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Markers of Musical Expertise in a Sight-Reading Task: An Eye-Tracking Study

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Classical music pianists of five different conservatory levels, from undergraduate to professional, were tested on a sight-reading task with eye-movement recording. They had to sight read both tonal classical scores that followed the rules specific to Western tonal music, and atonal contemporary scores, which do not follow these rules. This study aimed at determining the extent to which eye movements and musical performance metrics can account for the level of sight-reading expertise. First, the results indicated that with the acquisition of expertise, musicians process visual information more rapidly (increasing their played tempo while decreasing average fixation duration and their number of fixations), more structurally (tending to increase their eye–hand span), and more accurately (increasing their sight-reading accuracy). Second, when they sight read contemporary scores compared to classical scores, musicians decreased their played tempo, tended to be less accurate, increased their number of fixations, and tended to decrease their eye–hand span. Finally, expertise effects were moderated by the type of score. These results suggest (a) that visual perception is progressively shaped through music reading expertise and through domain-specific knowledge acquisition, (b) that tonal-specific cues play a significant role to use an efficient eye-movement behavior and (c) that the benefit conferred by expert prior music-specific knowledge seems to be even greater for sight-reading tonal rather than atonal scores. Our findings are discussed in the light of expert memory theories (long-term working memory theory; Ericsson & Kintsch, 1995; template theory, Gobet & Simon, 1996).

Keywords: eye movements, expertise, domain-specific knowledge, perceptual span

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One of the main characteristics of expertise is the ability to process information in a structured way. For more than half a century, it has been shown that while human working memory (WM) capacities appear to be limited (Cowan, 2001; Miller, 1956), experts demonstrate unimaginable memory capacities in their domain of expertise. In a landmark study by Chase and Simon (1973), an expert chess player was able to memorize and recall the position of 16 pieces on average after a 5-s presentation of a chessboard, but only when the pieces were organized according to familiar subconfigurations. His performance dropped to the level of a novice (2–3 pieces) when the pieces were presented in randomized positions. These observations led the authors to propose the chunking theory, which postulates that chess experts benefit from domain-specific knowledge and routine strategies allowing them to process chess pieces in the form of groups, called chunks, that have a perceptual or a semantic relationship instead of processing chess pieces one by one (Chase & Simon, 1973; Gobet et al., 2001; see Kowler, 2011; Waters et al., 1998, for an extension of the chunking theory to other domains than chess). This phenomenon is the result of many years of deliberate practice of a given activity (Chase & Ericsson, 1982; Ericsson et al., 1993; Ericsson & Lehmann, 1996), which enables an individual to accumulate knowledge into a superstructured memory organization. While the chunking theory, as initially presented by Chase and Simon (1973), assumes that during a domain-specific task, chunks would be stored in WM, later studies

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showed that expert memory is relatively resistant to interfering tasks (Charness, 1976; Chevet et al., 2022; Glanzer et al., 1981, 1984). Furthermore, the number of chunks an expert is able to keep active in WM is greater than the assumed WM capacities (Gobet & Simon, 1996). These results are not in line with studies showing that the active storage of information in WM should be affected by interfering tasks (Conrad, 1967) and limited to only a few chunks (Cowan, 2001; Miller, 1956). For these reasons, other expert memory theories, such as the long-term working memory theory (LTWM; Ericsson & Kintsch, 1995) and the template theory (Gobet & Simon, 1996, 2000), emphasize the importance of long-term knowledge networks to account for exceptional expert performance. The LTWM theory assumes that a part of the long-term memory (LTM) is activated and can be used as a support for information processing during domain-specific tasks involving WM. Experts would recognize similarities between elements of the task and elements acquired in LTM, allowing them to generate retrieval structures (hierarchical organization of the encoded information, linked to prior knowledge networks and enabling structured and efficient information retrieval). Overall, LTWM theory assumes that information is encoded in a meaningful way and retrieved in a structured way and that both encoding and retrieval are accelerated with expertise acquisition. In the case of chess, Gobet and Simon (1996) postulate that the generated retrieval structures can take the form of templates (structures larger than chunks comprising a core of fixed elements and variable parts called slots). These templates represent strategic knowledge about chess positions and are associated with a set of previous moves and possible future moves. These knowledge structures give the expert information about the context of the chess position, facilitating the encoding and retrieval of information. The activation of these long-term retrieval structures/templates would thus decrease the workload allocated to the short-term WM and facilitate information processing (for a review, see Guida et al., 2012). In fact, different studies show that the more elements of a task are encoded as a single meaningful unit of information, the more storage space this seems to free up in WM (Garavan et al., 2000; Jansma et al., 2001; Olesen et al., 2004). In a study by Thalmann et al. (2019), the authors showed that remembering a random list of words was easier when another list, to be remembered simultaneously, was a chunk than when it was another random list. Moreover, studies show a decrease in pupil size in experts compared to nonexperts, indicating a lower workload allocated to WM with expertise acquisition (Bednarik et al., 2018; Castner et al., 2020).

Expert Memory Shapes Visual Perception

As visual acuity is not the same at each location of the retina (Legge & Bigelow, 2011), only the fovea, a restricted area of about 1° of the visual angle of the retina, allows the processing of fine-grained visual information. The parafoveal area (2°–5° around the fovea) allows the processing of low-level visual information, such as shape recognition, whereas the peripheral region (the rest of the retina) does not allow any visual information to be extracted. For that reason, during reading or whatever the goal of the visual inspection, the gaze must move across the visual scene to process visual information, and eye movements are an alternation of fixations (to extract visual information) and saccades (jump from one fixated location to another).

To study expert perception and understand the cognitive mechanisms underlying expertise differences, eye tracking is a widely used technique (for reviews, see Brams et al., 2019; Gegenfurtner et al., 2011; Reingold & Sheridan, 2011). There is a consensus around the fact that retrieval structures stored in LTM shape visual perception (de Groot, 1965; de Groot et al., 1996; Drai-Zerbib & Baccino, 2018; Gobet, 2017; Reingold et al., 2001; Sheridan et al., 2020). First, consistent with the acceleration principle of encoding and retrieval (Chase & Ericsson, 1982), expertise leads to the acceleration of visual information extraction. Studies have shown shorter average fixation durations on a visual scene in experts compared to nonexperts (Dreiseitl et al., 2012; Francuz et al., 2018; Krupinski et al., 2014; Laurent et al., 2006; Piras et al., 2014; Prytz et al., 2018; Roca et al., 2013; Williams & Davids, 1998; Williams et al., 1994), while the number of fixations has been shown to be lower in experts compared to nonexperts (Bertram et al., 2013, 2016; Dong et al., 2018; Dreiseitl et al., 2012; Francuz et al., 2018; Godwin et al., 2015; Krupinski et al., 2014; Lex et al., 2015; Manning et al., 2006). Overall, the decrease in the average fixation duration and number of fixations in a given task reflects the accelerated information encoding thanks to the activation of high-level knowledge networks. Furthermore, consistent with the principle of meaningful encoding, most of the studies that focus on visual expertise have shown that experts are able to process more information during a single fixation (referring to the so-called perceptual span; Bilalić et al., 2011; Charness et al., 2001; Krupinski, 1996; Manning et al., 2006; Nodine et al., 1996; Reingold et al., 2001; Reingold & Charness, 2005; Ryu et al., 2015; Waters et al., 1998), in particular due to their ability to process more parafoveal information (Sheridan et al., 2020). It is thus commonly acknowledged that perceptual span increases with expertise (Kundel et al., 2007; Nodine & Kundel, 1987; Perra et al., 2021; Rayner, 1998; Reingold et al., 2001).

Music Reading Expertise

While chess and medicine are well-studied in visual expertise research, Brams et al. (2019), Gegenfurtner et al. (2011), and Sheridan et al. (2020) point to the need for the visual expertise literature to be more integrative by linking more domains of expertise to complete the knowledge about specificities and limitations in this field. Among the domains enabling the use of innovative paradigms, the study of music reading is relatively well documented. Music reading offers a unique insight into the research area of visual expert memory. In fact, music reading tasks are different from visual detection tasks proposed in the fields of medicine and chess because on the one hand, as in text reading, music reading involves sequential information processing in which the attentional focus continuously shifts to the upcoming note in the reading direction (Rayner, 1998), and on the other hand, it involves multisensory information processing (auditory, visual, motor; Drai-Zerbib & Baccino, 2005, 2018; Stewart et al., 2003).

In line with the characteristic principles of expert memory, expertise in music reading also results in structural processing. Indeed, several studies have tested the application of the chunking theory (Bennett et al., 2020), the LTWM theory (Drai-Zerbib & Baccino, 2005, 2018; Williamon & Valentine, 2002), and the template theory (Maturi & Sheridan, 2020; Sheridan & Kleinsmith, 2022) to the music domain. Expert musicians can benefit from a long-term knowledge network with the chunking of notes, chords,

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arpeggio, or rhythmic patterns, for instance (Bennett et al., 2020; Halpern & Bower, 1982; Maturi & Sheridan, 2020; Sheridan et al., 2020; Sheridan & Kleinsmith, 2022; Waters et al., 1997) but also from the processing of higher level, hierarchically linking elements in the musical structure of a score (Drai-Zerbib & Baccino, 2005; Williamon & Valentine, 2002). Studies using verbal protocols report that expert musicians use structural elements to memorize a score, such as phrasing marks, repeated note sequences or repeated phrases (Aiello, 2001; Chaffin, 2007; Chaffin & Imreh, 1997, 2002; Clarke, 1988), while analyses of musical performance indicate that expert musicians start and stop their production sequences more frequently at the beginning and end of structural bars as they learn a piece, highlighting the role of musical structures in expert information processing (Williamon & Valentine, 2002).

