Validation of the Continuous Tracking Paradigm for Studying Implicit Motor Learning

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Abstract: A continuous pursuit-tracking task is the typical experimental paradigm to investigate implicit motor learning. Implicit motor learning is proven by a greater improvement in tracking of a repeated segment of a target path compared to random segments (Pew, 1974). Recently, doubts about the validity of results obtained with this paradigm have been raised. Improved tracking of a repeated segment might simply be due to the characteristics of that particular segment. In response to these doubts, we seek to improve the continuous tracking task. Therefore, we computed a pool of 37 distinct target segments. Participants (*N* = 36) practiced the tracking task, each one with a unique repeated segment in the middle and varying outer segments, all taken from the pool of segments. After five practice blocks of 36 trials each, a test block was performed where the repeated middle segment was replaced with a random segment. The tracking performance on the repeated segment was better than on random segments. Furthermore, we assume that learning was implicit, because participants' answers to a posttest interview showed they were largely unaware of a repeated segment within the curves.

Keywords: implicit motor learning, continuous tracking task, complexity control

For the last four decades, several researchers used the continuous tracking task paradigm invented by Pew (1974) to investigate implicit motor learning. However, lately the tracking paradigm has been under attack. Here we seek to resolve several issues that researchers have brought against it in order to provide a tested paradigm for implicit motor leaning. The basic principle of the continuous tracking task paradigm is that participants have to pursue a target with a cursor that is controlled by an input device. The target follows an invisible path that consists of three segments. The path of the target is generated by superposition of sine waves, which are defined by a set of parameters. While the first and the last segment of the path change from trial to trial, being defined by randomly chosen parameters, the middle segment is repeated throughout all practice sessions. Pew (1974) was the first to report that participants improved their tracking performance in the course of the experiment, and that the improvement in the middle repeated segment was larger than in the outer random segments. Moreover, in his experiments the vast majority of participants did not become aware of the fact that the middle segment was identical over all trials, therefore indicating the implicitness of the learning process.

Pew's tracking paradigm has inspired many researchers to investigate implicit motor learning in different contexts. They used it to test whether learning hypotheses for explicit learning are also valid for implicit learning (Neilson, O'Dwyer, & Neilson, 1988; Sekiya, 2006; Shea, Wulf, Whitacre, & Park, 2001; Wulf & Schmidt, 1997), to test the capability of implicit learning for different age groups (Kramer, Larish, Weber, & Bardell, 1999) and people suffering from stroke or other diseases (Siengsukon & Boyd, 2008; Vidoni & Boyd, 2008, 2009; Vidoni, McCarley, Edwards, & Boyd, 2009), or to investigate the influence of contextual cues (Raab, de Oliveira, Schorer, & Hegele, 2013). Even the tracking capability of monkeys was tested (Brooks, Reed, & Eastman, 1978).

However, recently some researchers have raised serious doubts on the reliability of the paradigm. Chambaron, Ginhac, Ferrel-Chapus, and Perruchet (2006) replicated the experiments conducted by Wulf and Schmidt (1997). They were only able to find superior learning of the repeated segment when using the exact same parameters for the target path as Wulf and Schmidt (1997). However, when using other parameters, they failed to replicate the results. They presumed that the repeated segment in the Wulf and Schmidt (1997) experiment might be easier than the randomly generated segments. They cautiously concluded that implicit motor learning in a continuous tracking task is more difficult to establish than in a serial-reaction time task, which is considered to be a standard procedure to demonstrate implicit learning (e.g., Nissen & Bullemer, 1987).

