Psychological Research (2022) 86:1426–1441
https://doi.org/10.1007/s00426-021-01586-3

ORIGINAL ARTICLE

The benefit of assessing implicit sequence learning in pianists with an eye-tracked serial reaction time task

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Received: 25 October 2020 / Accepted: 23 August 2021 / Published online: 1 September 2021

Abstract
Playing piano professionally has been shown to benefit implicit motor sequence learning. The aim of the current study was to determine whether this advantage reflects generally enhanced implicit sequence learning unrelated to pianists' higher motor and/or visual-motor coordination abilities. We examined implicit sequence learning using the ocular serial reaction time (O-SRT) task, a manual-free eye-tracked version of the standard SRT, in 29 pianists and 31 controls. Reaction times (RT) and correct anticipations (CA) of several phases describing implicit sequence learning were analyzed. Furthermore, explicit sequence knowledge was compared between the groups, and relationships between implicit sequence learning with explicit sequence knowledge or demographic measures were evaluated. Pianists demonstrated superiority in all critical phases of implicit sequence learning (RT and CA). Moreover, pianists acquired higher explicit sequence knowledge, and only in pianists was explicit sequence knowledge related to implicit sequence learning. Our results demonstrate that pianists' superiority in implicit sequence learning is due to a higher general implicit sequence learning ability. Hence, we can exclude that higher motor and/or visual-motor coordination abilities are related to pianists' higher implicit sequence learning. Furthermore, the significant relationship of implicit sequence learning and explicit sequence knowledge suggests that pianists either used explicit strategies to support implicit sequence learning, had better explicit access to sequence knowledge, or both.

Introduction

Musical expertise such as playing piano professionally has been demonstrated to have a beneficial effect on nonmusical cognitive abilities (for reviews, see Rodrigues et al., 2010; Sittiprapaporn, 2012) including explicit (Talamini et al., 2017) and implicit memory processes (Landau & D'Esposito, 2006; Romano Bergstrom et al., 2012). The advantage in explicit memory abilities (i.e., when assessed with short-term or working memory tasks) as revealed through a meta-analysis was most pronounced in domain-specific tasks, such as when musical stimuli were involved (Talamini et al., 2017). This paper addresses the question of whether pianists' superiority in implicit memory is related specifically to their domain of expertise or rather depicts a general superiority, and whether their implicit memory is influenced by explicit strategies and/or demographic variables of musicianship.

Playing piano professionally is a skill that places great demand on the human brain. It requires the execution of fast and accurate movements under consistent auditory feedback (Altenmüller, 2003), which is also neuronally reflected in information exchange of secondary auditory and motor brain regions (Baumann et al., 2007). The coordination of motor movements is tremendously complex as they are required to occur with great spatio-temporal precision (Dalla Bella & Palmer, 2011). To acquire and develop this skill, extensive training is needed, usually from a young age. Most pianists are skilled in musical sight-reading, which includes reading notes and translating this symbolic visual information into highly coordinated movement actions at a given tempo (Kopiez & Lee, 2008; Wurtz et al., 2009). In professional pianists, sight-reading skills come into play particularly when studying a new piece of music. A pianist will usually first read the entire piece to get a global impression, and then start with intensive practice of sections and eventually the entire piece (Lehmann et al., 2018). Prior to performance before an audience, pianists are required to memorize a musical composition, which depends on the successful integration

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of both their implicit and explicit memory functions. While practicing a new piece, a pianist implicitly learns to associate chains of passages (Lisboa et al., 2014). However, it is also essential to memorize the piece explicitly (Globerson & Nelken, 2013), because if execution of the chains is accidentally interrupted during a performance, only explicit memory strategies would allow the professional pianist to continue playing without the audience noticing the mistake. Professional pianists develop "a mental map of the piece that allows them to keep track of where they are as the performance unfolds" (Chaffin et al., 2009, p. 353).

Procedural learning, a form of implicit memory processes, describes the kind of learning that occurs when an individual generates internal knowledge of the structure of repetitions. Such repetitions may be in the form of motor actions, perceptual procedures, or cognitive procedures (Vakil & Hoffman, 2004). Procedures have been presumed primarily to be learned implicitly, even if this kind of learning may be supported with explicit awareness (Clegg et al., 1998; Reber, 1993). The question of how and when implicitly acquired knowledge becomes explicit is still under debate (Esser & Haider, 2017). Procedures are often sequential and their implicit learning has been typically referred to as implicit sequence learning, commonly assessed with the Serial Reaction Time (SRT) task (Nissen & Bullemer, 1987). In this task, participants are presented with targets (e.g., symbols such as dots) which subsequently illuminate in different locations (e.g., usually four squares arranged horizontally) on the screen. The targets appear in a given sequence which is repeated several times within a learning block. Participants are asked to press a target-corresponding key as soon as they see the target. A commonly used SRT paradigm is composed of several learning blocks followed by a block containing a different sequence, and terminated with one or more blocks displaying the original sequence again (Medimorec et al., 2019; Shanks & Johnstone, 1999; Vakil et al., 2017). Importantly, participants are not informed that illumination of the targets occurs according to a given sequence. Due to repeated exposure to the original sequence, reaction time (RT) typically decreases gradually from the first to the last learning block (learning effect), increases when the block containing the different sequence is introduced (interference effect), and decreases when the original sequence is displayed again (recovery effect).

Only a few studies have used the SRT to examine pianists or other musicians. For example, Landau and D'Esposito (2006) tested a small group of pianists and controls executing a modified version of the SRT during an fMRI scan session. Instead of the four locations typically used in this task, this version displayed eight locations arranged horizontally, so that each location corresponded to one of the four fingers of both hands (except for thumbs). Furthermore, the nature of the sequence was not deterministic but probabilistic, i.e., generated by a given grammar. In addition, trial sessions were composed of random and sequence trials. Both pianists and controls showed a decrease in RTs, but pianists expressed better implicit sequence learning at the beginning and performed faster than controls. All participants expressed a minimal awareness of the sequential regularities, but were not able to reproduce the sequence. Similar findings were obtained by Romano Bergstrom et al. (2012) who tested a group of musicians including pianists on the Alternating (A) SRT task. This task differs from the standard SRT task by insertion of a random stimulus presented after each target stimulus of a given sequence. This modification was assumed to mask the sequence better and consequently reduce likelihood of the acquisition of explicit knowledge. In addition, Romano Bergstrom et al. (2012) added the constraint that certain sequence triplets occurred more frequently than others (i.e., high- vs. low-frequency triplets). In contrast to the standard SRT, the ASRT does not test how a participant reacts to a different sequence. Instead, the ratio of RTs in high-frequency triplets (lower RTs) is compared with the ratio of RTs in low-frequency triplets (higher RTs). This comparison revealed that both musicians and controls demonstrated an increased difference between high and low triplet types as the session progressed. However, musicians were generally faster, and the significant interaction of group and triplet type showed that implicit sequence learning was greater in musicians compared to controls. The results of a recognition task that was administered after the ASRT task showed that none of the participants had acquired explicit knowledge about the sequence structures. The authors suggested that pianists, due to their extensive exercise of their piano playing skills, also train a general ability of implicitly learning subtle sequential relations, which goes beyond their domain of expertise. Furthermore, the authors claimed that the pianists in their sample did not have an advantage of perceptual motor processing which may have contributed to the enhanced implicit sequence learning, based on results of the WAIS-III Digit-Symbol Coding test. In this task, the participants were asked to learn the association of a symbol with a number according to a given key by providing a manual response (i.e., penciling the number below each symbol). Notably, this task does not include any sequential structure. Therefore, considering that performance on the SRT and the piano involves encoding and translation of sequentially presented stimuli into perceptual motor responses (in which pianists are experts), it cannot be ruled out that this advantage may also have contributed to their enhanced ability in implicit sequence learning of the previous studies.

Both of these studies demonstrated enhanced implicit sequence learning abilities and low explicit sequence knowledge in musicians, including pianists. The SRT versions used in the studies displayed some significant overlaps with piano playing, since both SRT tasks required translating visuo-spatial information into manual actions by finger pressing of specific keys. This may be an explanation for the observed superiority in implicit sequence learning, raising the question whether enhanced implicit motor sequence learning was primarily driven by enhanced visuo-motor coordination and fine motor precision, or rather by superior implicit sequence learning abilities. If the latter is the case, then pianists would also be able to transfer this advantage to performance on a sequential task that shares fewer features with playing piano, thus excluding manual and visuo-motor coordination components.

Considering that pianists are usually trained to express explicit awareness to a certain degree during their piano performance (Chaffin et al., 2009), one may expect that pianists would show more explicit awareness than controls. However, this was not the case in the studies by Landau et al. (2006) and Romano Bergstrom et al. (2012). This finding may be related to the high grade of sequence masking. It may be that an SRT version in which the sequence is less disguised would be more sensitive to capturing differences in explicit knowledge among pianists and controls. This assumption is supported by the findings of Vandenberghe et al. (2006), that contrasted performance in a deterministic and probabilistic SRT version. Only in the deterministic version participants showed significant explicit knowledge (i.e., generation of the sequence).