During the development of music reading expertise, sight-reading is a highly trained task involving the execution of a score with very little or no preparation (Wolf, 1976). In Western musical training, musical practice is mainly based on Western tonal music, which follows a number of melodic, harmonic, rhythmic, and metrical rules structuring the succession of notes and chords and involves an alternation of features that generate and resolve tensions (Lerdahl & Jackendoff, 1983). Music reading expertise involves the construction of long-term retrieval structures based on these rules (Drai-Zerbib, 2016; Drai-Zerbib & Baccino, 2018). The knowledge structures related to tonal music acquired with music expertise would allow the expert to anticipate the upcoming features of a score and to benefit from the musical context in a sight-reading task. Concretely, the occurrence of a musical event within a tonal score can be anticipated by an expert musician according to the musical context. In a study by Waters et al. (1998), expert musicians benefited from a priming effect of a chord mode (major/minor) to encode the following ones, whereas this was not the case in novices. Insofar as some events are very likely for the expert musicians, visual processing of the score is more rapid (Truitt et al., 1997), and expert musicians do not pay attention to every single musical event (Drai-Zerbib & Baccino, 2005; Drai-Zerbib et al., 2012; Wolf, 1976). This phenomenon can be illustrated by the well-documented phenomenon of the proofreader's error (Wolf, 1976) experienced by Boris Goldovsky, a piano teacher. This teacher struggled more in identifying an erroneous impression of a note within a chord while reading a score than his student. The tonality of the score implied that the chord could not be other than the one Goldovsky inferred from the tonal context. He processed it as a chunk. This phenomenon highlights the fact that expert long-term knowledge structures can shape visual perception, leading to rapid and structural processing rather than individual event processing.

Moreover, expert musicians benefit from a multimodal expert memory. Studies have shown that experts can generate an amodal retrieval structure during the encoding of a score (i.e., expert musicians could retrieve information in a different modality of the encoding one). For example, expert musicians were found to ignore inappropriate fingering information on the score, in particular when they previously listened to the melody, emphasizing the use of cross-modal retrieval structures to perform the task (Drai-Zerbib & Baccino, 2018). Reading a score written in a given tonality would activate a set of notes, chords, and instrumental auditory–motor representations from LTM, facilitating musical information processing (Williamon & Egner, 2004).

Visual Expertise in Music Reading

Interest in expertise effects on eye movements in music reading was initiated by Goolsby's (1994a, 1994b) studies, in which he noticed that expert musicians make shorter progressive fixations than less expert musicians (Goolsby, 1994a) and that expert musicians tend to make fewer fixations per group of notes than less expert musicians (Goolsby, 1994b). Although these studies were conducted on a small number of participants, they laid the groundwork for the study of expertise in music reading through eye movements.

Overall, the literature's findings are consistent with the assumption that, compared to nonexperts musicians, expert musicians process the score more rapidly and based on musical structure rather than individual elements. The most robust results concern the average fixation duration. In a large majority of studies, expert musicians make shorter fixations than less expert musicians (Drai-Zerbib & Baccino, 2005; Drai-Zerbib et al., 2012; Imai-Matsumura & Mutou, 2021; Truitt et al., 1997; Waters & Underwood, 1998; for a recent meta-analysis, see Perra et al., 2022). The fixation duration is an indicator of processing time (Rayner, 1998). The longer fixation durations of the less expert musicians compared to the more experts indicate that the encoding of musical stimuli requires more time to process the score. These results are in line with the acceleration principle assumed in expert memory theories (Chase & Ericsson, 1982). Moreover, studies show that the average distance between the eye position and the played note on the score (the so-called eye–hand span, EHS; for a review, see Perra et al., 2021) is greater in expert than in less expert musicians (Furneaux & Land, 1999; Gilman & Underwood, 2003; Penttinen et al., 2015; Truitt et al., 1997). Consistent with expert memory theories (Ericsson & Kintsch, 1995; Gobet & Simon, 1996), expert musicians are able to keep active more elements in WM between the visual intake and the motor outcome of the score, emphasizing the fact that visuomotor information processing is more structural in expert musicians than in less expert musicians.

Cross-Study Consistency Limits in Music Reading

Most music reading studies are in line with theories of expert memory, showing that experts make shorter fixation durations than less experts and novices and that there is an increase in the perceptual span with expertise (Sheridan & Kleinsmith, 2022; Waters et al., 1998). However, the diversity of methodological design choices can affect the interpretation of findings obtained in the field of music (for related discussions, see Perra et al., 2022; Puurtinen, 2018; Sheridan et al., 2020).

First, it seems useful to mention that music reading studies have been carried out on different tasks. Among these tasks, we distinguish between those with an associated musical production, such as sight-reading or trained musical reading (to perform a score already practiced), and those without an associated musical production, such as silent reading, pattern-matching, or altered note detection tasks, in which the motor production is not required. Contradictory findings have been reported about how eye-movement behavior evolves with expertise depending on the task used. An increase in the total fixation duration on relevant areas has been observed as a function of expertise in a pattern-matching task (Maturi & Sheridan, 2020), which is not in line with the main results noticed in the literature regarding the effect of music reading expertise showing a decrease in fixation durations with expertise (Perra et al., 2022). However, this can be explained by the type of task being performed in which expert behavior results in an increase in fixation duration on task-relevant areas compared to nonexpert behavior (Gegenfurtner et al., 2011; Haider & Frensch, 1996, 1999). In this case, the task-relevant areas corresponded to the target pattern and the pattern to be found in the score. Moreover, the literature presents divergent results on the effect of expertise on the number of fixations. Expert memory theories assume a deeper encoding of information with expertise through rapid indexing of task information to a knowledge structure (Chase & Ericsson, 1982). This would imply a decrease in the number of fixations on the stimulus (for a meta-analysis, see Gegenfurtner et al., 2011). In the case of text reading, studies have shown that prior knowledge about the topic of a text (the situation model, van Dijk & Kintsch, 1983) induces a decrease in the number of fixations and refixations (Jian, 2022; Rayner et al., 2006; Wu & Liu, 2021). However, in a recent meta-analysis (Perra et al., 2022), the number of fixations has not been shown to be a discriminating metric of the level of expertise in music reading. This lack of effect could be due to methodological choices, such as the choice of imposing a tempo or not in a music reading task. Tempo has an impact on the duration of the notes to be played and, thus, on the time available to decipher them. In a study by Truitt et al. (1997), musicians were divided into two skill groups according to their chosen tempo. Musicians who played at a higher tempo were also those who made shorter fixation durations. On the other hand, whether a tempo is imposed can induce different eye-movement behaviors (Kinsler & Carpenter, 1995). In a study by Penttinen et al. (2015), in a task with imposed tempo, expert musicians showed interbeat gaze activity and inspected areas of interest that were adjacent to the note played, while less expert musicians did not. These results could be explained by the fact that expert musicians extracted visual information from the score more rapidly than less expert musicians and used the remaining time available between two musical beats to explore the score. In contrast, in the absence of an imposed tempo, musicians who decipher visual information more rapidly would be more likely to play the score with a faster-chosen tempo (Drake & Palmer, 2000; Truitt et al., 1997) than to use the time available between two musical beats to explore the score.

Second, methodological diversity could lead to a lack of consistency in the results related to the evolution of eye movements in music reading (Puurtinen, 2018). On the one hand, there is a great diversity in the musical material used. We can notice studies testing the effect of expertise on eye movements using relatively complex scores similar to what a musician encounters in their daily practice (Rosemann et al., 2016; Wurtz et al., 2009), while other studies favor simple material with low intrascore variability, such as scores composed mainly of diatonic notes (Huovinen et al., 2018). The criteria for manipulating the expertise factor also differ across tasks. Some studies compare experimental groups of expertise based on music conservatory level (Drai-Zerbib & Baccino, 2018; Drai-Zerbib et al., 2012) or years of musical practice (Huovinen et al., 2018; Penttinen et al., 2015). In other studies, experimental groups are formed by discriminating participants based on their task accuracy (Cara, 2018; Gilman & Underwood, 2003; Hadley et al., 2018; Lörch, 2021). To define their experimental groups, some authors distinguish, for example, between skilled and less skilled sight-readers based on the number of errors they make (Lim et al., 2019; Sloboda, 1974) or their chosen tempo (Truitt et al., 1997). Given these differences in determining expertise groups, some musicians considered to be in the less expert/less skilled group in some studies could have been considered as experts/skilled in other studies (Cara, 2018). Overall, methodological diversity makes the field of music reading rich, but these differences can be problematic for synthesizing findings on markers of visual expertise. Recent literature reviews on this topic (Perra et al., 2022; Puurtinen, 2018; Sheridan et al., 2020) highlight a need to further investigate the question of the evolution of eye-movement metrics as a function of musical expertise.

