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ORIGINAL ARTICLE

Implicit sequence learning in a continuous pursuit-tracking task

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Abstract Assessing implicit learning in the continuous pursuit-tracking task usually concerns a repeated segment of target displacements masked by two random segments, as referred to as Pew's paradigm. Evidence for segment learning in this paradigm is scanty and contrasts with robust sequence learning in discrete tracking tasks. The present study investigates this issue with two experiments in which participants ($N = 56$) performed a continuous tracking task. Contrary to Pew's paradigm, participants were presented with a training sequence that was continuously cycled during 14 blocks of practice, but Block 12 in which a transfer sequence was introduced. Results demonstrate sequence learning in several conditions except in the condition that was obviously the most similar to previous studies failing to induce segment learning. Specifically, it is shown here that a target moving too slowly combined with variable time at which target reversal occurs prevents sequence learning. In addition, data from a post-experimental recognition test indicate that sequence learning was associated with explicit perceptual knowledge about the repetitive structure. We propose that learning repetition in a continuous tracking task is conditional on its capacity to (1) allow participants to detect the repeated regularities and (2) restrict feedback-based tracking strategies.

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Introduction

Implicit learning is generally defined as a learning process that proceeds without intentional attempts to acquire useful information about the to-be-learned structure (Perruchet, 2008). Researchers elicited implicit learning using a variety of experimental situations (for reviews, see Cleeremans, Destrebecqz, & Boyer, 1998; Perruchet, 2008; Seger, 1994). Yet, well-founded implicit learning has been demonstrated in the serial reaction time (SRT) task. In this standard task introduced by Nissen and Bullemer (1987), subjects have to predict the location of a target that could appear in one of several (usually four) locations so as to press the key associated with the target location as quickly as possible. Traditionally, SRT tasks consist of a sequence of target displacements that is continually cycled during several blocks of trials. Inserting a different test sequence of the stimulus after extensive practice, sequence learning can be assessed comparing the performance on the training sequence and the test sequence.

Whereas implicit sequence learning in the SRT task appears to be robust (Chambaron, Ginhac, & Perruchet, 2008), the learning of a repeated target displacements is much more difficult when the target has to be tracked continuously (Chambaron, Ginhac, Ferrel-Chapus, & Perruchet, 2006). Indeed, Pew (1974) introduced a pursuit-tracking task paradigm into which the tracking pattern was decomposed in three segments with the middle one that was repeated through the trials. Studies conducted through Pew's paradigm have been referred to as implicit *motor* learning due to the greater importance of the motor components during the tracking; actually, SRT and the other classical paradigms for implicit learning investigation require responses from the participant in which the motor aspect does not have a primary influence (see Roberston, 2007). Yet while a few studies (e.g. Magill, 1998; Shea, Wulf, Whitacre, & Park, 2001; Wulf & Schmidt, 1997) have observed segment learning in Pew's task, others have not (e.g. Chambaron et al., 2006; Lang, Gapenne, & Rovira, 2011). Moreover, Chambaron et al. (2006) demonstrated that the learning observed by Wulf and Schmidt (1997) was probably due to the specific features of the repeated segment. A provisional and cautious conclusion of these authors was that learning a repeated segment in a pursuit-tracking task is much more difficult than learning a repeated sequence in SRT tasks (see also Chambaron, et al., 2008).

It could be argued that the difficulty of learning a repeated pattern in the pursuit-tracking task is related to the motor predominance during the tracking, so that the underlying mechanisms of learning would be different in tasks that are predominantly motor versus predominantly perceptual. However, we have recently shown (Lang et al., 2011) that learning occurred in a modified pursuit-tracking task in which the concurrent visual feedback of subject's own movements was suppressed. Indeed, a pursuit-tracking task implies superposing the concurrent visual feedback with the moving target (Adams, 1961) and thus a tracking task without visual feedback could not be considered as such. However, the motor components in the Lang et al. experiment were identical in both tasks with or without visual feedback. As a consequence, absence of learning in the pursuit-tracking task could not be attributed to the motor nature of the task per se, but rather to the perceptual elements toward which subjects orient their attention. Lang et al.'s study shows that the presence of the visual feedback in the pursuit-tracking task is likely to prevent subjects from detecting regularities in the stimuli.

The purpose of the present paper is to identify elements in the structure of the stimuli (and not in the structure of the task itself) that could promote learning in the pursuit-tracking task. Our general idea is that learning a repeated pattern in the pursuit-tracking task depends on the possibility of detecting regularities in the material. To start with, we reasoned that SRT and pursuit-tracking tasks are structurally similar—the first is a discrete tracking and the second a continuous one. An important difference, however, is that the repeated pattern in SRT is usually continuously cycled, whereas it is surrounded by random patterns in the pursuit-tracking task. As SRT allows detection of the repetition, we hypothesized that the difficulty of learning in the continuous tracking task could be attributed, at least partially, to this masking structure. Therefore, we devised a pursuit-tracking task inspired by the SRT in which the repeated tracking pattern was cycled. More specifically, the stimuli were constructed respecting the principle described by Reed and Johnson (1994) as in numerous recent SRT experiments (e.g. Shanks, Rowland & Ranger, 2005). That is, all components of the stimuli sequences respected some associative and dependency rules (see below). The purpose of this choice was to facilitate the analysis of the data in regard to what would be learned in a well-controlled sequence. Secondly, the training phase was similar to the protocol of Shanks & Channon (2002; Experiment 1) with a unique sequence that was repeated eight times across 14 blocks except in the block 12 in which a test sequence was introduced. This procedure, compared to a masked repeated segment as carried out in Pew's paradigm, made it possible to analyze sequence characteristics in which the contingency orders were controlled.