These open questions inspired us to test a group of pianists and controls with the Ocular (O)-SRT, developed by Vakil et al. (2017). The O-SRT is an eye-tracked SRT variant that allows replacement of a manual response by an oculomotor response mode, so that task slides are activated by eye fixations on the target instead of target-corresponding key presses. Furthermore, this task does not require stimulus–response mapping, as eye gaze is already perfectly mapped with a visual stimulus. In addition to the typical RT measure used in the standard SRT test, the O-SRT enables the generation of additional measures such as correct anticipations (CA). An eye tracker records eye movements during a 500 ms interval between targets, thereby allowing evaluation of whether or not a participant anticipates the subsequent target (see Vakil et al., 2017). Thus, using this method makes it possible to measure directly whether the subsequent target has already been anticipated before it appears. Furthermore, since the O-SRT is deterministic (i.e., repeated fixed sequences), differences in explicit sequence knowledge between pianists and controls may become more evident, since such task versions have been related to higher explicit sequence knowledge (see above, Vandenberghe et al., 2006). For the assessment of explicit sequence knowledge we used a sequence awareness questionnaire and a generate task. The integration of these measures together with the O-SRT generated measures enables better characterization of manual-free sequence learning in experts like pianists.

We hypothesized that pianists would demonstrate higher implicit sequence learning (i.e., implicit oculomotor-perceptual sequence learning), expressed in RT as well as CA measures by steeper learning rates. Following the suggestion of Romano Bergstrom et al. (2012), we based our hypotheses on the assumption that because of the frequent repetitions of musical sequences on the piano, pianists would show an enhanced general implicit sequence learning ability that is not restricted to manual action or speed. Moreover, we intentionally used a deterministic SRT version because it is more likely to unveil explicit knowledge. We expected that explicit sequence knowledge would be greater in pianists, which may be related to their ability to build a mental map while playing a piano piece (Chaffin et al., 2009; Globerson & Nelken, 2013). Finally, we expected to find a positive relation between onset age and implicit sequence learning scores. We based these assumptions on several findings from the literature. First, MRI studies have shown that intensive musical training is reflected in changes in brain structure and activity patterns which are particularly noticeable when musical training begins at an early age (Münte et al., 2002; Schlaug et al., 1995). Furthermore, Watanabe et al. (2007) showed that early vs. later onset of musical training can lead to enhanced performance in adults on a motor task, which could suggest the existence of a sensitive period for motor learning.

Methods

Participants

Two groups participated in the present study: a group of pianists and a control group of students. A total of 31 pianists participated in the study in return for a payment of NIS 40 (~ $10 US). Two pianists were excluded from the study due to technical matters (data loss of the eye tracker). This resulted in a group of 29 pianists (16 females) with ages ranging from 18 to 35 years ($M = 24.97$, $SD = 4.3$). Their onset age of playing piano ranged from 3 to 24 years ($M = 8.55$, $SD = 4.7$), and their years of playing piano ranged from 1 to 20 years ($M = 10.48$, $SD = 4.7$). The control group included 31 students (23 females) from Bar Ilan University, Israel. The students took part in the study to fulfill academic requirements. Their ages ranged from 19 to 35 years ($M = 23.48$, $SD = 3.9$). Gender did not differ proportionally between the groups ($X^2(1) = 2.38.54$, $p = 0.12$) and neither the groups' ages ($t(58) = 1.39$, $p = 0.17$) nor years of education ($t(54.6) = 1.92$, $p = 0.06$) differed significantly. Exclusion criteria for both groups were neurological or psychiatric disturbances or learning disorders. For the control group, the additional exclusion criteria were playing an instrument (currently or in the past). The study was approved as required by the Ethics Committee of Bar Ilan University, Israel.

Procedure

All participants completed the study procedures in a single testing session lasting approximately 30–40 min. First, the O-SRT was administered, followed by a questionnaire in which the experimenter posed two questions about their explicit awareness of the sequence. Then, the participants were informed about the nature of the task (i.e., the order the dots appeared was according to a given sequence which repeated itself during the first six learning blocks; a different sequence appeared in the seventh block, and in the last block the original sequence was displayed again). Thereafter, the experimenter asked the participants to reproduce the sequence explicitly (free generation task) to the best of their memory, if they could do so. Finally, the participants were debriefed about the nature and purpose of the experiment.

Test material

Ocular serial reaction time (O-SRT) task

The SRT design used for this experiment was a replication of the oculomotor-activated (OA) version of the O-SRT task in the study by Vakil et al. (2017). The task was programmed in E-Prime 2.0. Eye movements were recorded by the SMI iView 120 REDm Eye Tracker (SensoMotoric Instruments, Teltow, Germany) that has a sampling rate of 120 Hz and a gaze position accuracy of 0.5°. Stimuli were presented on an LCD computer screen (size 42 × 24 cm; resolution 1600 × 900 pixels). The recording device was installed beneath the screen. Participants were seated in front of the screen, approximately 60 cm away from it. Calibration was conducted at the beginning of every task using a standard 5-point grid for both eyes. A 4-point grid was used for validation after each calibration trial. If the accuracy was above 0.8°, calibration and validation were repeated.

O-SRT stimuli

Stimuli of the O-SRT consisted of five slides (see Fig. 1), each with a resolution of 1400 × 900 pixels. Each stimulus included four white squares arranged in a diamond shape on a grey background. Four slides contained a black dot (indicating the target) in one of the four white squares. One slide, which was used to measure anticipation, contained only the four white squares, without a black dot in any of the squares. The size of each square was 6 × 6 cm and the diameter of the dot was 1.5 × 1.5 cm.

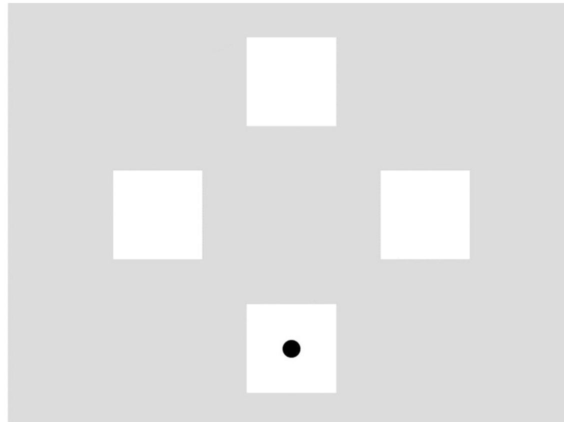

Fig. 1 The target slide of the ocular serial reaction time (O-SRT) task designed by Vakil et al. (2017)

O-SRT procedure

A black dot (the target stimulus) appeared in one of four white squares arranged in a diamond shape (see Fig. 1). Before each slide with a dot appeared on the screen, a blank slide with four empty squares was shown for 500 ms (i.e., the anticipation slide). Each block consisted of a 12-element sequence repeated nine times (see Fig. 2). The sequence in each block began from a different element of the sequence, i.e., a different starting point. No first-order predictive information was provided in the sequence (i.e., each location is preceded by the same location only once). Each element in the sequence was matched with one of the four squares: 1, 2, 3, and 4 to correspond with down, left, right, and up, respectively. Two sequences were used in the O-SRT which were adopted from Gabriel et al. (2013): *Sequence A* (3–4–2–3–1–2–1–4–3–2–4–1; the original sequence) and *Sequence B* (3–4–1–2–4–3–1–4–2–1–3–2; the interference sequence). See Fig. 2 for an illustration of *Sequence A*.

Participants were instructed to look as quickly as possible at the target dot when it appeared in one of the four squares arranged in a diamond shape. For the purpose of measuring anticipation of the subsequent target location, a blank slide was presented for 500 ms in between the target slides. Importantly, participants were not aware that a blank slide appeared, so that the task is perceived as a continuous flow from one to the next target slide. The target slides were oculomotor-activated (fixation on a square with target for a minimum of 100 ms).