The Present Study

The aim of this study was to determine how eye-movement and behavioral metrics in sight-reading evolve through the development of musical expertise. Specifically, we aimed to determine whether eye movements can reflect the level of elaboration of the memory structures developed with expertise and if there is a threshold in the musical education beyond which eye-movement and behavioral metrics no longer evolve. Since the theories of expert memory assume that during the practice of activity, knowledge structures develop in LTM and play a key role in domain-specific WM tasks (Ericsson & Kintsch, 1995; Gobet & Simon, 1996), allowing experts to process information in a rapid and structured way (Ericsson & Kintsch, 1995; Gobet & Simon, 1996), we hypothesized that this should be reflected in the evolution of eye movement and behavioral metrics in a sight-reading task.

Among the studies having already attempted to test the effect of expertise on eye movements in the music domain, only a few proposed a sight-reading task. Yet the sight-reading task is an unequaled resource for studying expert cognition, as it requires the musician to coordinate visual, auditory, and motor processing while respecting the temporal constraints imposed by the score, and this, while performing it for the first time or after very little preparation. Sight reading is a demanding task requiring a high level of information processing, which is not the same as in trained or silent reading tasks or in pattern matching tasks. In our study, the task that the musicians had to perform was strictly a sight-reading. Moreover, for ecological purposes, the chosen material was extracted from pieces written by professional composers so that the scores correspond to those used on a daily basis.

In addition, no study has tested the evolution of eye movements across multiple levels of musical training, and it remains unclear whether the information-processing benefits associated with the development of knowledge structures during musical training occur abruptly (with a rapid spike in performance after reaching a certain level of knowledge), or whether this phenomenon is more gradual. Moreover, the question of the existence of a skill threshold beyond which performance and eye movements would no longer evolve remains unanswered. In this study, pianists of five levels of musical training, ranging from undergraduate to professional level, performed a sight-reading task without tempo constraint. We expect that the novelty of using a sight-reading task with eye-movement recording on musicians from five conservatory levels will provide information on how long-term knowledge structures are elaborated and, if so, on the turning point(s) in music education at which skill progression occurs.

Finally, in our study, there were two different types of scores for sight-reading. Musicians were asked to sight-read scores from a classical repertoire that respected the rules of Western tonal music

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and scores from a contemporary repertoire that did not respect the rules of Western tonal music. On the one hand, during their musical training, musicians are usually confronted with scores from the tonal repertoire rather than the atonal repertoire, and on the other hand, scores respecting the rules of Western tonal music are structured based on a tonal architecture/hierarchy influencing the probability of occurrence of each musical event depending on the tonal context of a score (Lerdahl & Jackendoff, 1983). In concrete terms, given the tonal context of a score, some musical events are statistically more likely to occur than others. In an atonal score, all musical events are basically equiprobable, making it difficult, if not impossible, to form expectancies on future musical events when sight-reading the score and increasing the complexity of the sight-reading task. Based on expert memory theories (Chase & Simon, 1973; Ericsson & Kintsch, 1995; Gobet & Simon, 2000), which state that knowledge acquired by experts in a discipline is domain-specific, the musical knowledge structures elaborated with musical expertise should be predominantly determined by the greater exposition of the rules of Western tonal music. Thus, the musical knowledge structures acquired with musical expertise are expected to be more useful for sight-reading tonal than atonal scores. For this reason, we expected musicians to process information more efficiently as the level of expertise increased, and even more in the tonal condition than in the atonal condition.

Overall, since there was no tempo constraint, we assumed that eye movements and performance would reflect the acceleration of the encoding and retrieval of musical information through the acquisition of musical expertise as well as the greater difficulty in processing the score in the atonal compared to the tonal condition. For these reasons, we hypothesized that musicians would be more rapid (faster tempo) and accurate at the task and that they would show fewer fixations and shorter fixation durations, as well as a larger EHS with expertise acquisition. Second, we expected that sight-reading contemporary atonal pieces would lead to a decrease in performance accuracy, tempo, and EHS, as well as to an increase in time to process musical information compared to classical Western tonal pieces.

Method

Participants

Sixty-eight volunteer participants comprising students, teachers, and professional musicians from French conservatories were recruited. They were distributed into five groups depending on their level of musical training at the conservatory: 15 participants were students from the first cycle at the conservatory (M_{age} = 11.47 years; SD = 1.69), 15 from the second cycle (M_{age} = 14.00 years; SD = 3.14), 14 from the third cycle (M_{age} = 20.14 years; SD = 3.63), eight from *Classe Préparatoire à l'Enseignement Supérieur* corresponding to a college level in the international system (M_{age} = 21.63 years; SD = 6.80), and 16 were from the Conservatoire National Supérieur de Musique or professional musicians (M_{age} = 38.44 years; SD = 12.74). The sample size was defined with a power analysis using G*Power (Faul et al., 2009) with power ($1 - \beta$) set at 0.80 and $\alpha = 05$, and an expected medium effect size ($f = 0.25$) according to Cohen (1988). The analysis revealed that a total sample size per group (N = 15) would be needed to obtain sufficient statistical power at the recommended .80 level (Cohen, 1988). To be included in the experiment, the musicians had to be pianists at the end of a music conservatory cycle. Fifty-six participants were right-handed, and 12 were left-handed, and all participants had normal or corrected-to-normal vision. Participation was rewarded with a gift card of 15 €.

Material

The material consisted of 34 dual-staff excerpts of four bars extracted from piano compositions corresponding to ecological score (i.e., material musicians may encounter in their daily practice; see the Appendix section). Twenty-three of these excerpts were classical scores, and eleven were contemporary scores (Figures 1 and 2). We wanted to present musical scores that were ecological but did not generate a mental workload that was too intense for the less expert musicians. For this reason, the number of contemporary scores was reduced compared to classical scores. Classical scores (CL) respected the rules of the Western tonal system, which were studied extensively during musical training at the conservatory, whereas contemporary scores (CO) were outside of the tonal system and less studied than classical scores.

All scores were written with the Final music notation software. They were presented on a 17″ screen with a resolution of 1,920 × 1,080 pixels. The music performance was recorded by a musical instrument digital interface, which sent the input of the piano (KAWAI VPC1 with an RM3 Grand II wooden-key action) to the Reaper software installed on another computer. Eye movements were recorded using an EyeLink Portable Duo by SR Research, which was set on the computer (Figure 3). Both eyes were tracked with a sampling rate of 1,000 Hz.

The Digit span subtest of the Weschler scale was used to measure auditory–verbal WM capacities. The Coding subtest of the Weschler

Figure 1

Example of a Classical Score Used in the Experiment

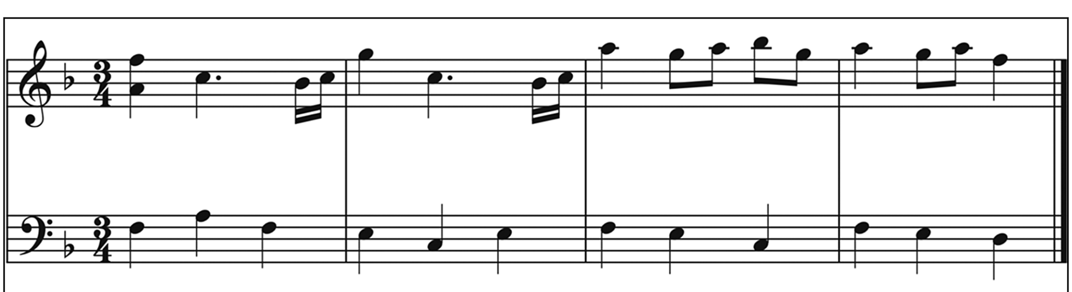
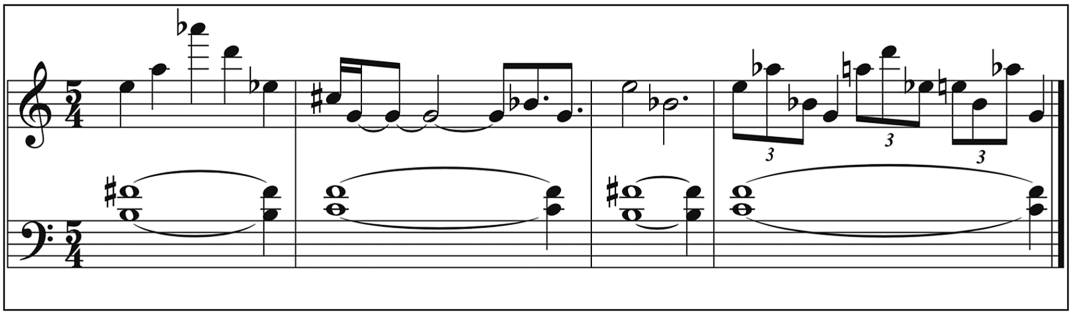


Figure 2
Example of a Contemporary Score Used in the Experiment



scale was used to assess the speed of processing. For musicians older than 16 years and 11 months, the material used came from the Wechsler Adult Intelligence Scale–Fourth Edition, while for musicians younger than 16 years and 11 months, the material used came from the Wechsler Intelligence Scale for Children–Fifth Edition. Finally, the Corsi block test (CBT) was used to measure visuospatial WM capacities.