Additionally, pursuit-tracking tasks involve keeping a cursor (visual feedback) on a target that moves continuously, usually in one dimension (e.g. horizontal). Reversal of the target movement in the opposite direction is crucial because it involves maximal inertia. In standard pursuit-tracking experiments, the duration between two reversals is variable, so that the time of the next reversal is not predictable. In comparison, the time of appearance of the next target in SRT tasks is usually predictable, because response-to-stimulus interval (RSI)—i.e. the time between subject's response and the appearance of the target at the next location—remains constant over a given block of trials. To our knowledge, no study has investigated this issue of intra-task time variability, either in SRT or in pursuit-tracking paradigms. We thus made a putative hypothesis according to which the variability of the target reversal time could prevent the learning of a repeated pattern in the pursuit-tracking task. In the present experiments, participants were thus presented with either variable (as in usual pursuit-tracking) or constant (novel condition) duration between two reversals.

Finally, participants performed a recognition test following the training phase in order to examine their explicit knowledge about the structure of the stimuli. In our view, the term *implicit* refers to incidental learning which is not incompatible with the constitution of explicit perceptual knowledge (Perruchet & Vinter, 2002). We expected that a detectable repeated pattern would favor explicit knowledge of the whole sequence or of substantial portions of the repeating sequence (Perruchet & Amorim, 1992) allowing specific improvement on the to-be-learned sequence.

Experiment 1

In this first experiment, participants performed a continuous pursuit-tracking task in which a repeated sequence was continuously cycled. The duration between two reversals was either constant (group CO) or variable (group VA). We expected that sequence learning would occur in the group CO but not in the group VA, because variable duration between two reversals usually fails to induce learning in the pursuit-tracking task.

Methods

Participants

Thirteen women and 15 men (mean age = 21.9 years, SD = 4.6 years) volunteered to participate in this experiment. All of them had normal or corrected-to-normal vision. None of the participants had prior experience with the task and they gave an informed consent before beginning the experiment. Overall, this research was conducted in accordance with the ethical guidelines of the American Psychological Association.

Apparatus

The apparatus consisted of an Intuos3 pen moving on a Wacom tablet that was superposed on the experimental board (see Fig. 1). The movements of the pen were sampled at 200 Hz by a Hewlett Packard Compaq 6910p computer. The target and the visual feedback (performers' pen position) were displayed on the computer screen (1,280 by 800 pixels), the target being a blue circle of diameter 50 pixels, and the visual feedback a red cross of dimension 9 by 9 pixels (3 pixels line width). Participants were comfortably seated in a chair in front of the vertical computer screen at a distance of about 50 cm. They were instructed to track the target by moving the stylus with the non-dominant hand to avoid transfer of writing skills. Before each block of trials, they had to place the stylus in the middle of the tablet (initial position) by aligning the visual feedback with a cross located in the middle of the computer screen. When the participant was ready, the experimenter manually triggered the block of trials which lead to replacing the cross with the target-to-track (blue circle).

Materials

The target moved horizontally and went back in the opposite direction after each reversal. As in other studies, the target displacement was slightly accelerated and decelerated between two successive reversals following a sinus profile. In addition, the target always started at the middle of the screen. Participants were trained in second-order conditionals (SOCs) sequences (Reed & Johnson, 1994). In SRT tasks, SOC sequences are those in which a given location can be predicted from the two previous locations (second-order dependency). In this experiment, the second-order conditional sequence concerned the mean velocity of the target displacement between two reversals. Therefore, a given velocity can be predicted from the velocity of the two previous displacements. Two 12-item SOC sequences were used in the practice phase: *A-B-A-C-D-B-C-A-D-C-B-D* (SOC1) and *A-B-C-D-A-C-B-A-D-B-D-C* (SOC2). *A*, *B*, *C* and *D* corresponded to four mean velocities with *A* = 183, *B* = 366, *C* = 549 and *D* = 731 pixels per second. In these two sequences (see Table 1), each item occurs three times and is preceded by each of the other items only one time (first-order transition frequency). Only the second-order conditional structure is different so that after two given items, the following item is different in SOC1 and SOC2. This structure of the stimuli is innovative in continuous pursuit-tracking and the timing parameter was thus chosen based on a working analogy with stimuli in SRT. As Perruchet, Chambaron & Ferrel-Chapus (2003) approximated the duration of a three-trial chunk in the usual SRT task at 2,250 ms, we considered that a mean duration of 700 ms for one item-movement would faithfully simulate typical timing features of SRT tasks. In the CO group, target displacement duration between two reversals remained constant and each reversal occurred 700 ms after the previous one. In the VA group, this duration varied and could be either 500, 700 or 900 ms (Table 1). The duration repartition was equated so that, in a given sequence, the target finishing location of the last item coincided with the departure location of the first item. In addition, each movement duration occurred four times and each velocity-duration combination occurred once, both in SOC1 and SOC2.