The O-SRT task contained a total of eight blocks, divided into three phases. First, the *learning phase*—the presentation of six blocks (1–6) containing the original A sequence. Second, the *interference phase*—the presentation of one block with the interference B sequence (block 7). Third, *recovery*—the presentation of one block with the original

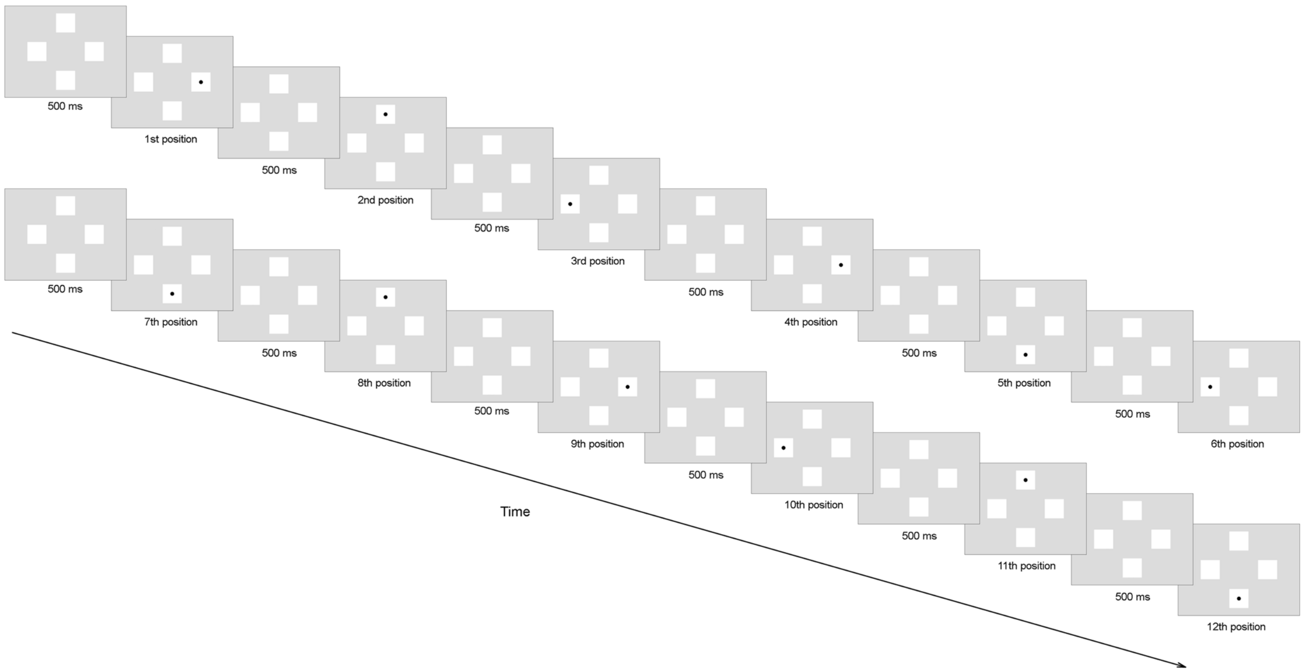

Fig. 2 One of the sequences used in the O-SRT experimental design. A sequence (*Sequence A*) consisting of 12 elements (=positions) was repeated nine times per block. At the beginning and in between the target slides, an empty slide containing only the squares was presented for 500 ms to measure correct anticipations

A sequence (block 8). After each block, a 1-min break was given before starting the next block. Participants received no prior information about the nature of the task (i.e., that the dots appear in a sequential order), nor the number of blocks.

Explicit sequence knowledge (sequence awareness and sequence reproduction)

To assess explicit sequence knowledge in the form of sequence awareness and the ability to reproduce explicitly the sequence, we administered a questionnaire and a free generation task subsequent to the O-SRT. The sequence awareness score was composed of the points given on two questions related to the awareness of the repeated order of the task. The first question was “Did you notice anything special about the experiment?” (one point was given for a “yes”). The second question was more specific “Did you notice any patterns during the experiment?” (one point was given for indications that there was a repeated sequence). The sequence awareness score had a maximum value of two. For the assessment of the sequence reproduction score, we used a free generate task. Before this task was applied, the participants were informed about the nature of the O-SRT task (i.e., repetition of same sequence during first six learning block, different sequence in block 7 and the original sequence again in last block). In this task, we presented a paper form containing the blank stimuli (i.e., the stimuli with the four squares without a target dot in it). The squares were numbered from 1 to 4. The participants were then asked to reproduce the sequence by pointing out the numbers of the squares, and the experimenter noted the pointed sequence on a paper form. For computing the sequence reproduction score, we applied a triple criterion, so that for a position to be scored as correctly recalled, it had to be included within a correctly recalled segment consisting of three consecutive correctly reproduced positions, as was done in previous studies (e.g., Willingham, 1999). By taking into account that learning may occur in chunks of the sequence (Tal & Vakil, 2020), correct segments did not need to be consecutive to contribute to the score. This approach was also used by other scientists (e.g., Knee et al., 2007; Willingham, 1999). However, considering that reproduction of segments of the sequence is more likely to occur by chance compared to a consecutive sequence, we applied a weighted scoring method approach comparable to that used in the study by Anaya et al. (2017). We therefore checked whether the triple responses occurred in a consecutive way, and multiplied the number of triplets within a correctly reproduced segment by the length of this segment. For example, if a participant had reproduced two segments of the sequence such as **3 4 2 3** *4 2* **1 2 1 4** *2 4* (i.e., bold is correct, italics is incorrect), in the first segment we counted 342 and 423 as two triplets. Since these two triple responses were consecutive, we multiplied the number of segments (two) by four (i.e., 2×4=8), the length of the sequence. We did the same for the second correctly reproduced segment (i.e., two triplets (121, 214) multiplied by four) and then added the two results, which came to a total of 16 points for this participant.

Demographic musicianship questionnaire

Pianists were asked to complete a brief questionnaire regarding the following measures: (a) onset age for playing piano, (b) years playing piano, (c) average practicing time per day in reference to the entire period since onset.

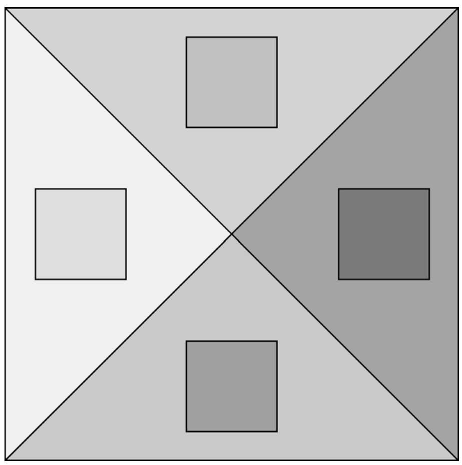

Fig. 3 The AOIs (areas of interest) used for calculating reaction time (i.e., RT to target) and the percentage of correct anticipations (i.e., during the blank slide)

Data analysis

Eye movement data were registered with iView (SensoMotoric Instruments, Teltow, Germany), and BeGaze™ (SensoMotoric Instruments, Teltow, Germany) was used to generate eye-tracking parameters. Two dependent measures were used: *Reaction Time* (to target), and *Percentage of Correct Anticipations* (in the anticipation slide). We used the function "area of interest" (AOI) in the BeGaze program and enlarged the squares into triangles, so that four triangles covered the four squares and the center point of the screen (see Fig. 3).

Reaction time (RT) was evaluated by calculating the elapsed time from onset of the target slide until participants fixated the correct AOI. The distribution of the raw RTs per block is illustrated for the pianists in Fig. 4, and for the controls in Fig. 5.

For the purpose of statistical analysis, we calculated the Median RT for each 12-item sequence (i.e., for each 12 target trials). Then, we analyzed the mean of medians of RT per block (i.e., 9 sequences of 12 items each; 108 trials).

Correct anticipation was evaluated by tracking transition of the participant's gaze to the correct subsequent position during the blank slide (i.e., the slide between the target slides presentation). Our analysis showed that across all blocks, in