Lang, Gapenne, and Rovira (2011) assumed that the lack of implicit learning might be due to the detrimental effect of the concurrent feedback provided by the target in the continuous tracking task. However, participants with feedback performed better than participants who produced the track without a concurrently visible target. As in Chambaron et al. (2006), they did not observe implicit learning in the pursuit-tracking condition, but could identify an improvement in the repeated segment in the production task without concurrent feedback. In contrast to the results of Chambaron et al. (2006) and Lang et al. (2011), in Zhu et al. (2014) participants performed a retention test. By this, they were able to demonstrate implicit motor learning of the middle, repeated segment. Moreover, they demonstrated a "time-on-task" effect and showed that participants performed better on the first segment, followed by the second and the third. They also tested different target paths with respect to mean speed and acceleration. In their discussion, they recommended to use different repeated segments, to control for segment differences in mean speed and acceleration, and to allow for consolidation. Furthermore, Zhu et al. (2014) recommended observing the time-on-task effect by averaging the tracking error of the first and the third (both random) segment and comparing this error to the error of the middle (constant) segment. For this reason, we kept only the middle segment constant.

The purpose of our experiment is to correct limitations of Pew's paradigm in order to exclude any effects of tracking path characteristics. Therefore, we assigned the segments of the tracking paths to the participants in such a way that on average over the participants each segment was practiced equally often. We also kept the middle segment constant during exercise. However, to analyze if implicit knowledge is bound to the position of the segment we presented the constant segment also as the first and the last segment in the test block. Additionally, we manipulated the speed of the target. Researchers have used different speeds in their tracking experiments beforehand. For instance, Lang et al. (2011) used much slower speeds than Chambaron et al. (2006). Target speed is clearly related to tracking difficulty. We analyzed if the pursuit-tracking task could be learned implicitly independent of the target speed or if there might arise interactions, such as floor or ceiling effects. Furthermore, we followed most of the recommendations suggested by Zhu et al. (2014).

Methods

Participants

Thirty-six right-handed students from the local university (M_{age} = 20.55 years, *SD* = 2.44, 19 male and 17 female) participated in the study. All of them had normal or corrected-to-normal vision, and none had prior experience with the task nor were they informed about the purpose of the experiment. All participants signed an informed consent form and received course credit for participation. Ethics approval for the procedures was obtained from the university's Ethics Committee.

Apparatus

Participants sat in front of a 22″ Fujitsu B22 W computer monitor (Fujitsu, China) with a resolution of 1,920 × 1,080 pixels and a viewing distance of about 65 cm. A C++ program computed the target paths and recorded the positions of the cursor. The target was a red square of 19 × 22 pixels and the cursor was a white crosshair of 1 pixel width and an extension of 19 × 22 pixels. The background was black. Participants controlled the cursor with a joystick (Dark Tornado Speed Link). Participants were only able to control the vertical movement of the cursor. The horizontal movement was synchronized with the target. To begin a trial, participants had to position the cursor over the target, which started at the middle of the left edge of the monitor, and then press a button on the joystick. Participants got feedback on their accumulated performance after every fifth trial. The average root mean square error (RMSE) over the last five trials was displayed on the monitor.

Stimuli

For computing the target segments we used the same formula as in Wulf and Schmidt (1997, p. 990).

$$f(x) = b_0 + \sum_{i=1}^{6} a_i \sin(i \cdot x) + b_i \cos(i \cdot x) \qquad (1)$$

with the coefficients $a_1 \ldots a_6$ and $b_0 \ldots b_6$ randomly selected within a range of −5 to +5 using a flat distribution. In this manner, we computed 1,000 target segments and sorted the segments by their length. For our experiment, we chose the 37 segments with a medium length, that is ranks 482 to 518, ranging from 138.01 arbitrary units for the shortest to 140.34 arbitrary units for the longest path. All segments were scaled with the same factor to assure that the complete horizontal range of the monitor was used, but no segment reached further than the edge of the monitor. The segments were numbered from S_1 to S_{37}. Each segment stretched over 545 pixels horizontally. In the gap between the segments, the target path was computed by a cubic spline function that guaranteed smooth transitions between the segments. The transition width was 73 pixels. In addition, a cubic spline function was used to connect the first