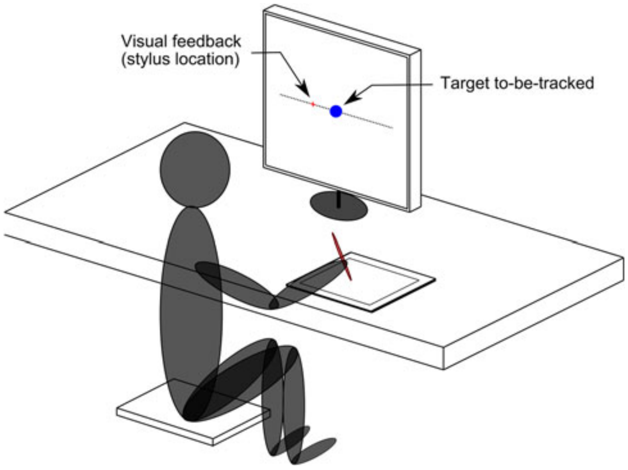

Fig. 1 Illustration of the experimental setup. Participant is seated in front of the screen and moves a stylus with the non-dominant hand (here the *right hand*) on a tablet

A set of patterns was constructed for the recognition test. This set was composed of: (i) the training SOC

Table 1 SOC1 and SOC2 sequences characteristics in constant (CO) and variable (VA) groups in Experiment 1

	Target velocity in CO and VA groups											
SOC1	*A*	*B*	*A*	*C*	*D*	*B*	*C*	*A*	*D*	*C*	*B*	*D*
SOC2	*A*	*B*	*C*	*D*	*A*	*C*	*B*	*A*	*D*	*B*	*D*	*C*
	Duration between two reversals (ms) in VA group											
SOC1	900	900	500	900	500	500	700	700	900	500	700	700
SOC2	900	900	700	700	500	500	700	700	500	500	900	900

Letters *A*, *B*, *C* and *D* (lines 2 and 3 in the table) refer to the increasing mean velocity of target. In the CO group, the duration between two reversals was 700 ms

sequence (SOC1 or SOC2 according to the training phase); (ii) three three-item chunks of the training SOC sequence, named chunk1 (*A-B-A* from SOC1 and *D-B-D* from SOC2), chunk2 (*C-B-D* from SOC1 and *C-B-A* from SOC2) and chunk3 (*D-B-C* from SOC1 and *A-B-C* from SOC2); (iii) a new SOC sequence different from SOC1 and SOC2, namely, *B-C-A-D-B-A-C-D-A-B-D-C*; (iv) three 3-item chunks of the new SOC sequence, *C-B-C* (chunk1), *A-B-D* (chunk2) and *D-B-A* (chunk3). For the VA group, this series of patterns was supplemented with: (v) the training SOC sequence in which the distribution of the duration values (500, 700 or 900 ms) was modified; (vi) three 3-item chunks of the modified SOC sequence in correspondence with the chunks described in (ii). The objective of these extra patterns was to evaluate whether the sequence learning was based exclusively on the target velocities or on the general spatio-temporal characteristics of the to-be-learned sequence.

Procedure

Participants were randomly assigned to one of the two groups that differed in terms of target reversal time predictability (constant or variable duration). Based on the procedure used by Shanks & Channon (2002; Experiment 1), the practice phase was composed of 14 blocks. In each block, a 12-item SOC sequence was repeated eight times constituting 96 primitive motions. The two SOC sequences were counterbalanced so that SOC1 was the training sequence and SOC2 the test sequence for half of the participants, and vice versa for the other half. During blocks 1–11, participants practiced on the training sequence. On block 12, they performed on the test sequence. On blocks 13–14, the training sequence was reintroduced. Importantly, participants were not informed about the repetition and the blocks composition. Between two blocks, a short break of about 10 s was administered. Following the practice phase, participants were given a recognition test. They were presented with the recognition patterns in a random order and had to indicate after each stimulus whether the target motion was familiar or not (yes/no).

Data analysis

The dependent measure was the root mean square error (RMSE) between the visual cursor and the target locations. RMSE was calculated throughout the whole duration of each block. The practice data were analyzed by the use of analysis of variance (ANOVAs). The recognition data were analyzed by the use of Chi-squared test (rate of correct answers on each recognition pattern vs. 50 %). Moreover, Bravais–Pearson correlation was calculated on each recognition pattern between performers' answers (1/0 if right/wrong) and the mean performance in practice in terms of RMSE. Significant correlation would indicate parallelism between motor performance and explicit perceptual knowledge. The alpha level was set at $p < .05$.

Results

Practice phase

Figure 2 presents the performance of the two groups (CO and VA) as a function of blocks. Data were analyzed in a Target Reversal Time Predictability (constant vs. variable) X Block (1–14) analysis of variance (ANOVA). As can be seen from Fig. 2, the two groups improved their performance over the blocks of practice. The significant main effect of block, $F(13, 338) = 37.10$, $p < .0001$, $\eta^2 = 0.59$, indicates that the participants became increasingly effective in the tracking task. Besides, this enhancement was identical in the two groups because the Target Reversal Time Predictability × Block interaction was not significant, $F(13, 338) = 0.86$, $p = .5936$. However, the CO group ($M = 75.6$, $SD = 10.7$) made less errors than the VA group ($M = 88.7$, $SD = 16.1$) as attested by the significant effect of the Target Reversal Time Predictability factor, $F(1, 26) = 8.47$, $p = .0073$, $\eta^2 = 0.25$. This result