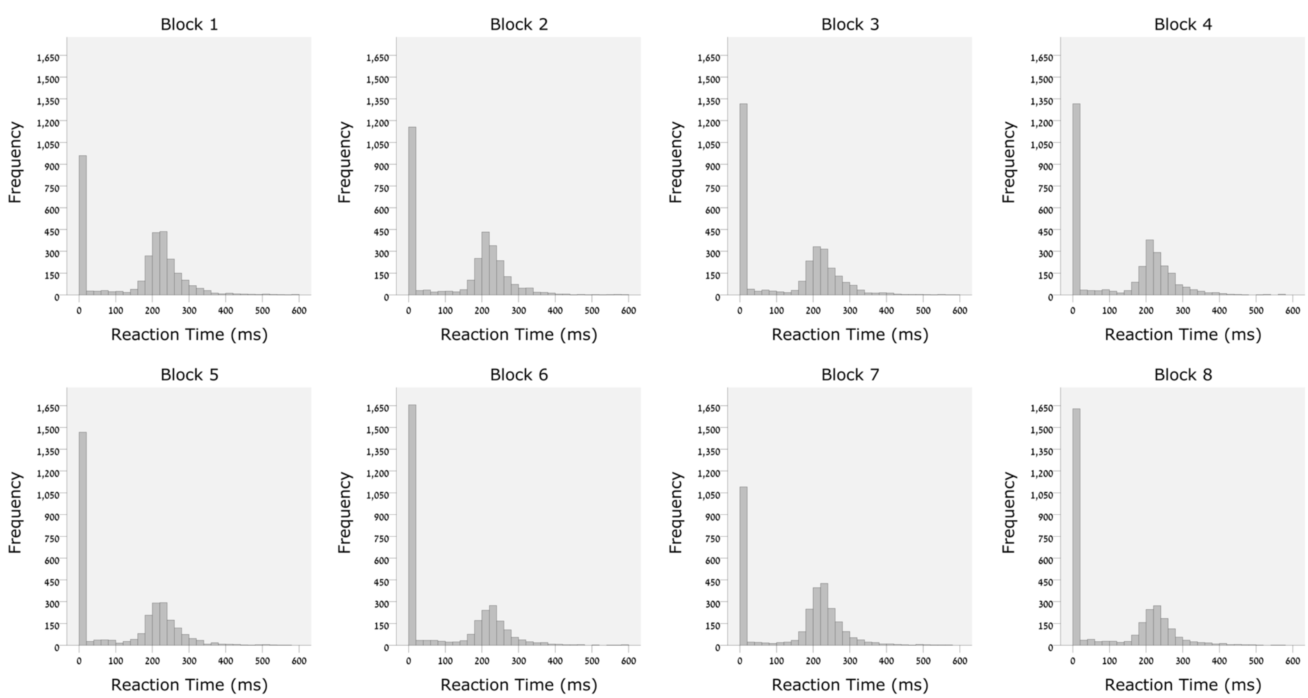

Fig. 4 The distribution of the raw reaction time (reaction time to target) per block for the pianists' group. The range between 0 and 20 ms contains mainly RTs with the value of zero or close to zero, which reflect correct anticipations by the participants

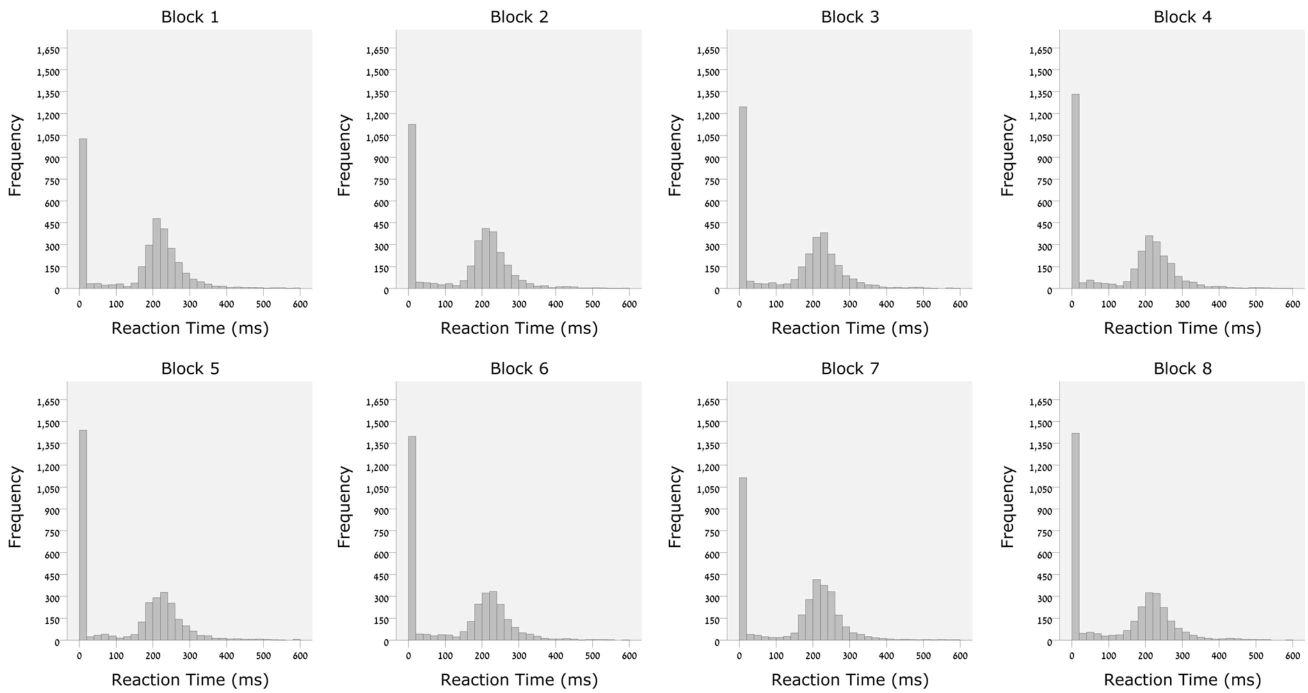

Fig. 5 The distribution of the raw reaction time (reaction time to target) per block for the control group. The range between 0 and 20 ms contains mainly RTs with the value of zero or close to zero, which reflect correct anticipations by the participants

the pianists' group, participants fixated on only one location in most (73.1%) of the trials. In 24.8% of the trials, their gaze remained at the same location, and only in a small percentage of trials (2.0%) they fixated more than one location. In the control group, these numbers were similar: in 70.4% of the trials, participants fixated on only one location, in 26.9% of the trials they remained at the same location, and in 2.6% of the trials, participants fixated on more than one location. In Table 1, group averages for fixation location categories are illustrated per block.

The measure *Percentage of Correct Anticipations* (Percentage CA) included only the trials in which participants shifted their gaze towards one different location. This means that trials where participants remained at the same location

Table 1 Fixation averages of all trials per group and fixation location categories

	Fixation averages per blocks							
	1	2	3	4	5	6	7	8
Fixation location								
Pianists								
Correct	27.6	33.4	38.5	39.5	43.3	50.2	32.8	48.1
Incorrect	36.6	33.8	34.7	34.0	31.7	29.4	42.4	29.1
Same location	33.9	31.0	24.2	24.3	22.5	19.4	22.5	20.7
Several locations	1.9	1.8	2.5	2.2	2.5	1.0	2.3	2.2
Controls								
Correct	27.7	31.2	34.5	37.0	39.6	39.3	30.2	37.6
Incorrect	36.6	36.5	35.9	35.3	33.9	35.0	40.5	32.2
Same location	33.0	29.5	26.8	25.2	24.2	23.1	26.2	27.6
Several locations	2.7	2.8	2.7	2.5	2.4	2.7	3.1	2.6

Group averages by percentage across all (fixated) trials per block and fixation location categories. The fixation location category "correct" reflects all trials where participants made only one move and fixated on the AOI where the subsequent target would appear. In the category "incorrect", all fixations are included where participants made only one move, but to the wrong location. In category "same location", all trials were included when participants did not shift their gaze, but remained at the same location. In category "several locations", all trials were included where participants fixated on more than one location or moved to more than one location were excluded from this analysis. An anticipation score of "1" was set for the slides in which there was at least one fixation only on the correct location (where the next target was going to appear), and a "0" score for fixations on one of the incorrect locations (i.e., only for the trials that moved to only one location). Then, the number of correct anticipations per sequence (range: 0–12) was counted. Subsequently, we calculated the percentage of correct anticipations out of the total number of correct and incorrect anticipated trials per sequence, and then averaged nine sequences per block. This established the Percentage CA score for each block for all participants.

The following phases were analyzed separately: (1) *Learning*—block 1 vs. block 6 in the learning session; (2) *Interference*—block 6, the last block of the learning session vs. block 7, the interference block in the test session; (3) *Recovery from Interference*—block 7 vs. block 8 in the test session, (4) *Recovery Level—Block*—block 6, the last block of the learning session vs. block 8, the recovery block in the test session, and (5) *Recovery Level*—Sequence—the last sequence of block 6 vs. the first sequence of block 8. Finally, in (6) *Baseline*, we also compared the base rate for learning the first blocks of each sequence (Sequence A, Sequence B)—block 1 of the learning session vs. block 7 of the test session.

Implicit sequence learning scores

For each participant, learning and interference phase scores, for both the RT and Percentage CA measures, were computed as follows:

1) *Learning score*: block 6 was subtracted from block 1 for the RT measures and vice versa, block 1 was subtracted from block 6 for the Percentage CA measures, thereby resulting in *RT* and *CA Learning scores*.

2) *Interference score*: block 7 was subtracted from block 6 for the RT measures and vice versa, block 7 was subtracted from block 6 for the Percentage CA measures, which resulted in *RT Interference* and *CA Interference scores*.

3) *Recovery score*: block 8 was subtracted from block 7 for the RT measures and vice versa, block 7 was subtracted from block 8 for the Percentage CA measures, which resulted in *RT Recovery* and *CA Recovery scores*.

For all resulting scores, the higher the scores are, the stronger the learning or interference effect. The implicit sequence learning scores are viewed as indicators of how well the sequence was learned. To evaluate possible relations of implicit sequence learning with explicit knowledge or piano playing measures, these implicit sequence-learning scores were used to perform correlation analyses (i.e., bivariate Pearson correlations and Spearman order correlations, respectively.

