Original Article

QJEP

Quarterly Journal of Experimental Psychology
1–21

DOI: 10.1177/17470218251325245
qjep.sagepub.com
Sage

Saccadic and visuo-motor flexibility towards local parafoveal complexity as a hallmark of expert knowledge-driven processing during sight-reading of music

Joris Perra[1], Bénédicte Poulin-Charronnat[2], Thierry Baccino[2], Patrick Bard[2], Philippe Pfister[2], Philippe Lalitte[3], Melissa Zerbib[4] and Véronique Drai-Zerbib[2]

Abstract

Expertise is associated with a knowledge-driven information-processing approach. Experts benefit from long-term knowledge structures—chunks and retrieval structures/templates—leading them to formulate expectations about local stimulus characteristics and to extract information projected onto distant areas from the fixation location. In an attempt to shed light on the way knowledge-driven processing impacts eye movements during music reading, this study aimed to determine how expert musicians deal with local complexity in a sight-reading task. Thirty musicians from two expertise levels had to sight read 4 bar score excerpts. Local analyses were conducted to investigate how the gaze behaves prior to and during the sight reading of different score characteristics, such as alteration, location of the notes on the staff, note count, and heterogeneity of notes. The more experts (1) were less affected by the foveal load induced by local complexity, showing a lower increase in fixation durations between noncomplex features and local complexity compared to the less experts; (2) presented a saccadic flexibility towards the local complexity projected onto the parafoveal area, being the only group to exhibit shorter progressive incoming saccade sizes on accidentals and larger progressive incoming saccade sizes on new notes compared to noncomplex features; and (3) presented a visuo-motor flexibility depending on the played complexity, being the only group to exhibit a shorter eye-hand span when playing accidentals or distant notes compared to noncomplex features. Overall, this study highlights the usefulness of local analyses as a relevant tool to investigate foveal and parafoveal processing skills during music reading.

Keywords

Expertise; eye movements; perceptual span; parafoveal processing; music reading; eye-hand span

Received: 11 June 2024; revised: 21 December 2024; accepted: 27 January 2025

Introduction

Expert knowledge-driven processing

Expert memory theories postulate that with the acquisition of expertise, informational units are no longer encoded and retrieved in an individual way but rather in a meaningful and structured way (Chase & Simon, 1973a, 1973b; Ericsson & Kintsch, 1995; Gobet & Simon, 1996). Experts perceive information in the form of microstructures of semantically linked elements, called chunks, facilitating information processing (Gobet et al., 2001). They also benefit from macrostructural high-level knowledge integrated in long-term memory (LTM) in the form of networks called retrieval structures (Ericsson & Kintsch, 1995, 2000) or templates (Gobet & Simon, 1996, 2000), which can be activated during information processing. In concrete terms, thanks to microstructural association mechanisms and the activation of macrostructural LTM knowledge, information is processed in a rapid (principle

[1]Centre de recherche PsyCLE—UR3273, Aix-Marseille Université, CEDEX 1 Aix-en-Provence, France
[2]Laboratoire d'Étude de l'Apprentissage et du Développement, LEAD—CNRS UMR5022, Université de Bourgogne, Dijon, France
[3]Institut de Recherche en Musicologie, IReMus UMR8223, Sorbonne Université, Paris, France
[4]Faculté de Musique, Université de Montréal, Montréal, Canada

Corresponding author:
Joris Perra, Centre de recherche PsyCLE—UR3273, Aix-Marseille Université, 13621 CEDEX 1 Aix-en-Provence, France.
Email: joris.perra@gmail.com

of acceleration) and structural (principles of meaningful encoding and of structured retrieval) way as expertise develops (Chase & Ericsson, 1982). Accordingly, expertise is associated with an increase in speed and accuracy (Gilis et al., 2008; Helsen & Starkes, 1999; Spitz et al., 2016; Williams et al., 2002), as well as an improved ability to handle domain-specific complexity with experts showing a decrease in both the perceived complexity (Perra et al., 2024) and the cognitive load allocated to working memory (WM, Thalmann et al., 2019).