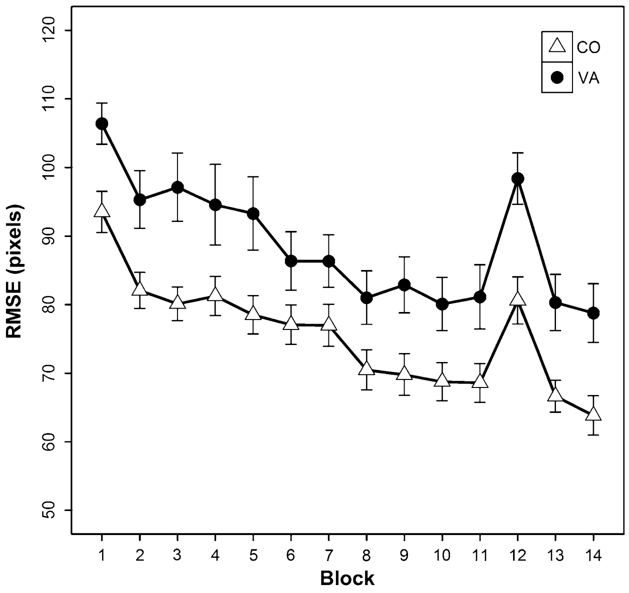

Fig. 2 Mean root mean square errors (RMSEs) on blocks 1–14 for the constant (CO) and variable (VA) groups in Experiment 1. The block 12 consisted in a test sequence. *Error bars* represent standard error

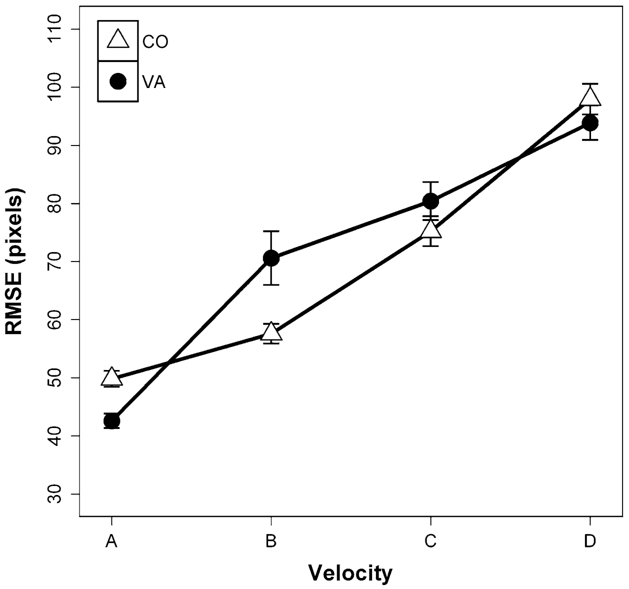

Fig. 3 Mean root mean square errors (RMSEs) on each velocity in the sequences for the constant (CO) and variable (VA) groups in Experiment 1. *Error bars* represent standard error

indicates that the task was more difficult with variable compared to constant time movement between two reversals.

On block 12, the test sequence was introduced. Sequence learning was evaluated by the use of a Target Reversal Time Predictability × Sequence (test sequence on block 12 vs. training sequence on the average of the RMSE of blocks 10–11–13–14) ANOVA. The main effect of Sequence was significant, $F(1, 26) = 83.23$, $p < .0001$, $\eta^2 = 0.76$ (see Fig. 2). The introduction of a new sequence induced increasing errors compared to the repeated sequence. Added to the absence of Target Reversal Time Predictability × Sequence interaction, $F(1, 26) = 1.77$, $p = .195$, these results indicated that both groups learned the training sequence.

These results were sufficient to claim that the participants learned some second-order dependency rules in SOC sequences. However, it remains unclear whether the performance was contingent on target velocity. A Target Reversal Time Predictability × Segment Velocity (*A*, *B*, *C* and *D* averaging on the 13 training blocks) ANOVA was applied on the data depicted on Fig. 3. This analysis indicates that a slower velocity resulted in a more accurate tracking, $F(3, 246) = 127.72$, $p < .0001$, $\eta^2 = 0.61$. However, the Target Reversal Time Predictability × Segment Velocity interaction was significant, $F(3, 246) = 6.07$, $p = .0005$, $\eta^2 = 0.07$. An inspection of the data (see Fig. 3) confirmed by paired comparison indicates that the performance was identical in both groups when the velocity was that of *C* [$F(1, 82) = 1.56$, $p = .2145$] and *D* [$F(1, 82) = 1.03$, $p = .312$], and that the performance of VA group was, respectively, lower or greater than those of CO group when the velocity was that of *B* [$F(1, 82) = 6.99$, $p = .0098$, $\eta^2 = 0.08$] and *A* [$F(1, 82) = 15.04, p = .0002, \eta^2 = 0.13$]. This interaction suggests that participants of VA group were at an advantage with the slowest velocity compared with those of CO group and that this advantage would probably increase with slower velocity.

Recognition test

Table 2 shows the number of correct answers (relative to the 7 subjects) in the recognition test in CO and VA groups as a function of the recognition patterns. A Chi-squared test was used to analyze these data by comparing the rate of correct answers on each recognition pattern versus 50 %, separately on each group. A significant Chi-squared would indicate that the answers were given at random.