Results

Reaction time

The phases involved in the assessment of implicit sequence learning such as *Learning*, *Interference*, *Recovery from Interference*, *Recovery Level—Block*, *Recovery Level—Sequence and Baseline*, were analyzed using a mixed-design analysis of variance (ANOVA; 2×2). In *Learning*, we explored the effects of the between-subjects condition factor of Group (pianists and controls) and the within-subjects factor of Learning (blocks 1 vs. block 6); in *Interference*, the effect of the between-subjects condition factor of Group (pianists and controls) and the within-subjects factor of Interference (block 6 vs. block 7); in *Recovery from Interference*: the effect of the between-subjects condition factor of Group (pianists and controls) and the within-subjects factor of Recovery from Interference (block 7 vs. block 8). Moreover, in *Recovery Level*, we tested the extent of recovery by testing the effect of the between-subjects condition factor of Group (pianists and controls) and the within-subjects factor of Recovery Level first on a block basis (*Recovery Level—Block*: block 6. vs. block 8) and second on a sequence basis (*Recovery Level—Sequence*: last sequence of block 6 vs. first sequence of block 8). Furthermore, in *Baseline*, we compared the first blocks of each sequence (i.e., A, B) to evaluate whether the initial performance differed on both. Therefore, we explored the effect of the between-subjects condition factor of Group (pianists and controls) and the within-subjects factor of Baseline (block 1 vs. block 7).

The mean of the medians of RT as a function of blocks 1–8 of the O-SRT for both groups is presented in Fig. 6.

Learning: The main effect of Learning, $F(1, 58) = 138.59$, $p < 0.001$, $\eta_p^2 = 0.71$, was significant. The main effect of

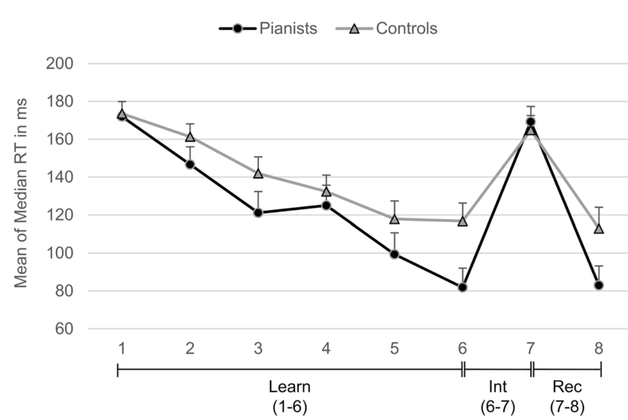

Fig. 6 The mean of the median reaction time (RT) of the pianists' and control groups. The error bars indicate standard errors. Abbreviations: *Learn*, Learning; *Int*, Interference; *Rec*, Recovery from Interference

Group, $F(1, 58) = 3.07$, $p = 0.09$, $\eta_p^2 = 0.05$, was not significant. Group by Learning interaction, $F(1, 58) = 7.15$, $p = 0.009$, $\eta_p^2 = 0.11$, reached significance due to a steeper decrease of RTs in the pianists' group. These results indicate that both groups significantly reduced RTs during the Learning phase (i.e., block 1 vs. block 6), which was more pronounced in the pianists (see Fig. 6).

Interference: Both Interference main effect, $F(1, 58) = 86.13$, $p < 0.001$, $\eta_p^2 = 0.60$, and interaction of Group and Interference, $F(1, 58) = 7.27$, $p = 0.009$, $\eta_p^2 = 0.11$, were significant. The Group effect was not significant, $F(1, 58) = 2.22$, $p = 0.14$, $\eta_p^2 = 0.04$. These results indicate that both groups were significantly affected when the different sequence was introduced, which led to an increase of RTs (see Fig. 6). However, the slope of performance was significantly steeper in the pianists' group.

Recovery from Interference: Recovery from Interference main effect, $F(1, 58) = 89.02$, $p < 0.001$, $\eta_p^2 = 0.61$, as well as Group by Recovery interaction, $F(1, 58) = 5.49$, $p = 0.023$, $\eta_p^2 = 0.09$, reached significance. Group main effect, $F(1, 58) = 1.32$, $p = 0.26$, $\eta_p^2 = 0.02$, was not significant. These results indicate that both groups had lower RTs once the original sequence was redisplayed. The significant interaction was due to a steeper Recovery effect of the pianists' group.

Recovery Level—Block: Recovery Level—Block main effect, $F(1, 58) = 0.05$, $p = 0.832$, $\eta_p^2 = 0.001$, and Group by Recovery Level—Block interaction, $F(1, 58) = 0.15$, $p = 0.696$, $\eta_p^2 = 0.003$, were not significant. Group main effect, $F(1, 58) = 6.17$, $p = 0.016$, $\eta_p^2 = 0.10$, was significant. To evaluate whether the performance on block 6 and block 8 was equivalent, we conducted the two one-sided tests (TOST) procedure to test equivalence (Lakens et al., 2018). We set the equivalence bounds to ± 16 ms, following the same equivalence bound we used in Vakil et al. (2021). The TOST procedure (based on paired sample t tests) revealed that equivalence was not statistically significant, neither in the pianists' group (block 6: $M = 81.84$, SD = 54.9, block 8: $M = 82.99$, SD = 55.0), $t(28) = -1.55$, $p = 0.066$, nor in the control group, (block 6: $M = 116.81$, SD = 52.73, block 8: $M = 112.93$, SD = 62.1), $t(30) = 1.42$, $p = 0.083$. The results of the TOST procedure need to be treated with caution since statistical power for these analyses was low (e.g., given a power of 0.8 and an alpha level of 0.05 at least 91 participants would have been needed per group). Based on the outcome of both conducted analyses, it is indicated that in both groups, the difference in the performance on block 6 and block 8 is small, but not small enough to be equivalent.

Recovery Level—Sequence: Recovery Level—Sequence main effect, $F(1, 58) = 14.87$, $p < 0.001$, $\eta_p^2 = 0.204$, and Group main effect, $F(1, 58) = 7.057$, $p = 0.010$, $\eta_p^2 = 0.108$, were significant. Group by Recovery Level—Sequence interaction $F(1, 58) = 2.17$ $p = 0.146$, $\eta_p^2 = 0.036$ was not significant. As can be seen in Fig. X, in both groups, RTs were significantly higher in the first sequence of block 8 than in the last sequence of block 6. Overall, control group's RTs were higher than the pianists' group's RTs. These results demonstrate that both groups performed better on the last sequence of block 6 compared to the first sequence of block 8.

Baseline: None of the three effects reached significance: Baseline main effect, $F(1, 58) = 0.92$, $p = 0.34$, $\eta_p^2 = 0.016$, Group by Baseline interaction $F(1, 58) = 0.025$ $p = 0.62$, $\eta_p^2 = 0.004$ and Group main effect, $F(1, 58) = 0.03$, $p = 0.88$, $\eta_p^2 = 0.0001$. To evaluate whether performance on block 1 and block 7 was equivalent, we conducted the two one-sided tests (TOST) procedure to test equivalence and used the same equivalence bounds (± 16 ms) as in the Recovery Block—Level comparison above. The TOST procedure (based on paired sample t tests) revealed that equivalence was not significant, neither in the pianist's group (block 1: $M = 171.97$, SD = 42.96, block 7: $M = 169.23$, SD = 43.55), $t(28) = 1.35$, $p = 0.095$, nor in the control group, (block 1: $M = 173.60$, SD = 35.28, block 7: $M = 164.85$, SD = 42.66), $t(30) = 1.04$, $p = 0.153$. These results show that although the difference between block 1 and block 7 was small, the difference in both groups was not equivalent. However, the results of the TOST procedure based on the paired sample t tests need to be treated with caution since statistical power for these analyses was low (e.g., given a power of 0.8 and an alpha level of 0.05 at least 91 participants would have been needed per group). Furthermore, we tested whether performance on block 1 was equivalent between the groups. For this purpose, we conducted the TOST procedure based on independent sample t tests using equivalence bounds of ± 25 ms. This analysis revealed that both groups performed equally on the first learning block (pianists: $M = 171.97$, SD = 42.96, controls: $M = 173.57$, SD = 35.28), $t(54.3) = 2.3$, $p = 0.013$.

Percentage of correct anticipations (Percentage CA)

As for the RT measure, we conducted the same analyses as for the Percentage CA measure for the phases: Learning, Interference, Recovery from Interference, Recovery Level—Block, Recovery Level—Sequence as well as Baseline (i.e., see detailed description in the reaction time results section). Figure 7 presents the Percentage CA (as a function of blocks 1 to 8 of the O-SRT) for both the groups.

Learning: A mixed ANOVA revealed a significant Learning main effect, $F(1, 58) = 84.20$, $p < 0.001$, $\eta p^2 = 0.59$., a significant Group by Learning interaction, $F(1, 58) = 10.60$, $p = 0.002$, $\eta p^2 = 0.15$, and a significant main effect for Group, $F(1, 58) = 5.46$, $p = 0.023$, $\eta p^2 = 0.15$. These results indicate that both groups significantly increased the Percentage CA and that the increase for pianists was steeper.