Consequently, expertise acquisition is linked with a shift in the way information is perceived and specifically in the way information is extracted in a visual scene (Rayner, 1998; Reingold et al., 2001; Reingold & Sheridan, 2011). On the one hand, experts are able to extract task-related visual information projected onto areas of the visual field from which novices lack capacity. For that reason, the amount of information being extracted in one fixation (the so-called "perceptual span"; Rayner, 1998) increases with expertise (Reingold et al., 2001; Reingold & Sheridan, 2011). Experts benefit from (1) chunking skills enabling to extract more visual information than allowed by the visual angle covered by the fovea (Reingold et al., 2001) and (2) LTM knowledge structures leading them to formulate expectations about visual information projected onto distant areas from the fixation location and enabling them to extract the meaning of features projected onto the parafoveal and peripheral areas (Sheridan et al., 2020). This phenomenon has been emphasised by studies showing expert/novice differences in terms of eye movements. For example, experts do not to need to fixate on all elements in a visual detection task, and a single fixation between elements has been shown to be enough to extract visual information projected onto distant areas from the fixation location (Bilalić et al., 2011; Charness et al., 2001; de Groot et al., 1996; Krupinski, 1996; Manning et al., 2006; Reingold & Charness, 2005; Reingold et al., 2001; Ryu et al., 2015). Furthermore, experts make larger saccades (Manning et al., 2006; Reingold et al., 2001), and studies using a visual mask technique, in which the information projected onto the parafoveal area is blurred while only foveal information remains available, show that experts are more affected by the reduction of the visual range than novices (Fox et al., 1996; Ryu et al., 2015). According to the theoretical model of the holistic processing of image perception (Kundel et al., 2007), experts such as radiologists in a tumour-detection task are able to analyse the visual scene in two steps: first, they perform a holistic or global analysis, allowing them to identify potential eccentric disturbances early on over a large area of the visual scene, sometimes identifying elements that are distant from each other during a single fixation. Then, experts perform a local-level analysis to validate or invalidate their expectations by investigating the potential local disturbances of the visual scene. Therefore, one of the hallmarks of visual expertise is the perceptual flexibility, with experts being able to use parafoveal processing to distantly identify relevant features and consequently adjust their eye movements. Consistently, experts show shorter "time to first hit" relevant features than novices in visual detection tasks such as in radiology (Donovan & Litchfield, 2013; Krupinski, 1996; Mallett et al., 2014; Wood et al., 2013), cardiology (Wood et al., 2014), air traffic controllers (van Meeuwen et al., 2014), chess (Sheridan & Reingold, 2014), or soccer (Vansteenkiste et al., 2014). Overall, these results suggest that during the development of expertise, the visual information processing evolves from a stimulus-driven to a knowledge-driven approach (Boshuizen et al., 2020; Gegenfurtner et al., 2022).

Another consequence of expert information processing and the increased speed of encoding of new information is the decrease of fixation durations with the acquisition of expertise, particularly in anticipation tasks (which require participants to predict upcoming events; Perra et al., 2024; Piras et al., 2014; Prytz et al., 2018; Roca et al., 2013; Williams & Davids, 1998 ; Williams et al., 1994). This indicates that experts rapidly extract the meaning of fixated features, by quickly indexing them into LTM knowledge structures (Ericsson & Kintsch, 1995). Moreover, the lack of experience and conceptual knowledge in novices compared to experts was found to be associated with higher pupil size (Castner et al., 2020; Tien et al., 2015; for a review, see Szulewski et al., 2015), highlighting the improved handling of the mental workload with expertise.

Music reading expertise

In recent literature reviews and meta-analyses (Brams et al., 2019; Perra et al., 2022; Sheridan et al., 2020), authors highlight the need for the field of expertise research to link up research on different areas of expertise. Indeed, there is a large body of research on expertise, notably chess and medical expertise, but there seems to be a lack of cross-citations. Yet, the interest of studying expertise relates both to the desire to better understand the shared cognitive processes involved in expert information processing and to understand which expert information-processing strategies and processes are domain-specific, and which are different in one area of expertise from another. Music reading activity allows to investigate both these questions.

First, in line with expert memory theories, music reading expertise also involves structural processing. Studies have investigated the application of theories such as chunking theory (Halpern & Bower, 1982), long-term WM theory (Drai-Zerbib et al., 2024; Drai-Zerbib & Baccino, 2005, 2014, 2018; Williamon & Valentine, 2002), template theory (Maturi & Sheridan, 2020; Sheridan & Kleinsmith, 2022), or even the CHREST model, a computational application of the chunking theory (Bennett et al., 2020), within the context of music. As in other expertise domains, expert musicians have been shown to benefit from a larger perceptual span than nonexpert musicians in studies involving musical material. This expertise effect has been emphasised by the fact that expert musicians exhibit larger saccade size (Sheridan & Kleinsmith, 2022) and spend less time looking at irrelevant regions of the score (Maturi & Sheridan, 2020) than less-expert musicians, indicating that they can benefit from domain-specific knowledge structures in the visual processing (Perra et al., 2024). At a microstructural level, musicians are able to chunk information to a greater extent as expertise develops (Burman & Booth, 2009; Halpern & Bower, 1982; Waters et al., 1998). In music reading, it has been highlighted that expert musicians encode and retrieve score features in larger groups of notes (Halpern & Bower, 1982) and retrieve more notes from briefly presented chords (Waters et al., 1998) than less-expert musicians. At a macrostructural level, musicians are able to use the musical structure in the encoding and retrieval of a score to a greater extent as expertise develops (Aiello, 2001; Chaffin, 2007; Chaffin & Imreh, 1997, 2002; Drai-Zerbib & Baccino, 2005, 2018; Neto & de Oliveira, 2019; Perra et al., 2024; Williamon & Valentine, 2002).