Procedure

The participant was hosted at the music conservatory and filled out a questionnaire about their musical background. Cognitive skills were assessed using the CBT (visuospatial WM), the Digit Span subtest (auditory–verbal WM), and the Coding subtest (processing speed). The participant was then asked to settle in the piano seat and to adjust the height so they were comfortable. The participant was presented with written instructions. After a training trial, the 34 musical excerpts appeared in a random order, and eye movements were recorded. Before each excerpt, the participant had to fixate on a cross corresponding to the location of the treble key on the next staff. When the staff appeared, the participant was instructed to start sight-reading the score immediately by avoiding as much as possible to replay the notes when they made mistakes. The participants had to play the score at a tempo that they considered as comfortable for them without any cue. After each excerpt, the participant was instructed to indicate the level of perceived difficulty of the musical score on a Likert scale ranging between 1 (*very easy*) to 5 (*very difficult*). Then, they had to indicate whether they already knew the excerpt or not by tapping 1 (YES) or 2 (NO) on a button box. The whole session lasted, on average, between 45 and 60 min (Figure 4).

Data Analysis

Experimental Checks

To ensure that the task corresponds to a conventional sight-reading task, we checked that the musicians knew only a few of the

Figure 3
Set Up of the Experimental Material

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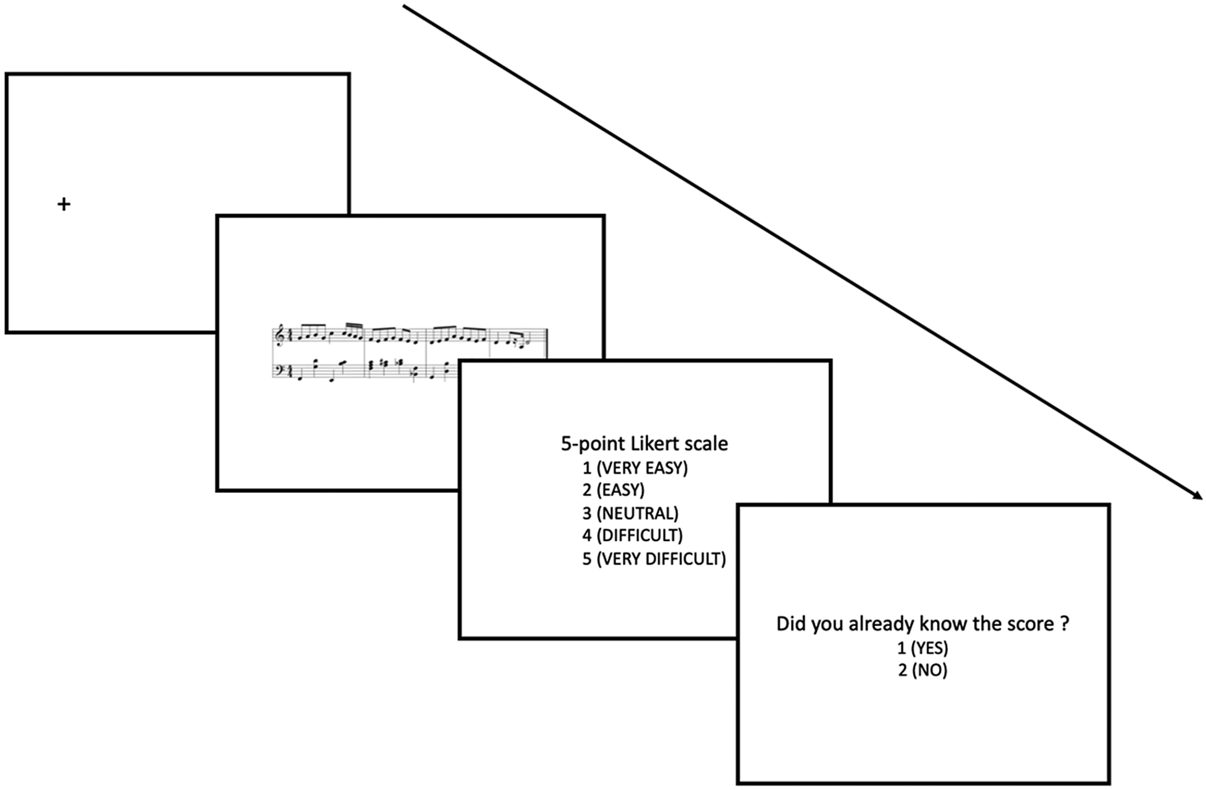
Figure 4
Illustration of One Trial



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musical scores. On average, the musicians knew 3.19 excerpts out of 34 ($SD = 3.54$), which corresponds to less than 10% of recognized scores. Moreover, to ensure that we were testing the effect of expertise in music reading (i.e., domain-specific knowledge of music reading), we ensured that the expertise groups did not differ in terms of general WM capacities. There was no effect of expertise on visuospatial WM capacities (CBT, $p = .211$), speed of processing (Coding, $p = .892$), and auditory–verbal WM capacities (Digit Span, $p = .562$).

Fixation Data

Each score was divided into as many areas of interest (AOIs) as there were events (i.e., notes, chords, or rests) in addition to an AOI, including key, time, and key signatures (Figure 5). To be considered, an eye fixation had to last at least 80 ms. The following variables were measured: the average fixation duration in ms, the number of fixations per note (since the musical material was realistic and presented a variability of the number of notes per score), and the number of fixations normalized by tempo.

Performance Data

To analyze sight-reading accuracy, the longest suites of correct notes were identified by discarding erroneous notes from the analyses. An AOI was considered correct when all its component elements were correct. The proportion of correct AOIs played was measured for each score. The tempo was quantified with the ratio of the time taken to play the score in milliseconds and the number of beats for each score. Then, by dividing 60,000 by this value, we obtained the chosen tempo in beats per minute (bpm). Finally, the perceived complexity was measured using a 5-point Likert scale ranging from 1 (*very easy*) to 5 (*very difficult*).

Synchronization of Eye-Movement and Performance Data

Since the musical material had a large variability of notes per AOI, the EHS was measured using the distance-in-music-unit method described by Perra et al. (2021). This method considers an AOI as a unit of span. The computer collected the musical performance, and the computer recorded eye movements that were synchronized. It was thus possible to determine at a given time the virtual position of the hand on the score (the played note) and the position of the eye on the score (the fixated note). Finally, the EHS normalized by tempo was measured.

Results

We performed a two-way mixed analysis of covariance with Musical Expertise (Level 1 to Level 5) as a between-subjects factor and the Type of Score (classical, contemporary) as a within-subjects factor. Since there were large differences in mean age between our five expertise groups, which could explain eye-movement differences, the age of the participants was used as a covariate in these analyses. We used Helmert contrast analyses to compare the

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Figure 5

Example of AOI Division in a Score

Note. AOI = areas of interest.

observations of each group with the average of the upper levels to determine the threshold at which each variable no longer changed with increasing expertise. In addition, this analysis enabled us to report the increasing or decreasing evolution of each variable through the level of expertise in music reading. To investigate interaction effects, we decomposed the analysis using a post hoc test with Bonferroni correction. Since the recording of the musical performance failed for five participants, we removed their data from the analyses for the following variables: Accuracy, Tempo, and EHS. Finally, we performed Spearman correlations to investigate how much eye movements are affected by tempo.

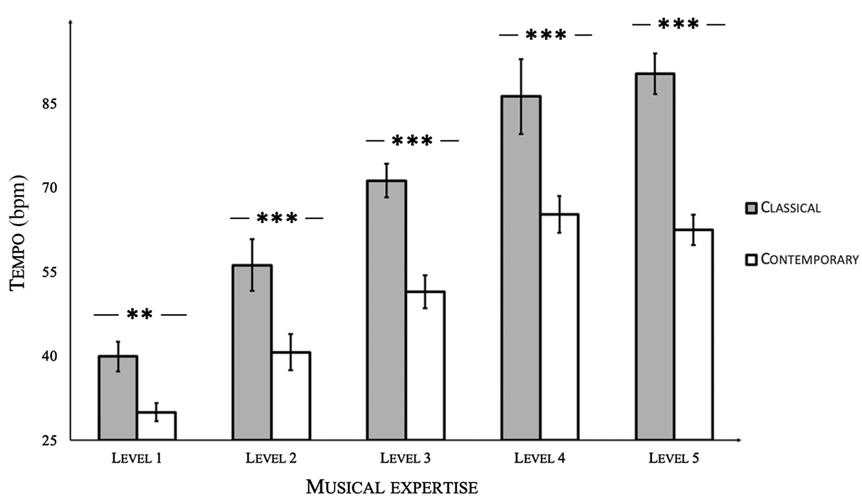
Sight-Reading Performance

There was a marginal effect of musical expertise on accuracy, $F(4, 57) = 2.358$, $p = .064$, $\eta_p^2 = .142$. Helmert contrast analyses between expertise levels revealed that the accuracy of musicians from Level 1 ($M = 72.5\%$, $SD = 12.5$) was significantly lower than the mean accuracy of musicians from Level 2 ($M = 77.2\%$, $SD = 7.68$), Level 3 ($M = 82.0\%$, $SD = 5.27$), Level 4 ($M = 79.2\%$, $SD = 5.21$) and Level 5 ($M = 82.0\%$, $SD = 4.64$), $t(57) = -2.718$, $p = .009$, $d = -0.342$, confidence mean difference interval 95% CI [−14.251, −2.159]. However, there was no accuracy difference between other Helmert contrast comparisons (all ps > .160). Furthermore, there was a marginal effect of the type of score on accuracy, $F(1, 57) = 3.768$, $p = .057$, $\eta_p^2 = .062$. Musicians tended to be more accurate in the classical condition ($M = 80.0\%$, $SD = 8.82$) compared to the contemporary condition ($M = 77.3\%$, $SD = 8.93$; Figure 6).