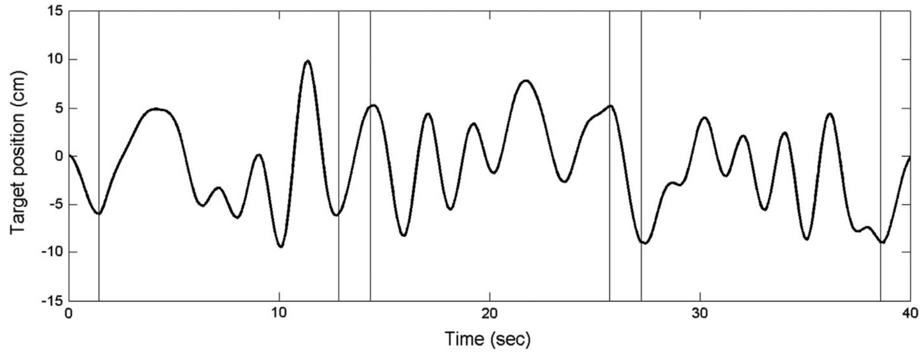

Figure 1. An example of a waveform used in the experiment in the middle speed condition (~40 s). The waveform gives the *y*-position of the target as it moves from the left to the right side of screen. The four smaller areas demarcated by the vertical bars are interpolated parts of the waveform that ensure smooth transitions between the three segments and equal starting and end positions of the target. The middle segment was always the same whereas the first and third were random.

segment with the starting point at the middle of the left edge of the monitor (width = 73 pixels) and to connect the last segment to the ending point, centered in the right edge of the monitor (width = 65 pixels), see Figure 1. Contrary to the above-mentioned experiments, in our experiment the target followed the path at constant speed. This prevents differences in mean speed and acceleration, as suggested by Zhu et al. (2014).

Procedure

In contrast to studies with a smaller amount of practice by Chambaron et al. (2006) and Zhu et al. (2014), we chose to adopt similar procedures as in Wulf and Schmidt (1997) and Lang et al. (2013), who used more practice trials. Participants executed six blocks on 3 days over 3 weeks, two blocks each day and had 1 week between each practice day. Each block consisted of 36 trials. Blocks 1–5 were practice blocks and block 6 was a test block. There was a short break of 5 min between each block.

Concerning the practice blocks, we arranged the segments that for each participant P_i, the segment S_i repeatedly occurred in the middle of the tracking path. The first segment started with segment S_{i+1}, followed in the next trial by the next segment in line, while S_{37} was followed by S_1. The last segment started with $S_{i+18 \bmod 37}$ and was followed in the next trial by the next segment in line. For every P_i, the segment S_i was never used as an outer segment, instead S_{i-1} was followed by S_{i+1} in the next trial. Thus, every segment S_i was used as a repeated segment for participant P_i and twice as a random segment for all other participants $P_{n \neq i}$, where the order of appearance within a block was evenly distributed over the participants. Therefore, the RMSE for the first, the middle, and the last segment of each block contain data of the same number of identical segments. This procedure ensures path characteristics as differences in tracking difficulty average out over all participants.

In the test block, the first 10 trials were identical to the practice blocks [middle (1) in Figure 3]. In trials 11–15, we also changed the middle segment randomly. Here the segments S_{i+1} to $S_{i+5 \bmod 37}$ were used. In trials 16–20, the repeated segment S_i was always the first segment, followed by two random segments. In trials 21–25, the segment S_i was always the last segment. Trials 26–36 were again identical to the practice block [middle (2) in Figure 3].

After the participants finished the test block, they were asked seven questions about their explicit knowledge of the structure of the target path, with each question asked being more specific.

The questions were (translated from German):

1. Did you notice anything special during the experiment?
2. Was there something that supported or hindered you while performing the tracking?
3. Did you apply any rules?
4. Did you notice anything special concerning the path of the target?
5. The target followed a certain path. Did you notice any segment in this path?
6. There have been three segments in that path, the first, the middle, and at the last segment. One of these segments was always repeated. Did you notice that?
7. Which segment was the repeated segment? The first, the middle, or the last segment?