Second, unlike domains such as chess or medicine, music is an inherently multimodal activity. During sight reading, musicians must decipher a score encountered for the first time or with very little preparation (Wolf, 1976). Excelling in this type of task, which is being as fluent as possible, requires to integrate multisensory information by simultaneously coordinating visual, auditory, and motor processing to convert a visual code into a series of motor responses as the score is played (Drai-Zerbib et al., 2012; Stewart et al., 2003), Thus, studying music reading activities allows to test the processes involved in the expert management of multimodality (Drai-Zerbib & Baccino, 2018). Moreover, music reading is a specific activity which differs from visual search tasks, in which the gaze does not have to follow a specific path to be performed. Reading tasks involve a specific information processing in which the gaze must move progressively in the reading direction to bring the items to be deciphered to the foveal and parafoveal areas (for reviews, see Rayner, 1998). However, to identify what constitutes effective behaviour, it is necessary to consider the characteristics and requirements of the task being performed. Depending on the type of visual task, what constitutes effective eye-movement behaviour will change (for reviews, see Brams et al., 2019; Gegenfurtner et al., 2011).

Eye-hand span

In a sight-reading task, the eye is typically ahead of the musical event that is actually played to anticipate upcoming event in the score (Rayner & Pollatsek, 1997; Truitt et al., 1997). Between the moment when a musician fixates a note and the moment they produce it with their instrument, they must extract visual information and plan a consequent motor response while respecting the temporal constraints of the score. The eye-hand span (EHS) refers to the distance between the position of the eye on the score and the location of the note being played at a given time. To highlight musicians' visuo-motor abilities, the EHS is an effective measure in sight reading of music (for a review, see Perra et al., 2021). Consistent with the principles of meaningful encoding and retrieval structures (Chase & Ericsson, 1982), it has been shown that EHS increases with expertise (Cara, 2018; Furneaux & Land, 1999; Gilman & Underwood, 2003; Huovinen et al., 2018; Imai-Matsumura & Mutou, 2021; Penttinen et al., 2015; Perra et al., 2024; Qi & Adachi, 2022; Sloboda, 1974; Truitt et al., 1997), suggesting an increase of the amount of visuo-motor information stored in WM between the time at which a note is fixated and the time at which it is played.

On the other hand, it was shown that EHS shrinks on complex scores compared to less-complex scores (Cara, 2018; Chitalkina et al., 2021; Gilman & Underwood, 2003; Penttinen et al., 2015; Perra et al., 2024; Rosemann et al., 2016; Sloboda, 1977; Truitt et al., 1997; Wurtz et al., 2009), indicating that musicians reduce the distance between the eye position and the played note to deal with the higher workload induced by a complex score. Interestingly, in a recent study, Lim et al. (2019) manipulated both musicians' skill and the complexity of musical material in a sight-reading task. Their findings suggest that sight-reading skills may be reflected in a greater EHS flexibility in the presence of score complexity, since there was a negative correlation between EHS and the complexity of the score in the more skilled musicians: the more complex the score, the shorter the EHS. However, this correlation was not observed in the less skilled musicians. Concretely, skilled sight reading might involve a higher ability to adjust saccadic programming to the local complexity of the score, reflecting a perceptual flexibility as regard to the stimulus in experts and emphasising the knowledge-driven processing approach described in expert visual perception theories (Gegenfurtner et al., 2022; Kundel et al., 2007).

Local feature analyses to investigate the sight-reading process

Several studies investigating the effect of expertise on eye movements in music reading use "global" measures (i.e., average eye-movement measures over the entire stimulus; Gilman & Underwood, 2003; Goolsby, 1994a, 1994b). However, different reviews (Madell & Hébert, 2008; Perra et al., 2022; Perra et al., 2021; Puurtinen, 2018) emphasise the interest of granularising eye-movement analyses at a "local" level on the score (this means comparing eye-movement patterns on different score regions as a function of their local characteristics).