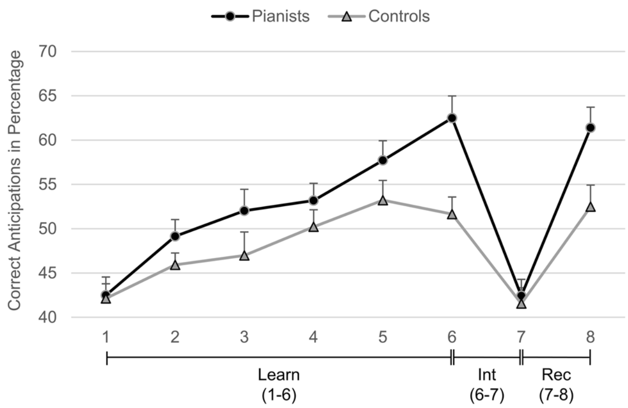

Fig. 7 The mean percentage of correct anticipations (Percentage CA) for the pianist and control groups. The error bars indicate standard errors. Abbreviations: *Learn*, Learning; *Int*, Interference; *Rec*, Recovery from Interference

Interference: All three effects reached significance: Interference main effect, $F(1, 58) = 71.25$, $p < 0.001$, $\eta_p^2 = 0.55$, Group by Interference $F(1, 58) = 7.77$, $p = 0.007$, $\eta_p^2 = 0.12$ and Group main effect, $F(1, 58) = 6.80$, $p = 0.012$, $\eta_p^2 = 0.11$. These results imply that both groups were significantly affected by the interference sequence, and therefore reached a lower Percentage CA rate at the interference block (block 7). However, the pianists reached a higher level in the last learning block (block 6), leading to a steeper decrease in Percentage CA.

Recovery from Interference: All three effects reached significance: Recovery from Interference main effect, $F(1, 58) = 71.95$, $p < 0.001$, $\eta_p^2 = 0.55$, Group by Recovery from Interference $F(1, 58) = 5.19$, $p = 0.026$, $\eta_p^2 = 0.08$ and Group main effect, $F(1, 58) = 4.04$, $p = 0.049$, $\eta_p^2 = 0.07$. These results demonstrate that both groups recovered significantly from the interference sequence, although the pianists recovered at a steeper rate.

Recovery Level—Block: Recovery Level—Block main effect, $F(1, 58) = 0.008$, $p = 0.927$, $\eta_p^2 = 0.001$, and Group by Recovery Level—Block interaction, $F(1, 58) = 0.452$, $p = 0.504$, $\eta_p^2 = 0.008$, were not significant. Group main effect, $F(1, 58) = 11.425$, $p = 0.001$, $\eta_p^2 = 0.17$, was significant. To evaluate whether the performance of block 6 and block 8 was equivalent, we conducted the two one-sided tests (TOST) procedure to test equivalence (Lakens et al., 2018). We set the equivalence bounds at ± 1.5. The TOST procedure (based on paired sample t tests) revealed that equivalence was not statistically significant, neither in the pianists' group (block 6: $M = 62.49$, $SD = 13.43$, block 8: $M = 61.39$, $SD = 12.51$), $t(28) = 0.2$, $p = 0.421$, nor in the control group, (block 6: $M = 51.65$, $SD = 10.77$, block 8: $M = 52.48$, $SD = 13.57$), $t(30) = 0.36$, $p = 0.362$. The results of the TOST procedure need to be treated with caution since statistical power for these analyses was low (e.g., given a power of 0.8 and an alpha level of 0.05 at least 381 participants would have been needed per group). Based on the outcome of both conducted analyses, it is indicated that in both groups the difference in the performance on block 6 and block 8 is small, but not small enough to be equivalent.

Recovery Level—Sequence: Recovery Level—Sequence main effect, $F(1, 58) = 12.19$, $p < 0.001$, $\eta_p^2 = 0.174$, and Group main effect, $F(1, 58) = 5.557$, $p = 0.022$, $\eta_p^2 = 0.087$, were significant. Group by Recovery Level—Sequence interaction $F(1, 58) = 0.53$ $p = 0.469$, $\eta_p^2 = 0.009$ was not significant. In both groups, the Percentage CAs were significantly lower in the first sequence of block 8 compared to the last sequence of block 6. Overall, the Percentage CAs of the pianists' group were higher compared to the Percentage CAs of the control group. These results demonstrate that both groups performed better in the last sequence of block 6 compared to the first sequence of block 8.

Baseline: None of the three effects reached significance: Baseline main effect, $F(1, 58) = 0.04$, $p = 0.84$, $\eta_p^2 = 0.001$, Group by Baseline interaction, $F(1, 58) = 0.03$, $p = 0.87$, $\eta_p^2 = 0.0001$ and Group main effect, $F(1, 58) = 0.09$, $p = 0.77$, $\eta_p^2 = 0.002$. To evaluate whether performance on block 1 and block 7 were equivalent, we conducted the two one-sided tests (TOST) procedure to test equivalence, and used the same equivalence bounds ± 1.5 as in the Recovery Block—Level comparison above. The TOST procedure (based on paired sample t tests) revealed that equivalence was not significant in both groups (*pianists*: block 1: $M = 42.50$, $SD = 11.05$, block 7: $M = 42.42$, $SD = 10.05$), $t(28) = 0.46$, $p = 0.324$, *controls*: block 1: $M = 42.13$, $SD = 9.21$, block 7: $M = 41.55$, $SD = 9.94$), $t(30) = 0.53$, $p = 0.300$). These results indicate that although in both groups the differences between block 1 and block 7 were small, they were not equivalent. The results of the TOST procedure need to be treated with caution since statistical power for these analyses was low (e.g., given a power of 0.8 and an alpha level of 0.05, at least 381 participants would have been needed per group).

Explicit sequence knowledge

A Kruskal–Wallis test revealed that compared to the control group, the pianist's group expressed significantly higher sequence awareness ($H(1) = 8.54$, $p = 0.003$), with a mean rank of 36.7 for pianists and 24.6 for controls. The pianists were also significantly better at reproducing the sequence ($H(1) = 5.40$, $p = 0.020$), with a mean rank of 35.2 for pianists and 2.1 for controls. However, there were participants in both groups who showed no awareness at all (pianists: $n = 6$, controls: $n = 15$), and participants that were unable to reproduce any part of the sequence (pianists: $n = 14$, controls: $n = 24$). Therefore, we performed a Chi-Square Test of Independence for both scores, to detect whether the groups did not only differ proportionally in extent of sequence knowledge, but also dichotomously: whether or not they showed any awareness or no awareness at all, and whether or not they were able to reproduce part of the sequence. Thus, for both sequence awareness and sequence reproduction we created separate dichotomic scores (1 = some awareness, some ability of sequence reproduction, respectively; versus 0 = no awareness, no ability of sequence reproduction, respectively. The relation between sequence awareness and group was significant, X^2 (1, $N = 60$) = 5.05, $p = 0.025$, whereby pianists were more likely to express sequence awareness than controls. Similar, the relation between sequence reproduction and group was also significant, X^2 (1, $N = 60$) = 5.48, $p = 0.019$, so that pianists were more likely than controls to reproduce part of the sequence.

Correlation analyses

Demographic factors and implicit sequence learning

We tested the relation of demographic variables (i.e., age, education) by performing two-tailed Pearson product moment correlations. In both groups, neither age (*pianists*: RT Learning; ($rs(27) = -0.037$, $p = 0.847$, CA Learning; ($rs(27) = -0.047$, $p = 0.809$, *controls*: RT Learning; ($rs(29) = -0.026$, $p = 0.888$, CA Learning; ($rs(29) = -0.059$, $p = 0.754$) nor education (*pianists*: RT Learning; ($rs(27) = 0.019$, $p = 0.921$, CA Learning; ($rs(29) = 0.148$, $p = 0.443$, *controls*: RT Learning; ($rs(29) = 0.072$, $p = 0.700$, CA Learning; ($rs(29) = -0.016$, $p = 0.930$) were significantly related to implicit sequence learning scores.