As can be seen from Table 2, participants in the CO group were not able to identify these patterns above chance ($M = 52.7$ %, SD = 27.4 %; $\chi^2 = 132.3$, $p < .0001$, $df = 1$). This result seems to reveal that the training sequences learning in CO group was not essentially based on explicit perceptual knowledge. However, we compared the performance in the practice phase with the rate of correct answers on each chunk and on the sequence. A Bravais–Pearson test on these data indicated a significant correlation regarding the training sequence chunks, $r = -0.47$, $p = .0015$, but no correlation on the training sequence itself, $r = -0.02, p = .9362$. In consequence, the participants failed to identify the all recognition patterns

Table 2 Number of correct answers (out of 7) in the recognition test in Experiment 1

	CO		VA	
	SOC1	SOC2	SOC1	SOC2
TS	4	4	7	6
Chunk1-TS	1	5	7	4
Chunk2-TS	6	3	6	7
Chunk3-TS	7	0	7	6
NS	6	5	5	5
Chunk1-NS	2	4	1	1
Chunk2-NS	2	2	3	1
Chunk3-NS	4	4	7	7
MTS	–	–	4	3
Chunk1-MTS	–	–	4	6
Chunk2-MTS	–	–	5	2
Chunk3-MTS	–	–	4	2

TS training sequence, *NS* new sequence, *MTS* modified training sequence, *CO* constant group, *VA* variable group

above chance, but lower errors in practice were found on sequence components that were better recognized.

In the VA group, participants were not able to identify the overall recognition patterns above chance ($M = 65.5$ %, SD = 30.1 %; $\chi^2 = 176.5$, $p < .0001$, $df = 1$); however, they well recognized the training sequence and chunks ($M = 89.3$ %, SD = 14.8 %; $\chi^2 = 7.3$, $p = .4011$, $df = 1$). The correlation between the performance and the recognition answers was not significant regarding the chunks ($r = -0.10$, $p = .5375$), but it was significant concerning the whole sequence ($r = -0.68$, $p = .0216$). Overall, these results suggest that the learning of the training sequence in VA group was associated with explicit perceptual knowledge about the target motion.

Discussion

The purpose of this experiment was to evaluate sequence learning in a continuous tracking task and to test the effect of time movement variability. Generally, performances of the CO group were more accurate than those of VA group, indicating that lesser predictability of target reversal time increases tracking difficulty. The main finding here is the presence of sequence learning in a continuous pursuit-tracking task. In addition and contrary to our hypothesis, the participants of both groups did learn the training sequence, indicating that the repetitive structure (cycled vs. surrounded repeated pattern) does account for the absence of learning in tracking tasks but that variable target reversal time does not.

However, the mean velocity of the target in this first experiment (457 pix/s) as well as the associated mean target motion time (700 ms) did not match those generally used in pursuit-tracking experiments. In our previous study (Lang et al., 2011), we calculated a mean velocity lower than 400 pix/s. It has to be noted that Lang et al. used the same software as Chambaron et al. (2006) to generate their stimuli. In the studies of Wulf et al. (Shea et al., 2001; Wulf & Schmidt, 1997), detailed indications of amplitude and/or velocity are not available. However, Wulf & Schmidt (1997) utilized 16 segments in their first experiment for which we calculated a mean duration of 904 ms between two reversals, noting minimum and maximum durations of 692 and 1,222 ms (see Wulf & Schmidt, 1997; Fig. 1). So considered, we estimated that a mean velocity of 355 pix/s and an associated mean duration of 900 ms, with variation between 700 and 1,100 ms in VA group, would be fairly representative of the usual target features in the pursuit-tracking task.

Finally, the recognition test indicated a parallelism between sequence learning and explicit perceptual knowledge, because the CO participants better recognized the chunks on which they performed more accurately, whereas the participants of VA group recognized the learned sequence chunks almost without mistake. It is worth noting that tracking under the VA condition was more difficult than under the CO condition. These findings suggest that the learning required some explicit perceptual knowledge commensurate with the tracking difficulty.

Experiment 2

The Experiment 2 replicated the procedure and utilized the same materials as in the first experiment, except that the mean duration in both groups (CO and VA) was substituted for 900 ms, resulting in slower target displacements.

Methods

Participants

A further 15 men and 13 women (mean age = 22.3 years, SD = 3.6 years) volunteered to participate in this experiment. None of the participants had prior experience with the task. They had normal or corrected-to-normal vision and they gave informed consent before beginning the experiment.

Apparatus, materials, and procedure

The apparatus, the task and the procedure were the same as in Experiment 1. Likewise, the stimuli were strictly identical to those used in Experiment 1 except in terms of movement duration. The amplitudes of the target displacement were conserved so that only the velocities were slowed down. Thus, the velocity values of each sequence item in Experiment 2 were $A = 142$, $B = 284$, $C = 427$ and $D = 569$ pixels per second. In the CO group, the movement duration of each item was 900 ms in SOC1 and SOC2. In the VA group, the duration of each target displacement lasted 700, 900 or 1,100 ms respecting the distribution described in Table 1 (200 ms is to be added at each value in lines 5 and 6).

Results

Practice phase

The performances of the groups CO and VA are displayed on the Fig. 4. Participants in both groups reduced their errors in the course of practice. The significant main effect of block, $F(13, 338) = 30.22, p < .0001, \eta^2 = 0.54$, indicates that the participants became increasingly effective in the tracking task, and this improvement was identical in the two groups, $F(13, 338) = 1.27, p = .2306$. Additionally, the global performance were similar in the two groups, $F(1, 26) = 0.18$, $p = 6776$. Thus, the task was not more difficult with variable compared to constant target reversal time.