One of the main issues in the study of eye movements in reading-type tasks is to know which factors are guiding saccadic programming (i.e., when and where the eye will move as a function of the local characteristics of the stimulus; Hyönä, 1995; Hyönä & Bertram, 2004; Kennedy & Pynte, 2005), which is only allowed with local feature analysis. When considering the field of text reading research, the study of eye movements shows that reading process and saccadic programming are affected both by foveal and parafoveal words. First, the fixation duration allocated to a word depends on multiple factors such as its frequency, its predictability, or its length (for a review, see Schotter et al., 2012). For example, foveal low-frequency words induce longer fixation duration than high-frequency words indicating that the foveal load (i.e., the cognitive load induced by foveal word processing) is higher when word frequency decreases (Breland, 1996; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl et al., 2006). Second, studies have shown a preview-benefit effect of parafoveal words: the eye can "skip" words as a function of their length (Brysbaert et al., 2005) or predictability (Rayner et al., 2011) and can be "attracted" by a given parafoveal word depending on its characteristics. For example, Hyönä (1995) showed that the first fixation on a word tended to locate on its beginning (rather than the usual closer to the centre of the word location) when it started with irregular letters. Furthermore, it has been shown that longer gaze durations were allocated to a n + 1 word when the word n was a low-frequency word compared to when it was a high-frequency word (Henderson & Ferreira, 1990; Rayner & Duffy, 1986; Schroyens et al., 1999; White et al., 2005), indicating that the preview benefit is dependent on the foveal load. Meixner et al. (2022) demonstrated that the perceptual span dynamically adjusts to the foveal load induced by a word n. In concrete terms, the lower the word frequency, the lower the perceptual span and so the preview benefit.

In a sight-reading of music task, Huovinen et al. (2018) studied the effect of local features on musicians' eye movements. They used a measure quite similar to the EHS: the eye-time span (ETS). The ETS refers to the distance in metric units between the position of a fixation and the virtual metric position of the metronome on the score in an imposed tempo sight-reading task. Since ETS is measured in the musical temporal referential, it indicates the extent to which the gaze "moves away" from the notes that are to be played at a given time, and the extent to which a local feature can "attract" the gaze during the task. In their study, Huovinen et al. (2018) made two major statements: the early attraction hypothesis, which assumes that musicians would fixate on local complexity earlier than on noncomplex notes, and the distant attraction hypothesis, which assumes that the incoming saccades would be larger on complex local features than on other features. In their study, the task was to sight read excerpts from simple scores (in which most notes were diatonic neighbours of the preceding ones, i.e., consecutive notes) but that included complex features (a note that skipped a diatonic step in a first experiment and a note that skipped a diatonic step with an accidental in a second experiment). Musicians showed higher ETS and larger incoming saccade size on the notes that skipped a diatonic step than on the other notes. The saccade size was even larger when the notes skipped a diatonic step with an accidental. Although these experiments were performed with simple single-staff material, these results show the musicians' ability to be early and distantly attracted by complex local features. They show an ability for musicians to adjust their saccadic programming as a function of local characteristics. The early attraction effect has been replicated in a study by Chitalkina et al. (2021), in which the authors additionally observed an ETS shrinking in the area following a local complexity. The authors interpreted these results by stating that the ETS shrink could emphasise a delay in the programming of the next saccade as a marker of processing difficulty.

Another reason that motivates the local analysis of eye movements is to understand how local features may explain why some musical characteristics involve different eye-movement behaviours within a score. Studies have shown intrascore variability in eye movements (Chitalkina et al., 2021; Hadley et al., 2018; Huovinen et al., 2018; Penttinen et al., 2015; Rosemann et al., 2016). Furthermore, as a marker of the rapid note deciphering in a tempo-controlled sight-reading task, it has been shown a higher interbeat gaze activity (Penttinen et al., 2015) and more progressive fixations (Goolsby, 1994a, 1994b) in expert compared to nonexpert musicians, both indicating the ability of expert musicians to investigate other features compared to those being deciphered in the score. Moreover, local complexity has been shown to impact eye movements. Chitalkina et al. (2021) observed that the fixation duration allocated during the first-pass fixation (FPF) can vary on complex measures with shorter FPF on the first half of the complex measure and longer FPF on the first half of following-complex measures compared to noncomplex measures. Similarly, pupil size has been shown to locally increase when sight reading complex features (Chitalkina et al., 2021; Hadley et al., 2018), while EHS shrinks when playing shorter notes (Penttinen et al., 2015) and complex measures (Rosemann et al., 2016) compared to other features.