Implicit and explicit sequence learning

For each group we conducted separate two-tailed Spearman order correlations of the explicit knowledge measures (i.e., sequence awareness, sequence reproduction) with the implicit sequence learning scores of RTs and CAs in the learning phase. We used Spearman order correlations, since the explicit knowledge measures were not normally distributed. We corrected for multiple comparisons applying the Bonferroni correction (i.e., per measure and group). With pianists, sequence awareness was significantly positively related to the RT Learning score ($rs(27) = 0.421$, $p = 0.023$) and the CA Learning score ($rs(27) = 0.435$, $p = 0.018$), and both survived the Bonferroni corrected significance level ($p < 0.025$). For controls, sequence awareness was not significantly related to these scores (RT Learning; ($rs(29) = 0.168$, $p = 0.366$, CA Learning; ($rs(29) = 0.240$, $p = 0.193$). None of the correlations of sequence reproduction nor the Learning scores of RTs or CAs were significant in either of the groups (*Pianist*: RT Learning; ($rs(27) = 0.145$, $p = 0.454$, CA Learning; ($rs(29) = 0.271$, $p = 0.155$, *Controls*: RT Learning; ($rs(29) = 0.103$, $p = 0.581$, CA Learning; ($rs(29) = 0.077$, $p = 0.681$). Based on those results, we hypothesized that in pianists explicit knowledge in the form of sequence reproduction may not be fully developed during the learning blocks, but rather towards the end of the task. To test this post hoc hypothesis, we conducted one-tailed Spearman correlations of sequence reproduction with the recovery scores (i.e., RT Recovery, CA Recovery) and sequence reproduction with the achieved values of the recovery block (i.e., mean of median RT and average percentage of CA of block 8). All of these correlations were significant. Sequence reproduction and the recovery scores (RTs ($rs(27) = 0.529$, $p = 0.002$) and CAs ($rs(27) = 0.552$, $p < 0.001$) correlated positively. This means that the better pianists recovered, the more they explicitly reproduced the sequence. The mean of median of RTs of the recovery block correlated negatively with sequence reproduction (RTs ($rs(27) = -0.458$ $p = 0.006$), which means that the lower the RT during the recovery block the higher the sequence reproduction score. Finally, the average percentage of CAs of the recovery block correlated positively with sequence reproduction ($rs(27) = 0.410$, $p = 0.014$), meaning that the higher the achieved CAs during the recovery block, the higher the sequence reproduction. Except for the latter, the three other correlations survived the Bonferroni corrected threshold of $p < 0.0125$.

Piano playing factors and implicit sequence learning

We performed bivariate one-tailed Pearson product moment correlations to test the relationship of piano playing-related variables (i.e., onset age of piano playing, years of playing piano, average practicing time since onset) with the Learning scores of RTs and CAs), corrected for multiple comparisons applying the Bonferroni correction, (i.e., per measure and group). Years of playing piano was not significantly related either to RT Learning ($r(27) = 0.172$, $p = 0.186$), or to CA Learning ($r(27) = 0.259$, $p = 0.087$). Average practicing time since onset was also not significantly related to any of the implicit sequence learning measures (RT Learning ($r(27) = 0.041$, $p = 0.418$, CA Learning ($r(27) = 0.267$, $p = 0.085$). Onset age of playing piano was not significantly correlated with RT Learning ($r(27) = -0.253$, $p = 0.093$). However, onset age of playing piano was significantly negatively correlated with CA Learning ($r(27) = -0.373$, $p = 0.023$), and also passed the Bonferroni corrected significance level of $p < 0.025$. This indicates that the earlier the onset age of playing piano, the higher the implicit sequence learning. Since onset age of playing piano was correlated with years of playing piano ($r(27) = -0.696$, $p < 0.001$), we also conducted partial correlations while controlling for years of playing piano. This analysis resulted in weakening the correlation ($r(26) = -0.277$, $p = 0.076$) to a near significance level only. On the other hand, the correlation between years of playing piano and CA Learning when controlled for onset age of playing piano ($r(26) = 0.001$, $p = 0.500$) did not provide any indication of a relation between years of playing piano and CA Learning. In sum, the only significant bivariate correlation we observed was between onset age of learning piano and CA Learning. Although this correlation remained only at a near significance level after controlling for the influence of years of playing piano, the explained variance (7.7%) was higher than the explained variance of the correlation between years of learning piano and CA Learning controlled for onset age of playing piano (0.0001%).

Discussion

This is the first study to investigate the effect of pianists' expertise on implicit oculomotor–perceptual sequence learning. For its evaluation, we used an eye-tracked variant of the standard SRT, the O-SRT, which enables the assessment of manual-free implicit sequence learning. Previous research has demonstrated enhanced implicit sequence learning of pianists in manual SRT versions (Landau et al., 2006; Romano Bergstrom et al., 2012). Whether this advantage was also related to higher motor and/or visuo-motor abilities could not entirely be excluded. Moreover, these versions were probably not sensitive enough to capture differences between pianists and controls in explicit memory sequence knowledge and/or strategies while performing on the SRT. Since professional pianists have also been reported to use explicit memorizing techniques while playing piano (Chaffin et al., 2009; Globerson & Nelken, 2013), it is possible that pianists would also acquire higher explicit knowledge of procedures other than their expertise. Shedding light on these aspects was the aim of the current study.

We examined the O-SRT task performance of two groups: pianists and controls. Both groups learned the sequence implicitly as expressed by significant main effects in all three critical phases of the evaluation of implicit sequence learning (i.e., Learning, Interference and Recovery from Interference) and this applied to both reaction time (RT) and correct anticipations (Percentage CA) measures. We found significant interactions of Group by Learning, Group by Interference and Group by Recovery from Interference for both RT and Percentage CA measures, presenting a very robust finding clearly demonstrating that pianists outperformed controls.

Both groups reached a high level of recovery as demonstrated by both measures (RT and Percentage CA) in *Recovery Level—Block* and in both groups, recovery was not immediate (i.e., as evaluated in *Recovery Level—Sequence*), Furthermore, equivalence tests we conducted to compare RT performance on block 1 between the groups were significant. This result implies that the advantage of pianists in learning the sequence is not related to possible differences in processing speed, which was previously reported to be higher in pianists (Bugos & Mostafa, 2011).

Our findings confirm the results of previous studies (Landau et al., 2006; Romano Bergstrom et al., 2012), showing that pianists express superior motor implicit sequence learning. However, these studies used manual SRT versions that demand manual responses and S–R mapping, in contrast to the O-SRT used in the present study. Compared to the standard manually activated versions of the SRT that measure primarily RT, the O-SRT provides an additional measure such as correct anticipations (CA). Whereas RT is considered to be an indirect measure of implicit sequence learning, the CA measure allows direct assessment of whether or not a sequence has been learned, and to what extent. Furthermore, the OA measure of RT is itself a purer measure than the manually activated measure of RT, because it does not involve the general learning skill of mapping the spatial location of the screen stimulus to the corresponding key press (stimulus–response mapping).

Practicing piano by its very nature strengthens the same abilities that are required to perform well on the manual SRT, namely visuo-motor coordination (Haslinger et al., 2005), learning complex sequential relationships and fine motor precision (Aoki et al., 2005; Globerson & Nelken, 2013). Furthermore, musicians have also been found to be faster during visual imaging tasks, suggesting that musicians are faster than non-musicians in linking visual stimuli to certain sensory-motor movements and actions (Brochard et al., 2004). Thus, a potential dependency on enhanced motor and visuo-motor abilities for their advantage in implicit sequence learning as tested in previous studies (Landau et al., 2006; Romano Bergstrom et al., 2012) was possible. Our findings, however, do provide evidence that pianists' superiority in implicit sequence learning was not due to better visuo-motor and/or fine motor processes, since our study did not require participants either to perform S–R mapping or to respond with finger presses. Furthermore, apart from RT we also measured CA, which is considered to be a purer measure of implicit sequence learning. CA expresses directly measured correct anticipations in contrast to RT, which measures anticipation indirectly (Vakil et al., 2017). Hence, our results strongly support the assumption that pianists are superior in general sequence learning ability that goes beyond their domain of expertise.

As expected, we found that most pianists tested in our study expressed sequence awareness, and more than half were able to reproduce at least part of the sequence. Moreover, compared to controls, pianists expressed significantly higher sequence awareness and demonstrated higher ability in sequence reproduction as reflected by the results of the generate task. These results confirm our hypothesis that pianists would show higher explicit sequence knowledge than controls. This finding is consistent with the demands that playing piano imposes on a professional pianist. To keep track of progress while playing a musical piece, it is essential to develop explicit memory techniques in the form of a mental map, in parallel to implicitly guided piano playing (Chaffin et al., 2009; Globerson & Nelken, 2013). Therefore, the attempt to explore situations explicitly may be enhanced in pianists. It is also likely that pianists possess an enhanced availability of cognitive resources as a result of faster implicit sequence learning. In other words, if a sequence is learned implicitly, then distractions caused by errors are reduced, which may in turn free cognitive resources in the form of explicit problem detecting strategies. Another possible explanation is that higher implicit sequence learning enables pianists to have better access to the explicit representation of the sequence in the form of bottom–up processes.