Concerning the sequence learning, the main effect of Sequence (block 12 vs. blocks 10–11–13–14) was significant, $F(1, 26) = 28.61$, $p < .0001$, $\eta^2 = 0.52$. However, the Target Reversal Time Predictability × Sequence interaction, $F(1, 26) = 7.43$, $p = .0113$, $\eta^2 = 0.22$, indicates that the introduction of the test sequence had a differential effect on the groups (see Fig. 4, block 12). In fact, the main effect of the sequence was significant in the CO group, $F(1, 13) = 31.69$, $p < .0001$, $\eta^2 = 0.71$, but it was not significant in the VA group, $F(1, 13) = 3.54$, $p = .0824$. Thereby, participants with constant target reversal time (CO group) clearly learned the training sequence, whereas those with variable target reversal time (VA group) were not able to take advantage of the repeated sequence.

To gain an insight into the inconsistent pattern for the VA groups in the two experiments, we analyzed the data for these two groups divided into epochs based on the three durations (see Table 1). As can be seen on Fig. 5, tracking errors were lower for longer duration, $F(2, 2908) = 442.93$, $p < .0001$, $\eta^2 = 0.23$. When considering only the two common durations in the two experiments (i.e. 700 and 900 ms), tracking errors were lower in Experiment 2, $F(1, 1454) = 171.25$, $p < .0001$, $\eta^2 = 0.11$; moreover, tracking errors were lower for 900- than 700-ms duration, $F(1, 1454) = 176.44$, $p < .0001$, $\eta^2 = 0.11$, and the interaction between this factor and the group (Experiment 1 vs. Experiment 2) was not significant, $F(1, 1454) = 0.00003$, $p = .9959$, $\eta^2 < .0001$. These results suggest that tracking is easier with longer duration, but that absence or inefficient learning in the VA group in Experiment 2 could not be attributed to this factor per se.

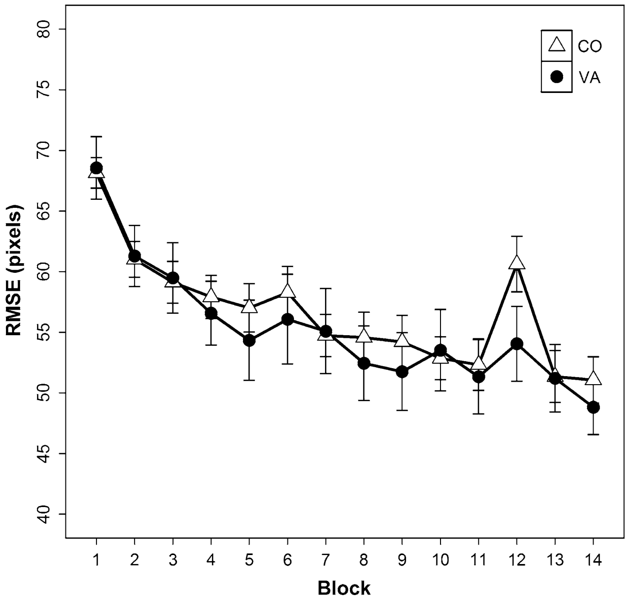

Fig. 4 Mean root mean square errors (RMSEs) on blocks 1–14 for the constant (CO) and variable (VA) groups in Experiment 2. The block 12 consisted in a test sequence. *Error bars* represent standard error

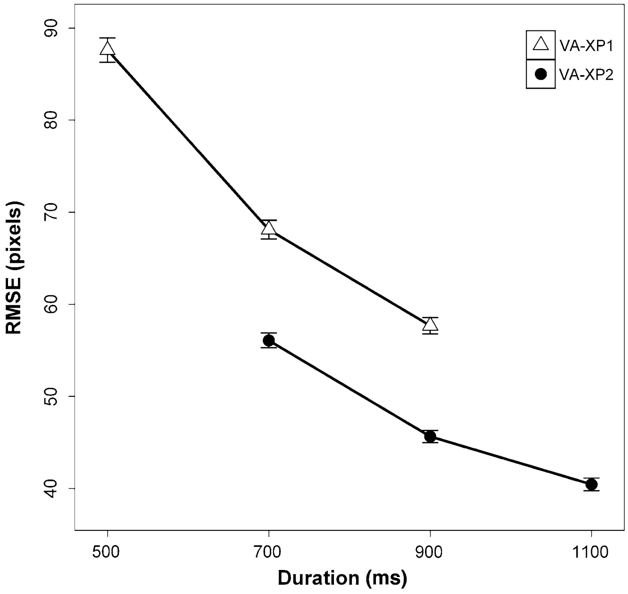

Fig. 5 Mean root mean square errors (RMSEs) on each duration epochs for the variable groups in Experiment 1 (VA-XP1) and Experiment 2 (VA-XP2). *Error bars* represent standard error

Table 3 Number of correct answers (out of 7) in the recognition test in Experiment 2

	CO		VA	
	SOC1	SOC2	SOC1	SOC2
TS	7	5	3	3
Chunk1-TS	6	4	4	5
Chunk2-TS	2	5	6	4
Chunk3-TS	2	6	5	4
NS	7	6	5	3
Chunk1-NS	2	0	2	1
Chunk2-NS	2	1	2	1
Chunk3-NS	5	3	4	5
MTS	–	–	5	3
Chunk1-MTS	–	–	2	6
Chunk2-MTS	–	–	6	2
Chunk3-MTS	–	–	3	4

TS training sequence, *NS* new sequence, *MTS* modified training sequence, *CO* constant group, *VA* variable group

Recognition test

Table 3 shows the number of correct answers (relative to the 7 subjects) in the recognition test in CO and VA groups.