Furthermore, the confound effect related to the diversity of the musical material used across studies motivates the local feature analysis in a sight-reading task (for a review, Puurtinen, 2018). On the one hand, the manipulation of complexity as an experimental factor has been defined differently. Studies have manipulated perceptual complexity by removing visual markers (Sloboda, 1977), adding misprinted note (Sloboda, 1976), or reducing the amount of accessible visual information (Gilman & Underwood, 2003; Truitt et al., 1997). Other studies have manipulated the structural complexity of the score (i.e., rhythmic features such as note duration; Penttinen et al., 2015; Wurtz et al., 2009), the note count per metric division (Cara, 2018; Lim et al., 2019; Rosemann et al., 2016; Wurtz et al., 2009), pitch features such as the presence of accidentals (Huovinen et al., 2018; Lim et al., 2019), pitch violation (Ahken et al., 2012), intervallic features (Huovinen et al., 2018; Polanka, 1995; Qi & Adachi, 2022), heterogeneity of notes constituting the score (Lim et al., 2019). On the other hand, across the literature on the effects of expertise and complexity on eye movements, there is a great variability in the musical material used. Some studies use simple musical material such as single-note-per-event material (Chitalkina et al., 2021; Hadley et al., 2018; Huovinen et al., 2018; Penttinen & Huovinen, 2011; Penttinen et al., 2013, 2015; Truitt et al., 1997), scores that contain mostly diatonic neighbouring notes (Huovinen et al., 2018), while others use more complex scores, such as double-staff scores (Imai-Matsumura & Mutou, 2021; Lim et al., 2019; Qi & Adachi, 2022; Rosemann et al., 2016), or scores made up of heterogeneous notes or patterns of notes (Lim et al., 2019; Wurtz et al., 2009). Furthermore, in some studies, the complexity lies in one part of the musical material (one note; Chitalkina et al., 2021; Huovinen et al., 2018; one beat, Penttinen et al., 2015; one bar, Rosemann et al., 2016), while other studies use fully complex scores (Cara, 2018; Gilman & Underwood, 2003; Qi & Adachi, 2022; Wurtz et al., 2009; Zhukov et al., 2019). In an attempt to generalise the main effects of expertise and complexity on eye movements in music reading, this variability in the definition of complexity and in the musical material used makes it difficult to interpret the results and highlights a need to granularise the analysis of eye movements at the local level on the score.

The present study

The perceptual span is both expertise and complexity dependent. On the one hand, expertise is associated with a knowledge-driven visual information processing with the ability to chunk visual information and extract information located in areas that are distant from the fixation location (Gegenfurtner et al., 2022), leading experts to formulate expectations about the stimulus (Sheridan et al., 2020). On the other hand, stimulus' complexity affects eye movements with the dynamic adjustment of the perceptual span to the foveal load induced by a word in a reading-type task (Meixner et al., 2022) and the increase in fixation durations with complexity (Chitalkina et al., 2021). One may ask whether the evolution of the perceptual span as a function of expertise in a music sight-reading task may be reflected in (1) an improved ability to deal with the foveal load induced by a local complexity, and (2) an improved ability to distantly identify a local complexity. The aim of this study was to determine the extent to which expertise in music reading impacts eye movements in a sight-reading task as a function of different local complexity of the score such as alterations (Huovinen et al., 2018; Lim et al., 2019), the note count (Cara, 2018; Rosemann et al., 2016; Wurtz et al., 2009), the location of the notes on the staff (i.e., whether a note is on the staff or outside the staff; Huovinen et al., 2018; Qi & Adachi, 2022), and the heterogeneity of notes (i.e., whether a note appears for the first time or not in the score; Lim et al., 2019). In this experiment, pianists from two expertise levels were asked to sight read dual-staff scores of complexities close to what a musician encounters in daily practice. An original approach of our study was the use of "local" measurement methods enabling to determine how the musician's gaze moves across the score, and how different local characteristics impact eye movements. By analysing eye movements at a local level on the score, we could understand how the eye behaves both when the gaze is approaching a local complexity (progressive incoming saccade size [PISS]), when the gaze first stares at a local complexity (FPF), when the gaze returns to a local complexity (SPF), or even the musician's eye movement when playing a local complexity (EHS).

In the present study, we first postulated that each of the score characteristics mentioned above and used in the literature on music reading was indeed a factor in the complexity of a score. We hypothesised that the more alterations, notes, distant notes, and heterogeneous notes a score contained, the higher the complexity perceived by musicians for these scores. Second, we expected to replicate results already observed in the literature concerning the main effects of expertise and complexity in music reading. We assumed both an effect of expertise and local complexity on performance and eye movements, with musicians being more accurate, showing a decrease in fixation durations and a larger perceptual span with expertise. On the other hand, we expected that musicians would be more affected by the sight reading of local complexities than other noncomplex features.

Second, as a major aim of this study, we wanted to delineate the extent to which expertise in music reading implies a modification in the processing of local complexity in a sight-reading task, both in terms of eye movements and saccadic control and, as a result, in terms of sight-reading performance. For that reason, we expected interaction effects between expertise and complexity that would emphasise how expert musicians deal with local complexity. We assumed that the local complexity effects on accuracy rate and eye movements would be less impactful as expertise develops, with experts being able to better deal with the foveal load induced by local complexity than less-expert musicians, resulting in a lesser impact of local complexity on accuracy and fixation durations in the more-expert musicians than in the less-expert ones. Furthermore, as a marker of the increased perceptual span and perceptual flexibility with respect to the type of information projected onto the parafoveal area, we expected that experts would have a specific eye-movement behaviour when encountering local complexity compared to the less experts. More specifically, we assumed a saccadic shift towards local complexity in more-expert musicians that would be less pronounced or not shown at all among less-expert musicians. Finally, as the study by Lim et al. (2019) suggested the more-expert musicians adjust their EHS by reducing it when dealing with score complexity, we hypothesised that the more-expert musicians would have a reduced EHS when playing a local complexity compared to a noncomplex event.