Participants were randomly assigned to one of three groups, which differed in the target speed. In the slow condition, the target needed about 50 s to complete the whole path, in the medium condition about 40 s, and in the fast condition about 30 s. These speeds were chosen

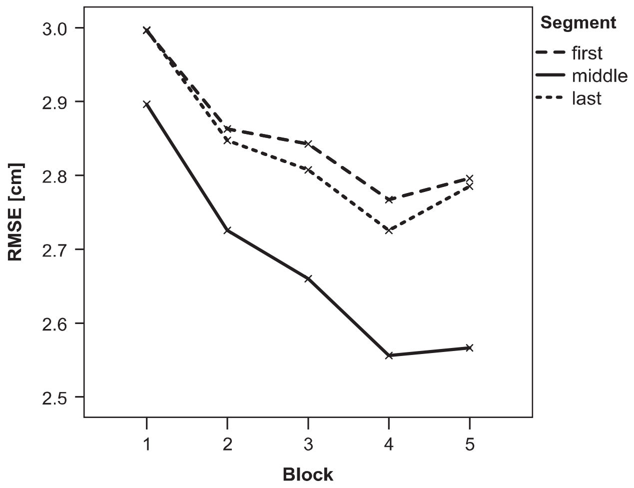

Figure 2. Tracking performance over the course of the five practice blocks. The middle segment is repeated in all five blocks, while the first and the last segment vary randomly. Error bars of the variation between the participants were not shown because they are misleading in a within participant design.

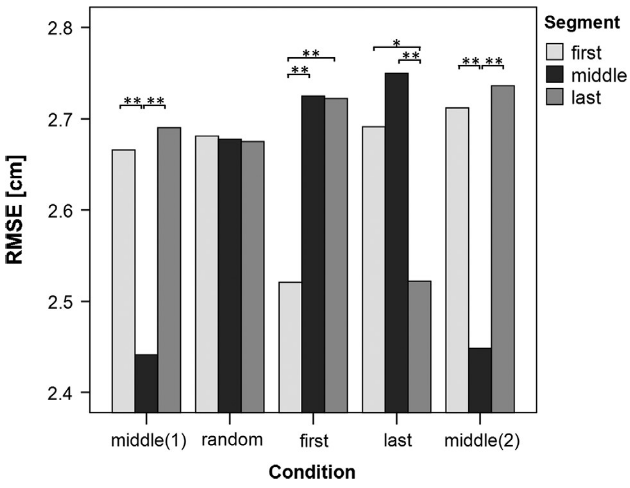

Figure 3. Means of the RMSE in the test block. The *x*-axis denotes which segment contains the repeated segment, in the random condition all segments were chosen at random. All participants completed all trials in the order specified here, beginning [middle (1)] and ending [middle (2)] with the repeated segment in the middle. Two asterisks indicate a highly significant difference ($p < .01$) between the respective segments.

after pilot studies revealed that trials faster than 30 s are possibly too hard and trials longer than 50 s are too easy. Due to the slightly different lengths of the paths and the constant path speed, the times for the paths could differ maximally by 12% from each other within each speed condition.

Statistical Analysis

We recorded the root mean square error (RMSE) for each segment and each trial. As a measure of the central tendency of the performance, we used the median of all 36 trials of the respective segments in one practice block. The median was used because the mean is more sensitive to outliers, which longer tracking experiments are prone to and which are not necessarily indicative of performance. We hypothesize that differences in performance depend primarily on the amount of practice and the constancy of the target path. Moreover, we expected an interaction between the factors block and segment, as the learning of the middle segment should be facilitated. We do not expect the difference between the segments nor differences between the learning rates of the different segments to depend on the speed of the target. Consequently, we analyzed the mean differences of the RMSE by a $5 \times 3 \times 3$ ANOVA with the within-subject factor block (practice block 1–5), the within-subject factor segment (first, middle, last) and the between-subject factor speed (slow, medium, fast). In the test block, we hypothesize a better performance of the repeated segment compared to the random segments, independent of the position of the repeated segment. In the test condition with three random segments, we do not expect any differences between the performance measures between the segments. We analyzed the mean differences of the RMSE in each test block condition separately by a one-way ANOVA with the within-subject factor segment (first, middle, last). Where Mauchley's test reveals that the sphericity assumption has been violated we applied Greenhouse-Geisser's correction of the degrees of freedom. To analyze the influence of the position of the constant segment in the test block, we computed a one-way ANOVA with the within-subject factor condition [middle (1), first, last, middle (2)] over the tracking performance of the constant segments within the four conditions. Moreover, we were interested in the development of the RMSE within the constant segments. As there is no clear-cut signal indicating the beginning of the constant segment, we assume that participants implicitly "groove in" the spatiotemporal pattern of the constant segment. To verify this assumption, we divided all constant segments in the test block into four quartiles of equal lengths. As the "grooving-in" process could be influenced by the position of the constant segment, we analyzed the RMSE separately for each of these quartiles in dependence on the position by computing a two-way ANOVA with the within-subject factors position (practiced, not practiced) and quartile (1st, 2nd, 3rd, and 4th quartile). For all statistical analyses Cronbach's α was set at 0.05.

