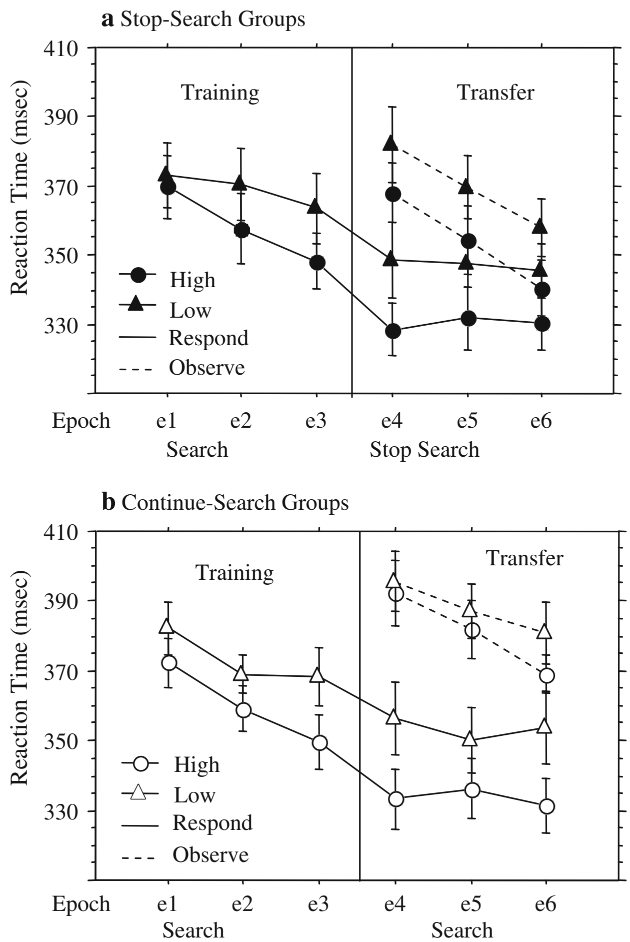

Fig. 6 Reaction Time measures for Experiment 2. Mean of Median Reaction Times for Stop-Search subjects are plotted in **a** (Stop-Search Observe and Respond) split by High (*filled triangles*) and Low (*filled circles*) frequency triplets and for Continue-Search subjects in **b** (Continue-Search Observe and Respond) split by High (*open triangles*) and Low (*open circles*) frequency triplets. Observe groups are plotted with *dashed lines* whereas Respond groups are plotted with *solid lines*

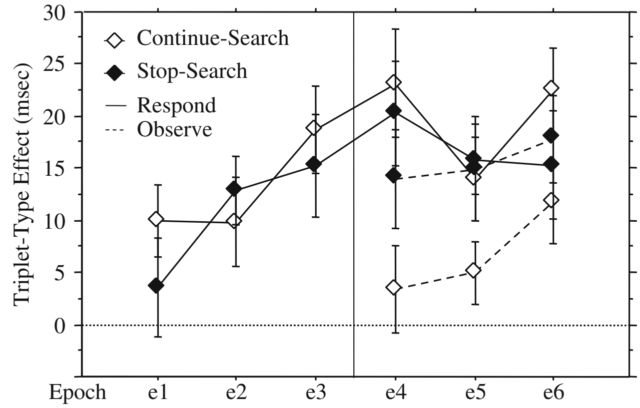

Fig. 7 Sequence learning measures for Experiment 2. Reaction Time Triplet-type effects (RT for Low minus RT for High frequency triplets) are plotted for all groups. Stop-Search subjects are plotted with *filled diamonds* and Continue-Search subjects are plotted with *unfilled diamonds*. Observe groups are plotted with *dashed lines* whereas Respond groups are plotted with *solid lines*. Analyses of the transfer session revealed that for those who stopped searching in the transfer session, Observe and Respond groups showed equal levels of sequence learning. Those who continued searching demonstrated impaired expression of observation based learning

For accuracy in the training session, a triplet-type (High or Low) by epoch (1 to 3) by Transfer condition (Stop-Search vs. Continue-Search) ANOVA revealed a significant main effect of triplet-type, $F(1, 29) = 25.12$, MSE = 0.0004, $P < 0.0001$, as High-frequency triplets were more accurate than Low-frequency triplets and a significant main effect of epoch, $F(2, 38) = 4.41$, MSE = 0.001, $P < 0.02$. Mean accuracy for the groups was 94.5% (Stop-Search) and 95.2% (Continue-Search).