Overall, findings in this vein could reflect expert visual processing specificities, with experts being able to benefit to a greater extent from musical knowledge structures such as chunks and retrieval structures/templates compared to less-expert musicians in a sight-reading task.

Method

Participants

Thirty volunteer pianists from French conservatories including students about to obtain their diploma of musical study (end of cycle 3) and professionals were recruited (18 women, 12 men). The musicians all had at least 8 years of conservatory experience. Fourteen participants were student from cycle 3 at the Conservatory, and 16 were from Conservatoire National Supérieur de Musique of Paris or professional musicians (M_{age}=38.44, 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 (N=24) would be needed to obtain sufficient statistical power at the recommended .80 level (Cohen, 1988). Twenty-five participants were right-handed, and five were left-handed. All participants had normal or corrected-to-normal vision. Participation was rewarded with a gift card of 15€. All participants freely gave their informed written consent in accordance with the Declaration of Helsinki.

Material

The material for the study consisted of 68 excerpts of piano scores that were selected from the repertoire for piano to represent the kind of music that musicians might encounter in their daily practice. These excerpts were four-bar long and were transcribed using the Final music notation software. The scores were displayed on a computer screen with a resolution of 1920 × 1080 pixels and were played on a KAWAI VPC1 piano. The performance was recorded using a Musical Instrument Digital Interface (MIDI) and transmitted via Reaper software. An EyeLink Portable Duo (*SR Research*™) tracked and recorded eye movements with a sampling rate of 1,000 Hz. The computer collecting the musical performance and the computer recording eye movements were synchronised.

Procedure

Each participant filled out a questionnaire about their musical background. They were seated at a piano and asked to adjust the seat height to their comfort. The participant was then given written instructions and asked to sight read the series of musical excerpts in a random order, while their eye movements were recorded. Before each excerpt, the participant had to look at a fixation cross where the stimulus will be located. A visual trigger was positioned on the fixation cross so that when the gaze moved to the fixation cross, the stimulus appeared. They were asked to play the excerpt at a comfortable tempo, and their performance was recorded. After each excerpt, the participant was asked to rate the difficulty of the piece on a scale from 1 (very easy) to 5 (very difficult) and to indicate if they already knew the excerpt by pressing a button, 1 (yes) or 2 (no). The entire session typically lasted between 45 and 60 minutes (Figure 1).

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 musical scores. On average, the musicians knew 6.16 excerpts out of 68 (SD=6.45), which corresponds to less than 10% of recognised scores.

Local characteristics

Each excerpt was divided into as many areas of interest (AOIs) as there were events (i.e., single note, chords [three or more tones played simultaneously], or rests) in addition to an AOI including treble and bass clefs, as well as key and time signatures (Figure 2).

For each manipulated local feature factor (e.g., *heterogeneity, alteration, note count*, and *location on the staff*), each AOI was assigned to either the "complex" or the "noncomplex" condition (Table 1). All AOIs that contained at least one new note (a pitch encountered for the first time since the beginning of the score) belonged to the complex condition of the *heterogeneity* factor; all AOIs that contained at least one accidental (#, *b*, or ♮) belonged to the complex condition of the *alteration* factor; all AOIs that contained more than two notes belonged to the complex condition of the *note count* factor; and all AOIs that contained at least one note outside the musical staff