The question of whether the pianists' advantage in implicit sequence learning was also related to their enhanced explicit knowledge, and whether and how explicit processes were involved in our samples, is difficult to answer. At first glance, the fact that pianists expressed significantly higher explicit sequence knowledge may suggest that explicit sequence learning processes contributed to enhanced implicit sequence learning. However, we need to consider several factors. First, the groups themselves were heterogenic, and both groups contained participants who expressed no explicit knowledge at all. Second, we need to bear in mind that sequence awareness reflects understanding of the sequential nature of the task. However, and in contrast to sequence reproduction, that does not necessarily mean that participants also knew the sequence explicitly or part of it. Third, we need to be cautious about the assumption that sequence reproduction (i.e., as measured by a free generate task) reflects pure explicit knowledge, since this may be modulated by implicit memory processes, as previously suggested (Destrebecqz & Cleeremans, 2001; Norman et al., 2006). Responses in a sequence recognition or generate task may be guided by "feelings of rightness and wrongness associated with the different target positions" (Norman et al., 2006, p. 729). Nonetheless, the results of our correlation analyses between implicit and explicit sequence measures provide insights that may offer some understanding about the relation of implicit sequence learning and explicit sequence knowledge in pianists. Our finding that sequence awareness was related to both of the pianists' learning scores but not controls (i.e., RAs, CAs) suggests that pianists' implicit sequence learning is directly related to sequence awareness, whereas in controls this relationship does not seem to play a significant role. However, based on this type of analysis we cannot state anything about the causal direction, such as whether pianists' explicit awareness may have contributed to better learning of the sequence, or whether better implicit sequence learning led to enhanced awareness. The fact that we did not find a significant correlation in pianists between sequence reproduction and learning scores may indicate that explicit knowledge in the learning phase was not yet fully developed and was only present in the form of awareness. An alternative explanation may be that pianists were heterogenic in their strategies while performing the SRT, so that some were more and others less engaged in explicit sequence learning. To test the former assumption, we conducted post hoc tests and correlated sequence reproduction of the pianist's group with the recovery scores (i.e., RT Recovery, CA Recovery), as well as with the values of the recovery block (mean of median RT and mean of percentage of CA of block 8). All these correlations were significant and survived Bonferroni correction (except for the correlation between sequence reproduction and absolute value of CAs in percentage). Thus, pianists with higher sequence reproduction also demonstrated a higher recovery effect as well as better absolute performance on the recovery block, confirming our assumption that sequence reproduction is not fully developed during the learning phase, but rather during the last block of the task. Based on this outcome, the picture emerging is that pianists demonstrate superiority in implicit sequence learning and also express higher explicit sequence knowledge in the form of awareness and sequence reproduction ability compared to controls. Moreover, only in pianists was sequence awareness related to better implicit sequence learning, and higher sequence reproduction ability in pianists was not related to better performance during learning but rather recovery. The latter indicates that explicit knowledge in the form of sequence reproduction is compiled rather towards the end phase of the task. It may be likely that confrontation with the interference sequence (i.e., block 7) further increased the pianists' awareness about the nature of the task, leading them to engage explicit strategies to solve the rest of the task together with their acquired implicit knowledge. The question of whether explicit sequence knowledge did contribute to higher implicit sequence learning cannot be resolved with our method, which leads to the limitation of our study. We cannot assume that "explicit knowledge" significantly contributed to better implicit sequence learning in our pianists. It is possible that pianists in our sample were better at translating their implicit knowledge into explicit knowledge when explicitly asked to do so (Jimenez et al., 2006). Moreover, the procedure of the free generation task may have been an advantage for the pianists, so that pianists were better in using the tactile information while pointing out the sequence. This is a limitation of our study, and in future research, evaluating pianists should use task versions with verbal instead of tactile responses. In general, the evaluation of disentangling the contribution of implicit and explicit sequence knowledge to improved performance on procedural learning tasks such as the SRT is a methodological challenge in the tradition of implicit sequence learning research (see Barth et al., 2019). Therefore, future research in the field of implicit sequence learning is needed to address this problem with newer approaches.

Finally, we aimed to understand the influence of measures related to piano playing such as onset age, years of playing piano and average practicing time since onset on implicit sequence learning. Our hypothesis that the lower the onset age is, the higher the implicit sequence learning, was confirmed. We found a significant negative correlation between onset age and CA Learning. In contrast, years of playing piano and average practicing time since onset were not significantly related to implicit sequence learning. These findings suggest that onset age rather than the amount of piano playing does play a critical role in implicit sequence learning abilities of pianists. This is consistent with the observation that adults with a musical training onset before the age of seven had higher motor abilities, compared to those with a musical training onset after the age of seven (Watanabe et al., 2007). Importantly, the groups were matched for years of musical practice, years of formal education and hours of current practice. Moreover, Vaquero et al. (2016) showed that early onset of piano playing, which was corrected for the amount of playing (i.e., the pianists differed in their age of onset of playing piano but not in their lifetime or present amount of practicing piano), was associated with lower volume of the right putamen and better performance in piano playing. The authors suggested that "neural efficiency due to intensive and long-term skill training seems to be determined by the age of commencement of musical practice" (p. 117). The putamen is part of the basal ganglia which is a key brain structure that has been associated with procedural learning (Janacsek et al., 2020; Keele et al., 2003; Vakil et al., 2000). Hence, our results may suggest that differences in neural efficiency previously linked to onset age of playing piano may also account for differences in implicit sequence learning abilities of pianists. There may possibly be a critical window of learning sequential relations during childhood which results in better implicit sequence learning in the future. Considering that implicit sequence learning and procedural learning respectively, have been associated with language and/or math processing (Evans & Ullman, 2016), future research could examine the link between early onset playing piano—higher implicit sequence learning—higher language and/or math abilities. At the same time, it may be of high importance to study whether playing piano at an early age can influence positively (i.e., protection factor) the development of possible language and/or math learning disorders. However, our finding needs to be treated cautiously, considering that we found only for CA Learning but not for RT Learning a significant correlation with onset age of playing piano. Furthermore, this correlation remained only at a near significance level after controlling for years of playing piano, but still explained more variance than the correlation between years of playing piano and CA Learning controlled for onset age of playing piano, for which the explained variance was practically nil. Therefore, future research is needed to confirm this relationship.

Our study has a few limitations in addition to the limitations mentioned above. First, musicians' abilities were assessed via self-report in a rather brief way. Whereas the onset age of playing piano and years of playing piano can be assumed to be reliable measures, this may not be the case for the average practicing time of playing piano. Therefore, our results in reference to practice aspects need to be treated with caution. Future studies should use standardized questionnaires (both self and external assessments). Second, we cannot exclude that higher visual tracking abilities also contributed to the higher performance of implicit sequence learning in pianists. Nevertheless, considering that the O-SRT as any other SRT task was intentionally designed in a simple fashion to avoid complex visual processing, we do not think that possible higher visual tracking abilities in pianist were a main factor leading to higher sequence learning performance. Third, our study group of pianists contained both professional and non-professional pianists, as part of the planned study design to provide a larger data spectrum for the correlation analyses. However, non-professional and professional pianists may provide a distinct implicit sequence learning pattern, and future studies may evaluate two groups of pianists such as professional and non-professional pianists.

In conclusion, our study presents robust findings that pianists are superior in implicit sequence learning. This kind of learning is not related to their ability to link visual stimuli to actions (Brochard et al., 2004) or enhanced finger motor precision (Aoki et al., 2005), since we used a SRT version that does not require such abilities. Furthermore, by directly assessing anticipations of the subsequent target location we were able to generate critical insights, since pianists not only showed a steeper learning curve of correct anticipations but also differed in its extent (i.e., higher Percentage CA during learning and recovery phase, lower Percentage CA during interference phase). The findings of the baseline comparison (i.e., first blocks with sequence A and sequence B) indicate that pianists did not demonstrate an advantage in the initial phase, but developed their superiority while learning the sequence. Although not directly assessed, this also indicates that differences in processing speed cannot explain pianists' advantage. Moreover, compared to controls, explicit knowledge was higher in pianists, as reflected by sequence awareness of their learning phase. Higher sequence reproduction was not related to their learning phase, but led to better performance during recovery, which suggests that this form of knowledge is present in the end phase of the task. We cannot infer the causality of these relations, but we also cannot exclude the likelihood that explicit processes helped pianists to perform better. Finally, although we do not know the direction of the negative correlation of onset age and implicit sequence learning (i.e., CA Learning), it is possible that early onset of piano playing results in higher implicit sequence learning ability.

Other future aspects worth studying in the field of pianists and implicit sequence learning are related to factors influencing explicit memory processes during procedural learning, including the assessment of an inherent disposition to its recruitment. Furthermore, it is likely that musicians other than pianists may demonstrate different patterns in implicit and explicit sequence learning, since professional pianists are especially required to perform from memory, which is not necessarily the case for other types of musicians. Finally, it would be interesting to study whether other groups of experts such as professional dancers or other sport performers show similar or different implicit sequence learning profiles.

Funding This work was supported by the Israeli Ministry of Defense, Rehabilitation Department under Grant number 203003-846. This sponsor had no role in writing the review or in the decision to submit the article for publication.

Declarations

Conflict of interest The authors report no conflicts of interest or competing interests.

Availability of data and material (data transparency) The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability (software application or custom code) Not applicable.

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