There was an effect of musical expertise on tempo, $F(4, 57) = 12.020$, $p < .001$, $\eta_p^2 = .458$. Helmert contrast analyses between expertise levels revealed that musicians from Level 1 ($M = 32.9$ bpm, $SD = 7.97$) sight read at a significantly lower tempo than the mean of musicians from Level 2 ($M = 48.0$ bpm, $SD = 14.4$), Level 3 ($M = 61.0$ bpm, $SD = 11.7$), Level 4 ($M = 71.9$ bpm, $SD = 11.2$) and Level 5 ($M = 73.3$ bpm, $SD = 9.94$), $t(57) = -6.279$, $p < .001$,

Figure 6

Tempo (in bpm) as a Function of Musical Expertise and the Type of Score



Note. Error bars represent standard errors. bpm = beats per minute.
$^{**}p < .01$. $^{***}p < .001$.

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$d = -0.791$, 95% CI [−36.469, −18.833]. Moreover, musicians from Level 2 sight read at a lower tempo than the mean of musicians from higher levels, $t(57) = -4.336$, $p < .001$, $d = -0.613$, 95% CI [−28.725, −10.574], and musicians from Level 3 sight read at a lower tempo than the mean of musicians from higher levels, $t(57) = -2.453$, $p = .018$, $d = -0.418$, 95% CI [−19.699, −1.919]. However, there was no significant difference between the tempo of musicians from Levels 4 and 5 ($p = .985$).

Furthermore, there was a significant effect of the type of score on tempo, $F(1, 57) = 32.270$, $p < .001$, $\eta_p^2 = .361$. Musicians sight-read classical excerpts with a faster tempo ($M = 65.1$ bpm, $SD = 20.8$) compared to contemporary excerpts ($M = 48.6$ bpm, $SD = 16.0$). Finally, a Musical Expertise × Type of Score interaction was observed on tempo, $F(4, 57) = 4.052$, $p = .006$, $\eta_p^2 = .221$. Post hoc analyses with Bonferroni corrections revealed that the tempo difference between the classical and contemporary conditions increased with musical expertise: Level 1: $M_{CL} = 39.9$ bpm, $SD = 10.2$; $M_{CO} = 30.0$ bpm, $SD = 6.12$; $t(12) = 4.617$, $p = .001$, $d = 1.281$, Level 2: $M_{CL} = 55.4$ bpm, $SD = 16.9$; $M_{CO} = 40.7$ bpm, $SD = 12.4$; $t(13) = 7.828$, $p < .001$, $d = 2.092$, Level 3: $M_{CL} = 70.5$ bpm, $SD = 12.8$; $M_{CO} = 51.5$ bpm, $SD = 11.0$; $t(13) = 11.575$, $p < .001$, $d = 3.094$, Level 4: $M_{CL} = 80.8$ bpm, $SD = 13.4$; $M_{CO} = 63.0$ bpm, $SD = 9.71$; $t(12) = 8.240$, $p < .001$, $d = 2.914$, Level 5: $M_{CL} = 84.0$ bpm, $SD = 10.8$; $M_{CO} = 62.5$ bpm, $SD = 10.1$; $t(13) = 8.956$, $p < .001$, $d = 2.394$; Figure 6.

Eye Movements

There was an effect of musical expertise on the average fixation duration, $F(4, 62) = 3.592$, $p = .011$, $\eta_p^2 = .188$. Helmert contrast analyses between levels of expertise revealed that musicians from Level 1 ($M = 293$ ms, $SD = 52.8$) made significantly longer average fixation duration than the mean of musicians from Level 2 ($M = 260$ ms, $SD = 33.0$), Level 3 ($M = 245$ ms, $SD = 30.4$), Level 4 ($M = 224$ ms, $SD = 24.5$), and Level 5 ($M = 224$ ms, $SD = 30.0$), $t(62) = 3.409$, $p = .001$, $d = 0.413$, 95% CI [18.824, 72.199]. However, there was no significant difference between other Helmert contrast comparisons (all $ps > .154$).

There was an effect of musical expertise on the number of fixations, $F(4, 62) = 6.406$, $p < .001$, $\eta_p^2 = .292$. Helmert contrast analyses between expertise levels revealed that musicians from Level 1 ($M = 4.07$, $SD = 1.51$) made significantly more fixations compared to the mean of musicians from (Level 2 [$M = 3.08$, $SD = 1.06$], Level 3 [$M = 2.64$, $SD = 0.66$], Level 4 [$M = 1.99$, $SD = 0.47$] and Level 5 [$M = 1.75$, $SD = 0.36$]), $t(62) = 4.897$, $p < .001$, $d = 0.594$, 95% CI [1.015, 2.415]. Moreover, musicians from Level 2 made significantly more fixations compared to the mean of musicians from higher levels, $t(62) = 2.611$, $p = .011$, $d = 0.316$, 95% CI [0.225, 1.695] and musicians from Level 3 made more fixations than the mean of musicians from higher levels, $t(57) = 2.094$, $p = .040$, $d = 0.254$, 95% CI [0.035, 1.515]. However, there was no significant difference between the number of fixations of musicians from Levels 4 and 5 ($p = .624$).

In addition, there was a significant effect of the type of score on the number of fixations, $F(1, 62) = 26.781$, $p < .001$, $\eta_p^2 = .302$, while a marginal effect of the type of score was observed on the average fixation duration, $F(1, 62) = 3.935$, $p = .052$, $\eta_p^2 = .060$. Musicians made more fixations ($M = 3.45$, $SD = 1.57$) and tended to allocate longer average fixation duration ($M = 253$ ms, $SD = 42.6$) on contemporary excerpts compared to classical excerpts ($M_{NOF} = 2.08$, $SD = .96$; $M_{AFD} = 249$ ms, $SD = 45.9$).

A significant musical expertise × type of score interaction was observed on the number of fixations, $F(1, 62) = 3.190$, $p = .019$, $\eta_p^2 = .171$. Post hoc analyses with Bonferroni corrections revealed that the difference in the number of fixations between classical and contemporary excerpts decreased with musical expertise: Level 1: $M_{CL} = 3.09$, $SD = 1.07$; $M_{CO} = 5.05$, $SD = 1.99$; $t(14) = -10.294$, $p < .001$, $d = -2.658$; Level 2: $M_{CL} = 2.36$, $SD = .84$; $M_{CO} = 3.8$, $SD = 1.32$; $t(14) = -8.138$, $p < .001$, $d = -2.096$; Level 3: $M_{CL} = 1.99$, $SD = .82$; $M_{CO} = 3.29$, $SD = .82$; $t(13) = -7.847$, $p < .001$, $d = -2.098$; Level 4: $M_{CL} = 1.44$, $SD = .32$; $M_{CO} = 2.53$, $SD = .66$; $t(7) = -4.966$, $p < .001$, $d = -1.170$; Level 5: $M_{CL} = 1.25$, $SD = 0.30$; $M_{CO} = 2.24$, $SD = 0.42$, $t(15) = -3.790$, $p = .015$, $d = -0.947$; Figure 7.

Finally, Spearman correlations analyses revealed that there was a significant negative correlation between tempo and the average fixation duration: $r(57) = -.688$, $p < .001$ and a significant negative correlation between tempo and the number of fixations: $r(57) = -.869$, $p < .001$. Moreover, there was a significant effect of expertise on the number of fixations normalized by tempo, $F(1, 57) = 11.533$, $p < .001$, $\eta_p^2 = .443$; a significant effect of the type of score on the number of fixations normalized by tempo, $F(1, 57) = 94.108$, $p < .001$, $\eta_p^2 = .619$ as well as a significant Expertise × Type of score interaction effect on the number of fixations normalized by tempo, $F(4, 57) = 8.583$, $p < .001$, $\eta_p^2 = .372$.