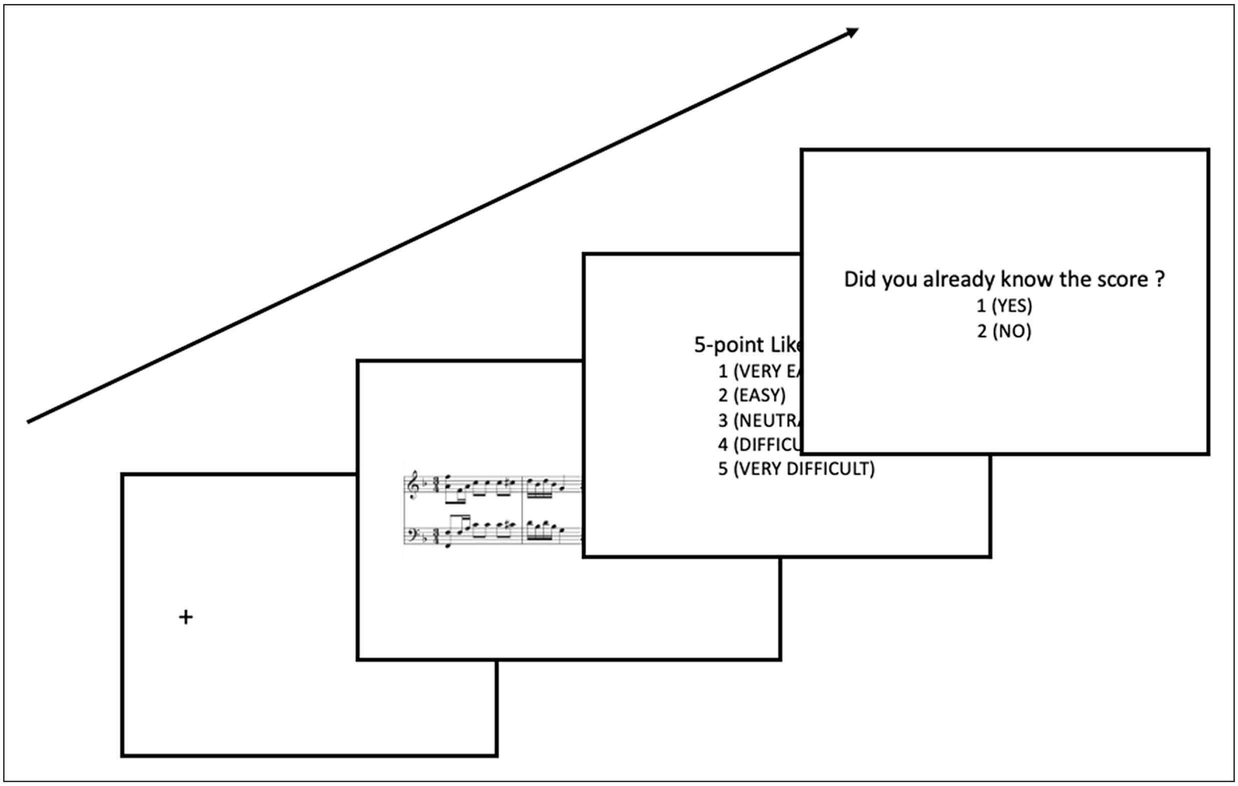

Figure 1. Illustration of one trial.