Two independent raters judged participants' answers to seven questions to record conscious awareness. If the answers to question 1–5 did not contain any information about the discovery of a repeated segment, it was rated with zero points, one point if there was information that could be interpreted as an explicit knowledge and two points if there was evidence of some explicit knowledge of the repeated structure of the tracking path. Questions 6 and 7 were rated with two points (hint of explicit knowledge) if participants gave the correct answer, one point for a correct answer to question 6 if it conflicted with question 7 and zero points in all other cases (no explicit knowledge). All points were summed up. The sum and the answer to question 7 were correlated with the tracking performance of the repeated middle segment in the test block. We hypothesize that there was no correlation between the tracking performance of the repeated segment and the points attained in answering the questions, and therefore, indicating that even if there would be an explicit knowledge of the repeated middle segment it does at least not lead to a relevant change in tracking performance.

Results

We asked whether the enhanced tracking paradigm could measure implicit motor learning. This was confirmed through learning improvements in the middle segment, see Figure 2. The tracking performance changed significantly over the blocks, $F(3.27, 107.99) = 25.41$, $p < .001$, $\eta^2_p = .44$, and differed between the segments, $F(1.31, 43.09) = 32.41$, $p < .001$, $\eta^2_p = .49$, and different target speeds, $F(2, 33) = 205.22$, $p < .0005$, $\eta^2_p = .93$. Moreover, we observed a significant Block × Segment interaction, $F(4.30, 141.94) = 4.53$, $p = .001$, $\eta^2_p = .121$. The interactions between Speed × Block, $F(6.54, 107.99) = 3.67$, $p = .002$, $\eta^2_p = .182$ and Speed × Segment, $F(2.61, 43.09) = 6.10$, $p < .001$, $\eta^2_{part} = .270$, were also significant, while the three-way interaction Block × Segment × Speed is not significant, $F < 1$.

The inspection of the data revealed that there was a significant difference between the segments already in the first block, $F(1.37, 48.19) = 6.60$, $p = .002$, $\eta^2_p = .159$. In order to find out if participants perform better in the middle segment at the very beginning of the test, we divided the first block into six sections of six trials each and analysed the differences in tracking performance between these sections. In sections 1, 2, and 4 differences between the segments were not significant. In section 3, the middle segment was tracked significantly more accurate than the last segment (mean difference $D = .15$ cm, standard error $SE = .056$ cm, $p = .027$). In section 5, both the first and the middle segment were tracked better than the last segment (first to last segment: $D = .15$ cm, $SE = .051$ cm, $p = .015$; middle to last segment: $D = .145$ cm, $SE = .049$ cm, $p = .017$). In section 6, despite an overall significance between the segments, we could not find significant differences in pairwise comparisons (first and middle segment: $D = .96$ cm, $SE = .039$ cm, $p = .061$; middle and last segment: $D = .92$ cm, $SE = .48$ cm, $p = .191$). Note that within the sections the level of the tracking difficulty was not balanced, so differences in tracking difficulty might confound the results.