Transfer session. As In Experiment 1, the most important comparisons concerned the transfer session, where we could look for evidence of perceptual and motor learning that occurred during training. The Stop-Search and Continue-Search groups had been treated identically during training, so any performance differences between them at the beginning of the transfer session could not be due to what was learned during training, but instead reflected differences in the expression of what had been learned.

For reaction time a triplet-type (High or Low) by epoch (4–6) by response condition (Observe vs. Respond) by transfer condition (Stop-Search vs. Continue-Search) ANOVA revealed a significant main effect of epoch, $F(2, 72) = 15.66$, MSE = 180.70, $P < 0.0001$, indicating that overall reaction time decreased across epochs 4–6, a significant effect of response group, $F(1, 36) = 15.52$, MSE = 3990.28, $P < 0.0004$ indicating that Observe groups were slower overall than Respond groups, and a significant epoch by response group interaction,

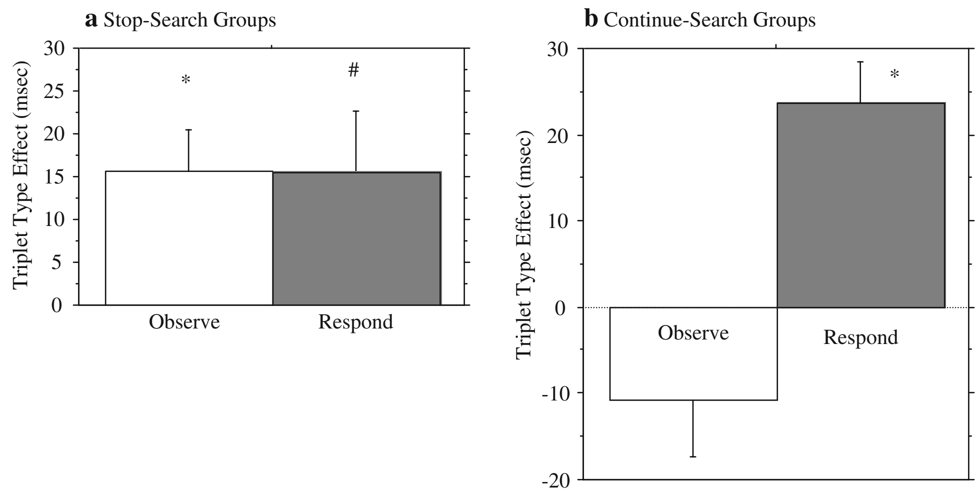

Fig. 8 Sequence learning at start of transfer session for Experiment 2. For those who stopped searching, Observe subjects showed significant triplet-type effects in the beginning of the transfer session which did not differ from those found for Respond subjects. For those who continued to search, expression of learning was impaired from the start of the transfer session for Observe but not Respond subjects

$F(2, 7) = 12.17$, MSE = 180.70, $P < 0.0001$ indicating that overall response time decreased faster for the Observe as compared to Respond groups, as overall speed generally decreases rapidly upon first responding. Implicit sequence learning was demonstrated by a significant main effect of triplet-type, $F(1, 36) = 103.42$, MSE = 127.22, $P < 0.0001$, indicating that High frequency triplets were faster than Low frequency ones. A triplet-type by response condition interaction, $F(1, 36) = 6.43$, MSE = 127.22, $P < 0.02$, indicated that Respond groups showed more sequence learning than Observe groups. However, Fig. 7 and a trend for a triplet-type by response condition by search condition interaction, $F(1, 36) = 3.97$, MSE = 127.22, $P < 0.06$, suggested that this was due to modulation of expression of learning by continued explicit search. Specifically, for those who had stopped searching in the transfer session, the Observe group seemed to show as much sequence learning as the Respond group. However, those who continued to search seemed to show impaired expression of learning in the Observe group.