Eye–Hand Span

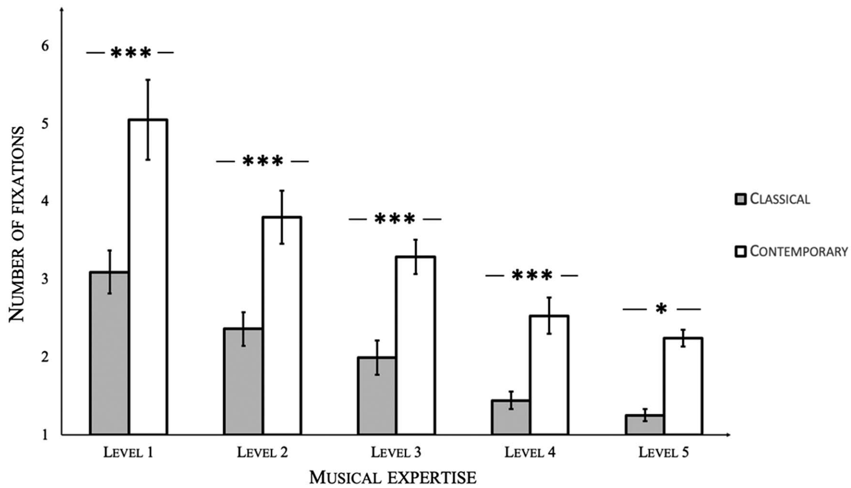
There was a marginal effect of musical expertise on the EHS, $F(4, 57) = 2.364$, $p = .064$, $\eta_p^2 = .142$. Helmert contrast analyses between expertise levels revealed that musicians from Level 1 ($M = 1.14$ AOI, $SD = 0.25$) showed a shorter EHS than the mean of musicians from (Level 2 [$M = 1.28$ AOI, $SD = 0.31$], Level 3 [$M = 1.48$ AOI, $SD = 0.37$], Level 4 [$M = 1.68$ AOI, $SD = 0.33$], and Level 5 [$M = 1.92$, $SD = 0.40$]), $t(57) = -2.624$, $p = .011$, $d = -0.330$, 95% CI [−0.602, −0.081]. Moreover, musicians from Level 2 showed a shorter EHS than the mean of musicians from higher levels, $t(57) = 2.260$, $p = .028$, $d = -0.284$, 95% CI [−0.570, −0.034], and musicians from Level 3 tended to have a shorter EHS than the mean of musicians from higher levels, $t(57) = -1.837$, $p = .071$, $d = -0.232$, 95% CI [−0.503, 0.022]. However, there was no a significant difference between the EHS of musicians from Levels 4 and 5 ($p = .573$). Furthermore, there was a marginal effect of the type of score on the EHS, $F(1, 57) = 3.536$, $p = .065$, $\eta_p^2 = .058$. Musicians showed a marginally larger EHS on classical excerpts ($M = 1.60$ AOIs, $SD = .49$) compared to contemporary excerpts ($M = 1.38$ AOIs, $SD = 0.47$). Finally, there was an effect of expertise on the EHS normalized by tempo, $F(1, 57) = 4.213$, $p = .005$, $\eta_p^2 = .225$, and there was a significant effect of the type of score on the EHS normalized by tempo, $F(1, 57) = 11.673$, $p = .001$, $\eta_p^2 = .168$.

Perceived Complexity

There was an effect of musical expertise on the perceived complexity, $F(4, 62) = 2.881$, $p = .030$, $\eta_p^2 = .157$. Helmert contrast analyses between expertise levels revealed that musicians from Level 1 ($M = 2.73$, $SD = 0.66$) perceived a higher complexity than

Figure 7

Number of Fixations Allocated per Note as a Function of Musical Expertise and the Type of Score



Note. Error bars represent standard errors.
* $p < .05$. *** $p < .001$.

the mean of musicians from Level 2 ($M = 2.20$, $SD = 0.44$), Level 3 ($M = 2.16$, $SD = 0.47$), Level 4 ($M = 2.00$, $SD = 0.42$) and Level 5 ($M = 1.81$, $SD = 0.61$), $t(62) = 3.342$, $p = .001$, $d = 0.405$, 95% CI [0.267, 1.063]. However, there was no significant difference between the other Helmert contrast comparisons (all $ps > .264$). Furthermore, there was a significant effect of the type of score on the perceived complexity, $F(1, 62) = 25.141$, $p < .001$, $\eta_p^2 = .290$. Musicians perceived a greater complexity when sight-reading contemporary ($M = 2.59$, $SD = 0.68$) compared to classical excerpts ($M = 1.80$, $SD = 0.63$, Table 1).

Discussion

This study aimed to determine the extent to which eye movements can account for the level of musical sight-reading expertise. Pianists of five different levels of expertise from the conservatory were asked to sight-read classical and contemporary scores at their own pace, without tempo constraint. We hypothesized that eye movements and performance at the task would be affected both by the level of expertise and the type of score. On the one hand, as postulated by the LTWM and template theories (Ericsson & Kintsch, 1995; Gobet & Simon, 1996), we assumed that during the years of musical practice, knowledge structures are developed in LTM, allowing experts to process information in a rapid and structured way during a WM task. We hypothesized that eye-movement and performance metrics would indicate an increase in sight-reading fluency through expertise levels. On the other hand, we postulated that the knowledge structures built with the acquisition of expertise in music reading are based on the architectural rules of tonal music. We thus assumed that sight-reading atonal scores would induce a difficulty in using long-term knowledge structures developed with musical practice and that eye-movement and performance metrics would indicate a decrease in fluency during sight-reading of contemporary materials compared to classical materials. Finally, this study aimed to investigate whether there is a threshold in musical education beyond which eye-movement and behavioral metrics no longer evolve. Overall, this study validated our hypotheses, showing that eye movements and sight-reading performances are affected both by the level of musical

Table 1

Means and Standard Deviations of the Different Measures as a Function of Musical Expertise and the Type of Score

Eye movement and performance measure	L1		L2		L3		L4		L5	
	CL	CO	CL	CO	CL	CO	CL	CO	CL	CO
NOF	3.09 (1.07)	5.05 (1.99)	2.36 (0.84)	3.80 (1.32)	1.99 (0.50)	3.29 (0.82)	1.44 (0.32)	2.53 (0.66)	1.25 (0.30)	2.24 (0.42)
AFD	293 (55.5)	293 (51.0)	260 (34.0)	261 (32.5)	244 (29.9)	246 (32.1)	219 (23.2)	228 (26.1)	219 (30.6)	230 (30.1)
ACC	74.4 (15.3)	69.1 (13.9)	79.3 (7.90)	74.6 (9.11)	84.0 (5.85)	79.5 (6.63)	81.5 (5.19)	77 (5.88)	81.0 (5.97)	82.0 (5.18)
TEMPO	39.9 (10.2)	30.0 (6.12)	56.2 (17.9)	40.7 (12.4)	71.3 (13.4)	51.5 (11.0)	86.3 (18.9)	65.3 (9.32)	90.3 (13.6)	62.5 (10.1)
PC	2.41 (0.75)	3.06 (0.63)	1.79 (0.41)	2.60 (0.56)	1.74 (0.46)	2.59 (0.56)	1.45 (0.42)	2.54 (0.54)	1.47 (0.51)	2.15 (0.76)
EHS	1.27 (0.30)	1.02 (0.28)	1.40 (0.45)	1.16 (0.25)	1.57 (0.43)	1.38 (0.46)	1.76 (0.48)	1.60 (0.24)	2.04 (0.43)	1.80 (0.51)

Note. Standard deviations are presented in parentheses. L = level; CL = classical; CO = contemporary; NOF = number of fixations per note; AFD = average fixation duration (ms); ACC = accuracy (%); TEMPO = tempo (beats per minute); PC = perceived complexity; EHS = eye–hand span (areas of interest).

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expertise and the type of score. Furthermore, our study suggests a threshold in music education after entering the Classe Préparatoire à l'Enseignement Supérieur, after which eye movements and musical performances seem no longer to differ, showing the installation of an expert memory (Ericsson & Kintsch, 1995).

First, our results revealed the main effects of musical expertise that are well established in the literature of music reading. On the one hand, as highlighted in previous studies (Drake & Palmer, 2000; Truitt et al., 1997; Zhukov et al., 2019), analyses of musical performance showed an increase in accuracy and chosen tempo with music reading expertise. On the other hand, eye-movement analyses showed a decrease in average fixation duration, number of fixations and a marginal increase in EHS with sight-reading expertise. These results are consistent with those reported in previous studies on music reading tasks that showed a decrease in fixation duration (Drai-Zerbib & Baccino, 2005, 2018; Drai-Zerbib et al., 2012; Goolsby, 1994a; Penttinen et al., 2013; Waters et al., 1997; Waters & Underwood, 1998; for a meta-analysis, see Perra et al., 2022), number of fixations (Waters et al., 1997), and an increase in EHS (Furneaux & Land, 1999; Penttinen et al., 2015; Sloboda, 1974; Truitt et al., 1997; for a review, see Perra et al., 2021) with music reading expertise. Since the average fixation duration and the number of fixations are indicators of processing speed (Holmqvist & Andersson, 2017; Rayner, 1998; Rayner et al., 2006), our results indicate that sight-reading expertise involves extracting visual information more rapidly from the score. Furthermore, our results concerning EHS indicate that the distance between the fixated note and the played note tends to increase with the development of music reading expertise, reflecting a marginally higher amount of information kept active in WM during sight-reading of music (Furneaux & Land, 1999; Rayner & Pollatsek, 1997).