The recognition results (Table 3) indicate that participants in the CO group were not able to identify these patterns above chance, $\chi^2 = 161.8$, $p < .0001$, $df = 1$. However, the numbers of correct answers on the whole sequences (training and new sequences) suggest that the participants were sensitive to some features of long-duration target motions. The correlation between performance in training and recognition answers was significant both on the chunks, $r = -0.40$, $p = .0085$, and on the training sequence, $r = 0.55$, $p = .0423$.

In the VA group, the Bravais–Pearson correlation was neither significant about chunks, $r = 0.16$, $p = .3207$, nor about sequence, $r = 0.27$, $p = .3453$. Overall, participants' answers did not differ from the chance level, $\chi^2 = 114.0$, $p < .0001$, $df = 1$. In consequence, the participants in the VA target reversal time condition neither learned the training sequences in terms of motor performance nor in terms of perceptual knowledge.

Discussion

The present findings are able to account for the setback observed in the implicit (motor) learning literature considering, on the one hand, the robustness of sequence learning in SRT task and, on the other hand, the difficulty of learning from repetition in tracking tasks (Chambaron et al., 2006). In Experiment 2, the duration between two successive reversals and the associated target velocity matched characteristics from Wulf & Schmidt (1997) and Lang et al. (2011). Thus, the situation in which duration varied (VA group) was closely related to the usual pursuit-tracking task conditions. The results of Experiment 2 demonstrated that the target reversal time factor (constant vs. variable) can affect sequence learning differentially because the performance when introducing a test sequence after the training period deteriorated in the CO group but not in the VA group. Consequently, the failures to obtain an implicit learning in the pursuit-tracking experiments (Chambaron et al. 2006; Lang et al. 2011) could also be attributed to a variable target reversal time combined with a relatively slow motion of the target.

General discussion

The present experiments were designed to promote detection of regularities and implicit learning in a continuous pursuit-tracking task. In this perspective, the to-be-learned repeated pattern was continuously cycled as is usually the case in the SRT tracking task. To our knowledge, this paper demonstrates for the first time sequence learning in a continuous pursuit-tracking task. Additionally, results from Experiment 1 are consistent with those from implicit learning in the SRT literature, as sequence learning concerned some second-order dependencies. Moreover, those results indicate a clear parallelism between sequence learning and explicit knowledge about perceptual features of some sequence components (Perruchet & Amorim, 1992). Together with the study of Lang et al. (2011), these findings show that failure in segment learning in continuous pursuit-tracking (Chambaron et al., 2006) cannot be attributed to the nature of this task in which motor components are predominant.

Following SRT stimuli's model that clearly enables subjects to detect and to learn sequence regularities, we tested the predictability effect of target initiation that is usually time-predictable in SRT but not in pursuit-tracking. To do this, target reversal time in our tracking task was either constant (group CO) or variable (group VA). Participants in the VA group within Experiment 2 (relatively slower target velocity), but not within Experiment 1 (relatively faster target velocity), were not able to take advantage of the repeated sequence. The task that was practiced by this group of participants is the most closely similar to the usual pursuit-tracking task in terms of both target velocity and reversal predictability. This result is in line with the studies of Chambaron et al. (2006) and Lang et al. (2011) that failed to induce repeated movement learning in a continuous tracking task.

Previous studies in the implicit motor learning area, which utilized the continuous tracking task, failed to induce learning of a repeated pattern (Chambaron et al. 2006; Lang et al. 2011) or induced changes in performance on a repeated segment that could not be attributed to segment learning (Shea et al. 2001; Wulf & Schmidt 1997). In fact, Chambaron et al. (2006) demonstrated that the presence of segment learning in Wulf and collaborators' studies (Shea et al., 2001; Wulf & Schmidt, 1997) was due, at least in part, to the use of a repeated segment that was probably easier to track than the other random segments. The present results show that, in all these implicit motor learning studies, learning was most probably impaired by stimuli characteristics that did not promote detection of the regularities.

In the following sections, we will briefly propose an attentional explanation and discuss the implicitness of learning in implicit learning tasks.

Tracking strategies and attention

Absence of, or at least inefficient sequence learning in the VA group in Experiment 2 results from the combination of relatively slow target velocity and a variable target reversal time, which does not allow the participants to know when the target reversal will occur. Because the reversal could substantially deteriorate the tracking performance (inertia is maximal and the target goes to the opposite direction instantaneously), participants have to pay attention to the moment of reversal. This watchfulness is likely to divert attention from the general pattern of the target motion. It is important to note that variable target reversal time did not impair sequence learning in Experiment 1 in which target velocity was relatively high. This could be interpreted in terms of mode of control and attentional strategies. In particular, a relatively slow velocity could lead the performers to reinforce the online control and thus to focus their attention on the corrective adjustments rather than on the general motion of the target. Experiment 1 indicates that the VA condition was more difficult than the CO condition. As sequence learning did not occur apparently in the VA group but did occur in the CO group in Experiment 2, it seems that unpredictability of time reversal motivated participants of the VA group to guide their performance essentially online. Such a feedback-based strategy was not prevalent in the first experiment because the target was probably too rapid.