To explore this trend, reaction time ANOVAs were conducted for each transfer condition separately. For Stop-Search groups, a triplet-type (High or Low) by epoch (4–6) by response condition (Observe vs. Respond) ANOVA revealed a significant main effect of epoch, $F(2, 36) = 11.20$, MSE = 154.69, $P < 0.0002$, a trend for a main effect of response condition, $F(1, 18) = 4.05$, MSE = 4048.70, $P < 0.06$, a significant epoch by response condition interaction, $F(2, 36) = 10.34$, MSE = 154.69, $P < 0.0003$, and a main effect of triplet-type, $F(1, 18) = 56.64$, MSE = 141.44, $P < 0.0001$, but no triplet-type by response condition interaction, $F(1, 18) = 0.13$, MSE = 141.44, $P = 0.72$. This latter finding suggests that for the Stop-Search transfer condition, Observe and Respond groups had significant and equivalent sequence learning measures during transfer.

For groups who continued to search in the transfer session, this same ANOVA revealed significant main effects of epoch, $F(2, 36) = 5.49$, MSE = 206.71, $P < 0.01$, of response condition, $F(1, 18) = 12.75$, MSE = 3931.86, $P < 0.003$, an epoch by response condition interaction, $F(2, 36) = 3.38$, MSE = 206.71, $P < 0.05$, a main effect of triplet-type, $F(1, 18) = 46.79$, MSE = 113.00, $P < 0.0001$, and a significant triplet-type by response condition interaction, $F(1, 18) = 11.54$, MSE = 113.00, $P < 0.004$. This latter interaction along with Fig. 7, and the contrast with the Stop-Search conditions suggests that continued explicit search impaired the expression of perceptual learning.

Because the transfer session was 15 blocks long, to more directly test whether observation alone supported learning, we analyzed reaction time separately for the first two blocks of the transfer session for each group, as we had done in Experiment 1. Triplet-type-effects in these initial blocks of epoch 4 are plotted in Fig. 8. For Stop-Search groups, t tests revealed significant triplet-type effects in the Observe group, $t(9) = 3.16$, $P < 0.02$ and a trend in the Respond group, $t(9) = 2.14$, $P = 0.06$, with no significant difference between the two groups, $t(18) = 0.17$, $P = 0.99$. This suggests sequence learning occurred via observation alone during the training session. For the Continue-Search groups, only the Respond group showed a significant triplet-type effect, $t(9) = 4.75$, $P < 0.002$, supporting the conclusion that continued intentional search during transfer impaired the expression of perceptual learning.

For accuracy in the transfer session for all groups, a triplet-type (High or Low) by epoch (4–6) by Response Condition (Observe vs. Respond) by Transfer condition (Stop-Search vs. Continue-Search) ANOVA revealed only a main effect of triplet-type, $F(1, 36) = 41.34$, MSE = 0.001, $P < 0.0001$ as High-frequency trials were more accurate than Low-frequency ones, For the four groups, overall mean accuracy ranged between 92.8 and 95.2%.

Discussion

In contrast to Experiment 1, Experiment 2 showed that observation alone could support implicit sequence learning for a complex probabilistic sequence. This suggests that the color cue manipulations in the first experiment hurt either the acquisition of implicit learning and/or its expression during transfer. More importantly, however, the results from the Stop-Search condition demonstrate clearly that observation alone can support perceptual learning even in the absence of explicit knowledge. This finding is in keeping with previous evidence for perceptual sequence learning (Howard et al. 1992; Mayr 1996; Remillard 2003), but the present findings minimized the confounds of explicit awareness (as in Howard et al. 1992) or large ocular movements (as in Mayr 1996).