Second and for the first time in a sight-reading study, our results show that the evolution of eye-movement and performance variables is progressive over the course of musical training, and expertise effects on both the number of fixations and the EHS remain even when controlling for tempo. In fact, several music conservatory levels were discernable in terms of both performance and eye movements. While average fixation duration and task accuracy only discriminated Level 1 musicians with higher levels, EHS did discriminate each of Levels 1 and 2 with higher levels, while Level 3 musicians showed only a marginally lower EHS than higher level musicians. Finally, the decrease in the number of fixations as well as the increase in the chosen tempo turned out to be relevant markers of the expertise level in a sight-reading task without tempo constraint since they have been shown to discriminate Levels 1, 2, and 3 with their respective higher levels. Furthermore, according to our results, there is a stage of musical training (at the end of Cycle 2) at which musicians no longer differ in terms of accuracy in a sight-reading task without tempo constraint but still differ in terms of their chosen tempo (slower for the Cycle 2 and 3 than for higher level musicians). Furthermore, according to our results, there is a stage of musical training (at the end of Cycle 2) at which musicians no longer differ in terms of accuracy in a sight-reading task without tempo constraint but still differ in terms of their chosen tempo (slower for the Cycles 2 and 3 than for higher level musicians). This phenomenon could be explained by the fact that pitch and rhythm are processed independently in a music reading task (Fasanaro et al., 1990; Palmer & Krumhansl, 1987; Penttinen & Huovinen, 2011; Schön & Besson, 2002; Waters & Underwood, 1999) and music education put an emphasis on playing a note correctly in pitch before trying to respect the rhythmic and temporal aspects of the score (Gudmundsdottir, 2010; Henry, 2011; McPherson, 1994; Pike & Carter, 2010). The less expert musicians would prioritize the processing of pitch over rhythm, leading them to perform as well as musicians with higher levels of expertise in terms of pitch accuracy. On the other hand, this prioritization of pitch processing could take place at the expense of processing the temporal aspects of the score in the less expert musicians, who play at a much lower tempo than the more expert ones. The gradual increase in the chosen tempo with expertise could reflect the fact that musicians are increasingly able to handle the pitch and temporal characteristics of the score in parallel through the years of musical training.

Overall, each of our results indicated an increase in sight-reading fluency with the acquisition of expertise. Musicians processed musical information more accurately and rapidly (faster tempo, shorter average fixation duration, smaller number of fixations) and more structurally (larger EHS) with expertise. Moreover, our results indicated that eye movements are affected by tempo since there were significant correlations between the number of fixations and tempo and between the average fixation duration and tempo. On the other hand, our study provided some answers to the question of whether there is a gap or a threshold for learning during the stage of music education. There were no variables allowing the distinction between *Classe Préparatoire à l'Enseignement Supérieur* and professional musicians. According to our results, the acquisition of expertise in sight-reading of music would be progressive and would reach a threshold after entering *Classe Préparatoire à l'Enseignement Supérieur* (at this stage, musicians have accumulated between 8 and 15 years of musical practice).

To another extent, the musicians performed with a significantly lower tempo and a marginally lower accuracy in the contemporary condition compared to the classical condition, while they showed a significantly higher number of fixations, a marginally higher average fixation duration, and a lower EHS in the contemporary condition compared to the classical condition. These results indicate a lower fluency when sight-reading atonal (contemporary) compared to tonal (classical) scores. These results validate our assumptions that sight-reading atonal scores would induce difficulty in using long-term knowledge structures developed with expertise and would imply difficulty in processing information in a rapid and structured way. In addition, contemporary scores have been evaluated by all the musicians as being more complex than classical ones, and the present results are consistent with those already reported on the effect of the complexity of the musical material on eye movements and performance (Cara, 2018; Chitalkina et al., 2021; Gilman & Underwood, 2003; Lim et al., 2019; Penttinen et al., 2015; Rosemann et al., 2016; Sloboda, 1977; Wurtz et al., 2009). The presence of a tonal architecture in the score seems to be a decisive factor for the achievement of fluent sight-reading. Since contemporary score does not follow the rules of tonal music, it could be more difficult for musicians to generate expectations about the upcoming event in the score. In a tonal score, the musical events are organized in such a way that some of them generate harmonic, melodic, rhythmic, or metrical tensions, while others resolve these tensions (Lerdahl & Jackendoff, 1983). Hence, prior knowledge about a given tonality, or time signature, but also the tonal context of the sight-read score plays a facilitating role in predicting upcoming events and would accelerate their encoding

(Waters et al., 1998). However, in a contemporary score, in which it is difficult to apply prior knowledge acquired from intensive training on tonal music, little or no prior knowledge can help the sight-reading processing. This may explain the fact that musicians sight read less rapidly, made more errors, and had longer and higher numbers of fixations when they faced contemporary scores. It also explains the marginal reduction of EHS, indicating that musicians maintained less information in WM between the fixated note and the played note in the contemporary condition compared to the classical condition.

Furthermore, the present results indicated an interaction between musical expertise and the type of score on the chosen tempo. The beginner musicians (Level 1) showed a shorter difference in tempo between the contemporary and classical conditions than the expert musicians (Level 5). These results indicate that professional musicians benefit more from sight-reading of tonal scores compared to atonal because of their retrieval structure of Western tonal music, notably in terms of performance (their chosen tempo increases as a function of expertise and even more in the tonal conditions than in the atonal condition). In addition, there was an interaction between musical expertise and the type of score on the number of fixations performed by the musicians. The difference in the number of fixations between the classical and the contemporary conditions was greater for beginner musicians (Level 1) than for expert musicians (Level 5). These results indicate that beginner musicians (Level 1) are even more affected by the sight-reading of atonal scores compared to tonal scores than expert musicians (Level 5) in terms of number of fixations per note. It is interesting that there are opposing interaction patterns for the chosen tempo compared to the number of fixations. The effect of the type of score on tempo increased as a function of expertise. However, for the number of fixations, the effect of the type of score decreased as a function of expertise. These two indicators reflect two different components of the sight-reading task: on the one hand, the number of fixations is an indicator of the ability to extract visual information (Rayner, 1998), and on the other, the chosen tempo is an indicator of musical performance (Truitt et al., 1997). We can assume that, in order to optimize the attentional and memory resources employed in the extraction of visual information (characterized by the number of fixations), expert musicians (Level 5) adapted their performance by reducing their chosen tempo in the atonal condition compared to the tonal condition. The reduction of the chosen tempo in atonal scores for expert musicians (Level 5) may have allowed them to take more time to extract visual information per fixation compared to the tonal scores, lowering the impact on the number of fixations allocated per note. In contrast, beginner musicians (Level 1) showed a higher number of fixations in the atonal condition than in the tonal condition, and this difference was even greater than in the more expert musicians (Level 5), indicating greater difficulty in extracting visual information in the atonal condition compared to the tonal condition for the beginners (Level 1). This difference with the more expert musicians' behavior could be due to the fact that the beginner musicians (Level 1) reached a low threshold in performance, as they chose a tempo that was very low in both conditions (30 bpm in the atonal condition, corresponding to 1 beat played every 2 s, and around 40 bpm in the tonal condition). Beginner musicians seemed unable to sufficiently reduce their chosen tempo in the atonal condition to minimize the impact on the extraction of visual information. Overall, these interaction effects indicate, on the one hand, that the benefit conferred by expert prior knowledge seems to be even greater for sight-reading tonal rather than atonal scores and, on the other hand, that experts can reduce their chosen tempo with regard to the sight-reading complexity, while the beginners, who play at a low tempo regardless of the type of score, have no room to reduce their chosen tempo.

We can connect our results with those observed in the literature on expert perception of chess (Chase & Simon, 1973; Gobet & Simon, 1996) and expert cognitive processing (LTWM, Ericsson & Kintsch, 1995). Given that a longstanding debate in the literature on expert processing is the extent to which expertise is domain-specific or domain-general, our results indicate that musical expertise is knowledge-specific (i.e., it is the result of how developed the knowledge structures relating to the rules governing a given activity are). The classical scores corresponding to a type of musical material that is highly studied during music education and respecting a tonal architecture can be compared to the familiar chessboard subconfiguration condition of Chase and Simon's (1973) pioneering experiment and schemas in LTWM (Ericsson & Kintsch, 1995). Our study indicates that through years of musical practice, musicians develop an expert memory with knowledge structures specific to tonal music that could take the form of templates (Gobet & Simon, 1996) or retrieval structures facilitating the encoding and retrieval of information during the task (Ericsson & Kintsch, 1995, 2000). When reading the key signature or the time signature of a score, indicating respectively the tonality of a score and its rhythmic and metric rules, musicians could activate high-level knowledge structures and generate expectations about the musical structure of the score. Subsequently, the encoding of musical events in the form of chunks and hierarchical structures would be facilitated by these predictions. On the other hand, the contemporary material, less studied during music education and which does not respect the rules of tonal music, can be compared (at least in part) to the randomized material of Chase and Simon's (1973) study. Obviously, the atonal material is not totally meaningless for expert musicians, because they can identify chords or even sequences of notes that can correspond to already integrated chunks in LTM. Nevertheless, atonal scores are devoid of a tonal architecture. The benefit given by expert previous knowledge to perform the task is likely to be less notable when sight-reading contemporary scores compared to classical scores.