Table 1. RMSE scores in centimeters and confidence intervals of the trials in the test block with the repeating segment in the middle

Group	Segment	Mean	95% CI
Slow	Random	1.72	1.59–1.86
	Repeated	1.65	1.53–1.77
	Random	1.79	1.66–1.91
Medium	Random	2.66	2.52–2.79
	Repeated	2.28	2.16–2.40
	Random	2.70	2.57–2.82
Fast	Random	3.69	3.56–3.83
	Repeated	3.41	3.29–3.53
	Random	3.66	3.54–3.79

In the test block, the repeated segments were pursued more accurately than the random segments, independent of the order of the segments. The RMSE in the different test conditions are displayed in Figure 3.

All constant segments in the test blocks were divided into four quartiles. The mean RMSEs were 2.70 cm ($SD = 0.97$ cm), 2.45 cm (1.01 cm), 2.31 cm (0.84 cm), and 2.38 cm (0.77 cm) for the 1st to the 4th quartile, respectively. These differences are significant, $F(2.28, 80.0) = 4.96$, $p = .007$, with a medium effect size, $\eta^2_p = .124$. Pairwise comparisons reveal significant differences between the first and the 3rd and 4th quartile. There was no difference in the development of the RMSE of the constant segment over the quartiles between the previously practiced condition (constant segment in the middle) and the previously not practiced condition (constant segment first or last), $F(2.54, 88.70) = 1.13$, $p = .34$, $\eta^2_p = .031$.

In all five test conditions, there were highly significant differences in the speed condition. Moreover, in the first and the last test condition, which are equal to the practice condition, there was a significant Speed × Segment interaction. Post hoc analyses revealed that there were no significant differences between the three segments in the slow condition, whereas the means of the repeated segment of both the medium and fast condition fell out of the confidence intervals of the random segments (Table 1).

Concerning the analysis of the interviews, Cohen's κ for inter-rater reliability between the two raters for all questions was calculated. There was excellent agreement, $\kappa = 0.953$ (95% CI, 0.912–0.994), $p < 0.0005$. No participant gave an answer that was a clear indication of explicit knowledge to any of the first five questions about features of the tracking path (Table 2). Note that 21 participants

Table 2. Number of answers in the different categories

	No hint of explicit knowledge	Unclear hint of explicit knowledge	Clear hint of explicit knowledge
Question 1	33	3	0
Question 2	36	0	0
Question 3	32	4	0
Question 4	22	14	0
Question 5	28	8	0
Question 6	29	0	7
Question 7	15	0	21

named the middle segment in the forced choice question 7, thereof six out of the seven participants who claimed to have noticed a repeated segment (question 6). In total, participants attained 0–6 points out of 14 possible points, with a mean of 2.30 points (SD = 1.75). The correlation between the performance in repeated middle segments of the test block and the total points is $r = -.058$, $p = .737$, the correlation between the points in question 7, and the performance in the test block is $-.018$, $p = .916$.

In summary, the results indicate that the repeated middle segment was learnt easier than the changing outer segments without any awareness of the repetition of the segment.

Discussion

The aim of the study was to validate the pursuit-tracking paradigm in order to investigate implicit motor learning independently of special features of the tracking path. The results indicate that we were able to demonstrate implicit motor learning: we found a clear difference in the development of the tracking performance between the repeated middle segment and the outer random segments. This is evident in all five practice blocks and proven in the test block. Moreover, the interaction between block and segment indicates that the learning of the repeated segment is facilitated. The strict experimental design ensures that characteristics of the target path cannot influence this result. Therefore, it can be stated that the pursuit of a repeated segment leads to improved performance compared to the pursuit of random segments.