The present results also extend evidence for implicit perceptual sequence learning to apply to probabilistic sequences containing 2nd order structure. Previous research by Remillard (2003) had suggested that observational learning was possible for 1st order, but not for 2nd order probabilistic sequences. Remillard used a variant of the SRTT with targets being bigrams rather than circles. In this study, subjects viewed a horizontal row of 6 pairs of letters (e.g. all pairs were either “mn” or “nm”). One pair of letters (or bigram) in each row was underlined. Subjects responded to the underlined bigram by making either a left or right key press depending on whether “mn” or “nm” was underlined. The next trial would be another row of these same letter pairs except this time another bigram would be underlined. Though motor responses followed no set sequence, the spatial position of the underlined stimulus followed a probabilistic sequence. These sequences had either 1st order (event n is predicted by event $n - 1$), 2nd order (n is predicted by $n - 2$) or 3rd order (n is predicted by $n - 3$) transitions. Remillard found perceptual learning for 1st order transitions, but not for 2nd or 3rd order transitions. It is not clear why we found observational learning of 2nd order probabilistic sequences, while Remillard did not. However, a study by Deroost and Soetens 2006b suggests that observation based learning is sensitive to stimulus characteristics and attention. In their study, perceptual learning did not occur when single targets were used instead of bigrams, or if in the trial, each bigram was presented in a blank field instead of underlined along a horizontal row of six bigrams. Deroost and Soetons concluded that rows of bigrams attracted more attentional resources and that this attention was necessary for observation based learning. In the current study, Intentional instructions may have encouraged attention to the stimuli and facilitated perceptual learning for more complex probabilistic sequences.

Another important finding in Experiment 2 is that continued Intentional search impaired the expression of observation based learning. This detrimental effect of intentional search or divided attention on the expression, but not acquisition of learning, has been demonstrated in the past (Frensch et al. 1998; Jimenez et al. 2006). The fact that in the present experiment continued search did not impair expression in the Respond groups suggests that learning based on motor responses is less sensitive to the effects of divided attention and explicit search. Explicit search can in many instances interfere with the expression of learning perhaps by competing for limited resources at the time of performance (Frensch et al. 1998; Jimenez et al. 2006; Song et al. 2007).

General discussion

Two main findings emerged for the present study. First, observation alone supported implicit sequence learning for complex probabilistic sequences and when spontaneous explicit awareness did not occur. The magnitude of perceptual learning was identical regardless of whether or not motor responses had been made. Second, this observation-based learning or its expression was sensitive to variations in the colors of targets, and the expression of observation-based learning was impaired by continued explicit search. Learning based on motor responding, however, was insensitive to such manipulations.

The first finding addresses a controversy in the literature concerning the contribution of perceptual learning to performance measures on SRTT tasks. The finding that perception can support implicit sequence learning is consistent with some reports (Howard et al. 1992; Mayr 1996; Remillard 2003) and in contrast to others (Willingham et al. 1989; Willingham and Goedert-Eschmann 1999; Kelly and Burton 2001).

Spontaneous explicit knowledge is not a likely explanation for the learning observed here. Probabilistic sequences were used to prevent spontaneous explicit awareness, although some subjects were cued to purposefully develop explicit knowledge in Experiment 1. In Experiment 2, where perceptual learning was found to occur, tests of explicit awareness given after each block and at the end of sessions demonstrated that all learning was implicit.

Oculomotor learning is not a likely explanation for the learning observed here. The distances used here are comparable to the horizontally separated (4.7°) targets used in the study by Willingham et al. (1989) which found no evidence for perceptual sequence learning. The fact that perceptual sequence learning occurred in the second but not the first experiment reported here gives further support for the idea that visuo-spatial and not oculomotor processes led to sequence learning. Subjects in the first experiment had the same stimulus size and dimension parameters as subjects in the second experiment and thus would have had the same degree of ocular movement. This is not to say that sequence learning could not occur via oculomotor sequencing or that in fact, sequence learning in previous studies was not based on eye movement. For example, Rüsseler et al. failed to replicate Mayr (1996) when distances between object stimuli were reduced (Rüsseler et al. 2002). Hence, it is likely that in Mayr (1996), sequence learning was in fact driven by eye movements. In the current study, perceptual learning occurred in the absence of large eye movements. However, future experiments involving steady fixation are needed to resolve this issue.