Finally, our results showed the effects of musical expertise and the type of score on perceived complexity. Less expert musicians reported a higher perceived complexity compared to higher expertise groups, while musicians perceived a higher complexity during sight-reading of contemporary scores compared to classical scores. The results regarding the effect of expertise on the perceived complexity are consistent with the fact that the workload allocated to WM decreases with the presence of LTM structures (Garavan et al., 2000; Jansma et al., 2001; Olesen et al., 2004; Pesenti et al., 2001; Thalmann et al., 2019; for a review, see Guida et al., 2012). In their literature review on Positron Emission Tomography and functional Magnetic Resonance Imaging in experts and novices, Guida et al. (2012) highlight the fact that the activation of prefrontal and parietal areas, usually dedicated to WM tasks, decreases during learning for novices, whereas an activation of brain areas usually active in LTM tasks is observed for experts. These observations suggest a functional brain reorganization set up with expertise, which has already been pointed out in expert musicians (Bermudez et al., 2009; Groussard et al., 2014; James et al., 2014; Sato et al., 2015) and would explain the decrease in cognitive load allocated to WM during a domain-specific task.

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Overall, expert memory theories (Chase & Ericsson, 1982; Chase & Simon, 1973; Ericsson & Kintsch, 1995; Gobet & Simon, 1996) offer a more than satisfactory explanation concerning our results that indicate an evolution of performance and eye-movement metrics as a function of both musical expertise level and the type of score (Figure 8). There is an increase in structural processing abilities through the acquisition of music sight-reading skills and tonal-specific cues play a significant role to use an efficient eye-movement behavior and to sight read fluently. This indicate that the long-term domain-specific knowledge structures elaborated through music education play a facilitating role in the encoding of information from a score. The expectations resulting from the intensive practice of Western tonal music, allow musicians to anticipate upcoming musical events. Therefore, the more elaborated these knowledge structures (we postulate that they become more elaborated with the acquisition of expertise in music reading), the more fluent the sight reading.

In our study, the metrics that most discriminated between groups of expertise levels were the chosen tempo and the number of fixations (Figure 8). Even though further studies are needed to test whether these metrics are the main markers of sight-reading expertise, our results suggest that the chosen tempo and the number of fixations are relevant metrics to account for the expertise level in a sight-reading task. Moreover, our results suggest that there is a threshold during musical training when entering *Classe Préparatoire à l'Enseignement Supérieur*, after which musicians no longer seem to differ with the eye-movement and performance measures we used in this study. However, it should be noted that as the pianist population was rather difficult to recruit, it turned out that the number of participants belonging to the *Classe Préparatoire à l'Enseignement Supérieur* was relatively lower than that of the other groups. Nevertheless, a G*Power analysis indicated that five participants per group was sufficient for the present design and the number of pianists in Level 4 was greater than 5 (i.e., 8). For future research, it would be interesting to design experiments in which eye movements and performance are compared in populations with varying degrees of high-level expertise (10 years vs. 30 years of musical experience) or by using material of even more challenging complexity level, to test whether differences between groups of musicians with high levels of expertise might appear as a function of score complexity. It would also be worthwhile to analyze other measures of performance and eye movements (e.g., measures assessing expertise behavior as a function of local characteristics in a score; Chitalkina et al., 2021; Huovinen et al., 2018). The aims would be to determine whether the expertise threshold observed in this study is reliable enough regardless of the musical material, and whether finer-grained measures could discriminate between high-level expertise musicians.

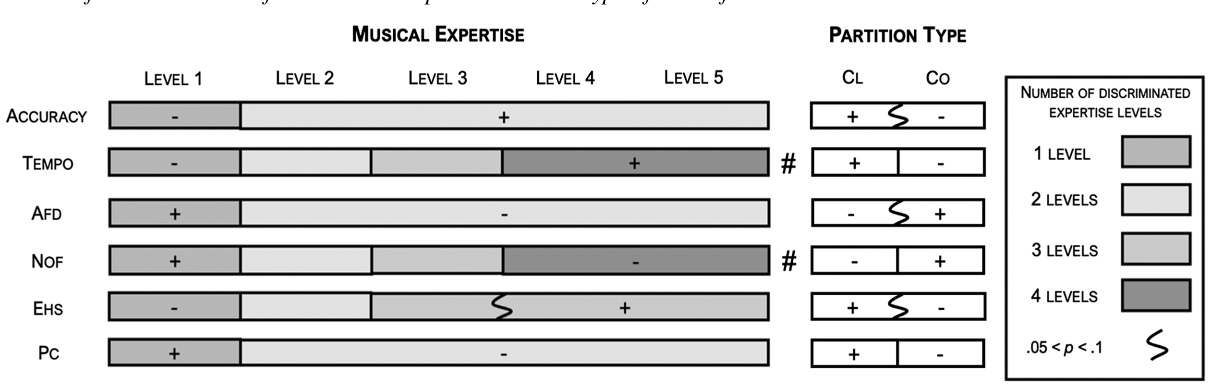
Limitations

Since the workload allocated to WM has been shown to be positively correlated with pupil size (Beatty, 1982; Granholm et al., 1996; Sibley et al., 2020), and as suggested by studies having addressed the effect of expertise on pupil size in other disciplines than music (Castner et al., 2020; Szulewski et al., 2015; Tien et al., 2015), we could have investigated how musical expertise and the type of score impact pupil size in a sight-reading task. However, to make the experimental conditions as ecological as possible, we used an eye tracker that allowed for free head movement (i.e., the musicians were not constrained by a chin strap). We noticed that the distance between the musician's face and the eye tracker varied drastically during the task, which could have interfered with the measure of the pupil size. For that reason, we choose not to analyze this measure.

Another limitation of our study lies in the fact that the factor of visual complexity could be confused with that of the type of score and could also explain the intercondition differences we noticed. Indeed, contemporary scores have their own visual characteristics that classical scores generally do not (e.g., wider intervals), which indirectly makes atonal scores visually more complex. To select scores that are as ecological as possible, it is technically difficult to control and hold constant all score characteristics in each condition, and we did not aim to propose a material for which all visual score characteristics were controlled, but which would not have been ecological in terms of musical repertoire. However, to test for potential confounding factors, we carried out further statistical analyses a posteriori, taking into account the characteristics of each partition. We carried out multiple regression analyses to test whether

Figure 8

Power of Discrimination of the Musical Expertise and the Type of Score for Each Metric



Note. + and − signs indicate in which direction the dependent variable evolves as a function of musical expertise and the type of score. TEMPO = tempo (beats per minute); AFD = average fixation duration; NOF = number of fixations; EHS = eye–hand span; PC = perceived complexity; CL = classical scores; CO = contemporary scores; # = Musical Expertise × Type of Score interaction effect.

the average fixation duration could be correlated with different visual characteristics, namely, the number of notes per score, the number of accidentals per score, the distance of the note from the score, note heterogeneity and the intervals between notes. These analyses indicated that only the intervals between notes was significantly correlated with the average fixation duration. In contrast, none of the other local characteristics had a significant impact on the average fixation duration. Insofar as contemporary atonal music generally consists of large intervals, these results do not change the nature of our interpretations.

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(*Appendix follows*)

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Appendix

Musical Material Used

Tonal score	Atonal score
Menuette and Aria, Joseph Haydn	Notes et Menottes Vol. 1, Claude Baliff
Menuette Trio, Joseph Haydn	Notes et Menottes Vol. 1, Claude Baliff
Menuette and Aria II, Joseph Haydn	Blackbird, Henri Dutilleux
Allegro, Joseph Haydn	Hana-Bi, Joe Hisaishi
Vagabond's song II, Béla Bartok	In a Landscape, John Cage
A little song, Dmitri Kabalevsky	In a Landscape, John Cage
Rondo, Wolfgang Amadeus Mozart	In a Landscape, John Cage
Menuetto, Wolfgang Amadeus Mozart	Metamorphosis I, John Cage
Rigaudon, Johann Ludwig Krebs	Metamorphosis I, John Cage
Menuett, Johann Sebastien Bach	Strophe I, Claude Baliff
Sarabande, Georg Friedrich Haendel	Strophe II, Claude Baliff
The fair, Karl Czerny	Strophe II, Claude Baliff
Six scottish, Ludwig van Beethoven	
Vagabond's song, Béla Bartok	
Minuet, Georg Friedrich Haendel	
Op., 37, 10è étude, Book 1, Henry Lemoine	
Sarabande, Arcangelo Corelli	
Fantasia, Georg Philip Telemann	
Marcia, Wolfgang Amadeus Mozart	
Menuet II, Johann Sebastien Bach	
Menuet, Wolfgang Amadeus Mozart	
Personal composition, Jean-Louis Luzignant	
Personal composition, Jean-Louis Luzignant	

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