This attentional perspective is consistent with the study of Lang et al. (2011) in which learning occurred only in a group where the visual feedback was removed, that is when performers were prevented from focussing their attention toward the corrective adjustments. However, the materials in Lang et al. (2011) and in the present study were not the same; further studies investigating the effects of attentional load and/or focus on implicit sequence learning would provide complementary data of importance. This attentional account is also in line with motor skill learning studies that provided good evidence of the importance of attentional focus (Wulf, 2007). In particular, it has been shown that a focus of attention directed toward the performer's movements is less effective than attentional focus directed to the effects of these movements (Wulf, Hoss, & Prinz, 1998; Wulf & Shea, 2004). The view here is that the more the performer is engaged in a tracking strategy encouraging continuous corrective adjustments, the more the attentional focus is directed toward these adjustments and thus diverted from the to-be-learned structure.

The implicitness of implicit learning

In the present study, participants performed a forced-choice recognition test during which they had to indicate their familiarity impression about target displacements. The presence of explicit perceptual knowledge was indicated by a practiced pattern that seemed familiar to them, or/and by a correlation between performance in training and answers in recognition.

Importantly, sequence learning when present was always associated with explicit perceptual knowledge. More specifically, participants in the CO group in Experiment 1 failed to recognize the learned sequence and chunks of this sequence above chance, but performances in the training phase were correlated with those in the recognition test. In contrast, participants in the VA group in Experiment 1 performed better than chance in the recognition test, but answers in this test and performance in practice were not correlated. It is, however, to be noted that this absence of correlation was most likely due to a ceiling effect because the recognition patterns from the learned sequence were almost perfectly recognized as having been performed. This result is interesting because this group performed the task condition that was the more difficult as indicated by the higher level of tracking error. We argue that challenging tracking promotes learning of perceptive regularities, at least when other compensatory strategies such as online control are prevented. Finally, results from the CO group in Experiment 2 indicate that performances in training and in recognition were correlated on both the chunks and the training sequence, and that the recognition answers were higher than the chance level.

Implicit learning was defined as learning that occurs without intentional attempts to acquire useful information about the to-be-learned structure (see Introduction). Owing to the incidental nature of the task, implicit sequence learning could be concluded for each group in Experiment 1 and for group CO in Experiment 2. However, subjects from the VA group (Experiment 1) and the CO group (Experiment 2) probably utilized their knowledge intentionally (i.e. explicitly), at least at the end of the training phase, because performances in the recognition test were higher than chance.

The question as to whether the term “implicit” has to be restricted to the incidental nature of the task, or to whether it can also be extended to the mode of utilization of the relevant knowledge, addresses a current debate in the implicit learning literature, namely the implicitness of the so-called implicit learning. On the one hand, some researchers distinguish between implicit and explicit learning processes (e.g. Berry & Broadbent, 1988; Cohen, Ivry, & Keele, 1990; Destrebecqz & Cleeremans, 2001). The “dissociation hypothesis” asserts that implicit learning can be unconscious, i.e. that learning can occur without attentional encoding. On the other hand, others claim that learning is based on a unitary explicit system, and thus reject the possibility that learning can be unconscious (e.g. Perruchet & Vinter, 2002; Shanks & St. John, 1994; Wilkinson & Shanks, 2004). In general, implicit learning is demonstrated through dissociation between learners’ performance during the training phase and their awareness of the learned structure in a subsequent test. The problem is that the absence of awareness about the learned information does not necessarily demonstrate that learning was not based on explicit knowledge, but merely that the information provided by the experimenter was related to other aspects of the learned structure (Perruchet et al., 2003; see Shanks & St. John, 1994). Recent studies have provided strong support for the need of attentional processing in any form of learning, suggesting that learning relies on explicit knowledge (see Perruchet, 2008; Perruchet & Vinter, 2002). Specifically, Perruchet & Amorim (1992) demonstrated that the specific changes in performance in Nissen and Bullemer’s SRT paradigm were correlated with explicit perceptual knowledge about the learned sequence. So considered, a unitary-process approach argues that the implicitness of implicit learning does not designate the absence of explicit knowledge, but rather concerns the unintentional acquisition of explicit knowledge about the learned structure. The present results lend credence to an attentional-based view in which explicit perceptual knowledge and sequence learning in a continuous pursuit-tracking task occur in parallel.

Finally, the implicitness of the learning in this study is consistent with the implicit learning literature (see Perruchet, 2008), but not with that on implicit *motor* learning. In particular, Wulf et al. (Shea et al., 2001; Wulf & Schmidt, 1997) concluded that the changes in performance observed in their studies were dissociated from explicit knowledge about the to-be-learned segment evaluated through post-experimental tests. In particular, Shea et al. (2001) demonstrated that when participants were instructed about the repetition, they performed worse than when they were not. This result seems to provide evidence for a dual-system theory of learning, in which the intervention of the explicit system can be detrimental to the learning which is efficiently regulated by implicit processes. Wilkinson & Shanks (2004) indicated that explicit instructions provided in Shea et al.’s (2001) study may have changed the focus of attention of the participants and thus diverted their attention from the useful information (see also Perruchet et al., 2003). Moreover, Perruchet et al. (2003) proposed that the post-experimental interview of Wulf et al. did not focus on the pattern regularities responsible for the performance improvement. The present data support these latter reinterpretations of the results in the implicit motor learning literature, because it provides evidence that attention is required in the incidental learning processes involved in a continuous pursuit-tracking task.

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