Wulf and Schmidt (1997) have shown that a repeating segment can be learned regardless of its position within the tracking path. Surprisingly there seems to be a lack of studies that test whether performance on the repeated segment is still better than that on a random segment when the repeated segment is presented on a different position than the position it was practiced with. The current study demonstrates that performance on the repeated segment is better regardless of its position. This is strong evidence that an abstract spatio-temporal structure of the track was learned independently from the position on the monitor. In implicit serial sequence learning, Schuck, Gaschler, Keisler, and Frensch (2012) have shown that the temporal structure can be represented in two forms: as a chain of sequences or as an ordinal position coding. Our results are in line with a sequential chaining model, as the tracking errors decrease significantly independent of the position of the constantly practiced segment. Additionally, we could not find that participants discovered the spatio-temporal structure later in the unfamiliar positions. Nevertheless, there is a noticeable, close to significant difference between the RMSE of the constant segments in the practiced and the unfamiliar conditions (Figure 3, middle (1) and middle (2) vs. first and last). This result might suggest an additional influence of positional coding, even if it might as well be a random effect.

By dividing the constant segments in four quartiles we could demonstrate that the "grooving-in" into the spatio-temporal structure of the constant segment needs some time. While the RMSE of the first quartile of the constant segment equals more or less the RMSE in the random segments, it rapidly decreases in the second quartile until it reaches the best performance in the third quartile.

Though we could clearly demonstrate implicit motor learning, we also showed that it's prove is susceptible to the target speed. In the test block, participants of the slow conditions group did not show a significant improvement in the tracking performance of the middle segment compared to the outer segments. As the target speed is clearly related to the level of the tracking difficulty, there seems to be a ceiling effect in pursuit tracking. This might cause the lack of proof of implicit motor learning in the Lang et al. (2011) experiments. They carried out their experiments on a laptop with a 14.1″ monitor, which corresponds to a screen width of approximately 30 cm and a height of approximately 19 cm. Their target moved 30 cm from left to right in 36 s with a speed of 8.33 mm/s in the horizontal direction. In the slow condition of our experiment the target moved 47.4 cm from left to right in approximately 50 s with an average speed of 9.48 mm/s in horizontal direction. Chambaron et al. (2006) investigated pursuit tracking at speeds similar to the medium and fast condition in the current experiment. They did not find evidence of implicit motor learning in either condition but they only used 12 and 24 trials for the medium and fast condition, respectively. This might be insufficient for any effect of practice to occur. Furthermore, in the study by Chambaron et al. (2006) participants performed only a single practice session. Zhu et al. (2014) did not find a learning effect within the first practice phase either. Learning of the repeating segment was shown by a retention test on a second day, in line with the hypothesis that sleep consolidates motor learning (e.g., Bapi, Doya, & Harner, 2000). An alternative explanation for the lack of a training effect in the current study may lie in the way learning was evaluated. It might be the case that learning did occur but that the *expression* of knowledge was suffering from a ceiling effect, and that learning effects would have been found if we had used a faster speed in the test block (Frensch, Lin, & Buchner, 1998).

Another important issue in implicit learning studies is in determining how far implicit knowledge is really implicit. In the present study, we found no correlation between correctly identifying the repeating middle segment (forced-choice) and the tracking performance. If one assumes that tracking performance with explicit knowledge is superior to tracking performance with implicit knowledge, the zero-correlation would indicate that participants only guessed when specifying the repeated segment. However, this assumption may not be right. It might well be that performance with explicit knowledge is even or inferior to performance with implicit knowledge. Possibly some participants acquired both implicit and explicit knowledge. If the implicit knowledge leads to superior performance than explicit knowledge, then additional explicit knowledge would not lead to a relevant performance improvement, which in turn would lead to a zero correlation between performance and explicit knowledge.

The current study provides evidence that the tracking paradigm is a reliable method to demonstrate implicit learning. Future research could use this paradigm to further investigate implicit learning, for instance the use of brain activity measurements and dual tasks in order to elucidate the role of attention and awareness during learning.

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Electronic Supplementary Materials

The electronic supplementary material is available with the online version of the article at http://dx.doi.org/10.1027/1618-3169/a000343

ESM 1. Questionnaires (PDF).
Completed questionnaires from the participants of the study.

ESM 2. Data (sav).
SPSS data file blockwise.
ESM 3. Data (sav).
SPSS data file testblock quartiles.
ESM 4. Data (spv).
SPSS output file blockwise analysis.
ESM 5. Data (spv).
SPSS output file quartile analysis.

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