Attentional variations may be one cause of variations in findings across studies. Studies which did not find perceptual learning, specifically Kelly and Burton (2001), did nothing to ensure that observation groups were paying attention to the stimuli, as they were simply passive onlookers with no task to perform. In the current study as subjects were actively looking for a pattern or counting targets, Observe groups were more apt to pay attention to the stimulus events. It remains unclear from the present experiments whether implicit perceptual sequence learning can occur without intentional search. In the second experiment, though subjects did not gain any explicit knowledge, they were searching for a pattern during the learning phase. Unfortunately, an Incidental condition for this experiment was difficult to create because there was no way to ensure subjects were attending to the stimuli without some task. However, Experiment 1 makes it clear that intentional search for a pattern is not enough to demonstrate perceptual learning. During transfer, the Observe–Intentional subjects in the first experiment failed to show any evidence for perceptual learning, even though they had gained full explicit knowledge of the pattern during training. Other studies using rows of letter targets which have used Incidental learning conditions have found evidence for perceptual learning (Remillard 2003; Deroost and Soetens 2006a, b). Remillard found perceptual learning only for 1st order sequences, and not 2nd order sequences. Deroost and Soetens (2006a) found that only 1st order deterministic sequences led to perceptual learning, while 1st order probabilistic and 2nd order ones did not. In a separate experiment, Deroost and Soetens (2006b) found that stimulus characteristics and attentional requirements could affect this perceptual sequence learning. In the current experiment, perceptual learning of 2nd order probabilistic sequences was found to occur and attentional requirements were high as subjects were constantly searching for a pattern. Attention is also likely to be necessary at the time of the expression of perceptual learning. In Experiment 2, continued Intentional search impaired the expression of observation based learning but not motor-response based learning.

However, attention is not the only other explanation for the discrepancies in the literature. Several reports which did ensure attention to stimuli still found no evidence for perceptual learning. This may be due to similar factors which prevented either the acquisition or expression of perceptual learning in the first experiment reported here. The studies which have offered the most convincing arguments for the lack of perceptual learning used varying color cues along with spatial cues (Willingham et al. 1989, 1999). It is possible that such a simple variation could affect the sensitive perceptual processes which support temporal sequence learning for visuo-spatial targets. In the current Experiment 1, the alternation between grey and black targets on every other trial could have disrupted adjacent perceptual associations during acquisition.

Alternatively the switch from alternating grey and black cues to all black cues could have prevented the expression of perceptual learning in the transfer phase. In an SRTT study, it was shown that disruption of the dorsolateral prefrontal cortex by TMS only disrupted sequence learning when it was driven by location cues and not when it was driven by color cues (Robertson et al. 2001). A switch from Cued epochs with alternating grey and black targets to Uncued epochs with black targets could have likewise altered the underlying attentional resources, thus masking the expression of perceptual learning. However, it is noteworthy that for Respond subjects who did make a motor response, sequence learning did transfer from Cued to Uncued epochs which suggests that motor response based learning is not similarly sensitive to alterations in target color.

It is also important to note that in the second experiment, the Respond Stop Search group did not show any more learning from the start to the end of the transfer session than the corresponding Observe group. This suggested that perceptual and motor learning occurred to the same extent, and overlapped with each other in performance measures. However, the two types of learning were differentially sensitive to other manipulations as demonstrated.

In sum, the current experiments show that implicit perceptual sequence learning of a 2nd order probabilistic structure can occur. An account in terms of increased spontaneous explicit awareness was ruled out, and an account in terms of oculomotor sequences was unlikely. In the absence of motor responding, either alternating color cues or the switch from the Cued to Uncued conditions disrupted perceptual sequence learning or its expression. When motor responses were made however, sequence learning was unaffected by cue variations (Fig. 3). Concurrent explicit search clearly disrupted the expression of perceptual learning, but not of motor learning (Fig. 7). Another important point is that, though in the current experiment, perceptual and motor learning are treated and for the most part behave as separate albeit overlapping processes, it is also possible that when perceptual learning does occur, motor response representations become tied to perceptual ones, at which point perceptual learning may limit the expression of motor learning. This would explain why motor sequence learning does not transfer when location cues are replaced by color cues (Robertson and Pascual-Leone 2001). It is unclear at this time how perceptual and motor learning interact. Nonetheless, it is clear, that perceptual learning can occur and affect performance measures on SRTT tasks. Thus, the SRTT should be considered a mixed perceptual/motor learning task and perceptual contributions to learning should be taken into account when interpreting findings.

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