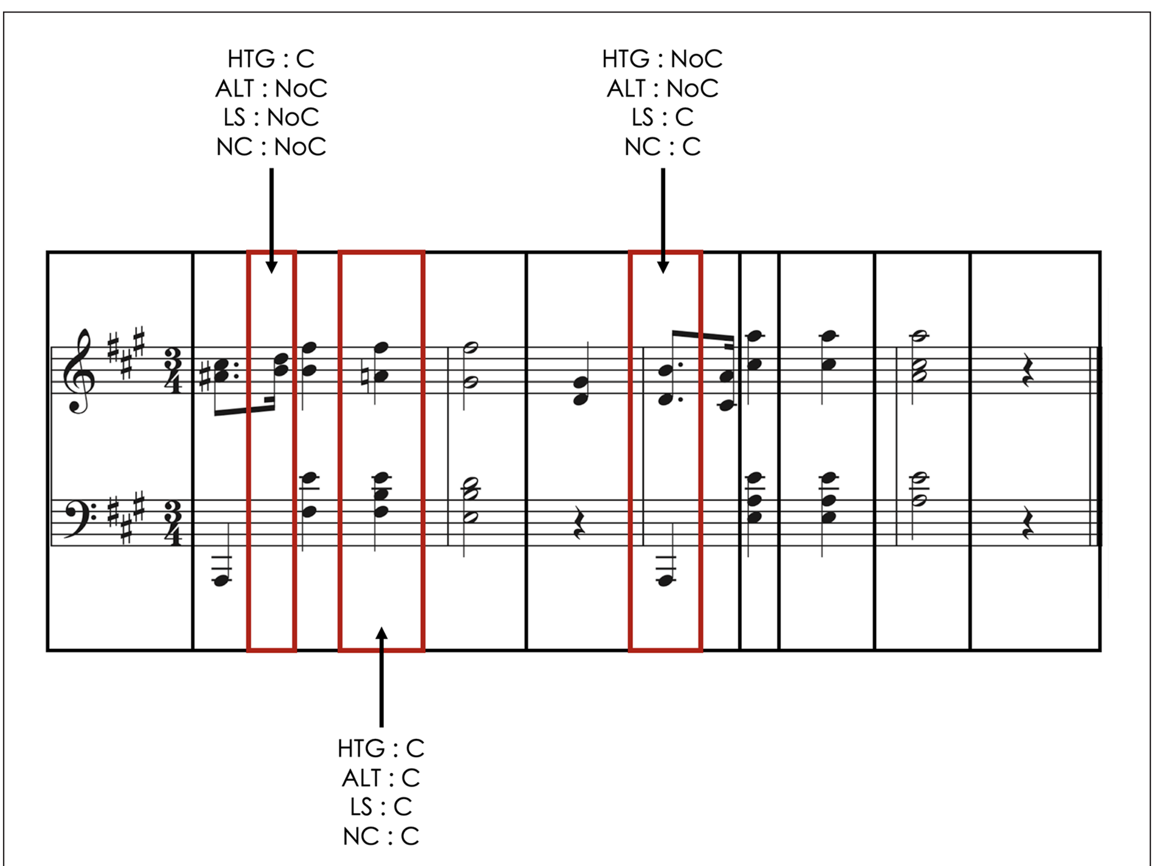

Figure 2. Example of a score divided into AOIs related to musical events (notes, chords, or rests).
Note. HTG = heterogeneity; ALT = alteration; LS = location of the staff; NC = note count; C = complexity; NoC = no complexity.

Table 1. Number of AOIs for each condition and factors.

Area of interest	Heterogeneity	Alteration	Note count	Location of the staff	Others
Criterion	New	Accidental	More than two	Distant	Other
Complex	708	252	254	635	—
Noncomplex	646	1,102	1,100	719	—
Key and time signatures	—	—	—	—	68
Rest	—	—	—	—	62
Slur	—	—	—	—	20
Total	1,354	1,354	1,354	1,354	150

belonged to the complex condition of the *location of the staff* factor. The same AOIs could be considered as complex for several factors (Figure 2).

Fixation data

To be included in the analysis, an eye fixation had to last at least 80 ms. The following variables were measured for each AOI: the FPF in ms, which corresponds to the sum of the fixation durations that occurred during the first run of the eye on the AOI; the second-pass fixation (SPF) in ms, which corresponds to the sum of the refixation duration on the AOI; and the PISS, which corresponds to the size of the saccades in degrees of visual angle (°VA) performed in the reading direction that are reaching an AOI.

Performance data

An AOI was considered correct when all its component elements were correctly played. The accuracy rate measure corresponded to the proportion of correct AOIs for each condition of each complexity factor. Finally, the perceived complexity was measured using a 5-point Likert-type scale ranging from 1 (very easy) to 5 (very difficult).

Synchronisation of eye-movement and performance data

The computer that recorded the musical performance was connected to the piano using the Reaper software. This computer and the computer that tracked eye movements were synchronised, allowing us to determine the specific notes being played on the piano and the notes being fixated on by the performer at any given time. The EHS was calculated using the distance-in-musical-units method described by Perra et al. (2021). This method considers an AOI as a unit of span. For each correct AOI, the distance between the AOI being fixated on at the time of the last fixation and the currently played AOI determined the EHS. Because the MIDI data recording failed for two participants from the more-expert group, they were excluded from the analyses for the measures for which these recording data were necessary: EHS and accuracy rate.

Results

Perceived complexity as a function of score characteristics

We performed Pearson correlations to measure the relationship between perceived complexity and the different characteristics of the score (alteration; heterogeneity; location of the staff; note count). More specifically, the Pearson correlations were performed between the perceived complexity on the 5-point Likert-type scale and the number/sum of each characteristic in the score (i.e., the number of accidentals for alteration, the number of new notes for heterogeneity, the sum of note distances in semitones for the location of the staff, and the number of notes for the note count). There were significant positive correlations between perceived complexity and alteration, $r(66) = .674$, $p < .001$; between perceived complexity and heterogeneity, $r(66) = .593$, $p < .001$; and between perceived complexity and location of the staff, $r(66) = .455$, $p < .001$ (Figure 3). In contrast, the correlation between Note count and perceived complexity was not significant ($p > .05$, Table 2).

Linear mixed model analyses. We ran linear mixed model (LMM) analyses in JAMOVI version 2.6.2. For each LMM, we included one dependent variable, namely the FPF, SPF, PISS, EHS, and ACCURACY and included as fixed effects the Expertise (between-subject) and the four score characteristics (within-subject), namely alteration (accidental, no accidental), Location of the staff (distant, on staff), Note Count (more than two notes, less than three notes), and heterogeneity (new note, repeated note). We included each participant and each score as a random effect factor. For the sake of simplicity, only significant results or results regarding our assumptions are reported in the following section (for exhaustive data analyses, see Supplementary Data).

First-pass fixations. There was a significant main effect of Expertise on the FPF, $\beta = -85.8$, 95% CI [−136, −35.9], $SE = 25.5$, $p = .002$. The more-expert musicians allocated significantly shorter FPF ($M = 347$ ms, $SD = 73.9$) than the less-expert musicians ($M = 413$ ms, $SD = 47.7$). In addition, we observed significant main effects of the four score

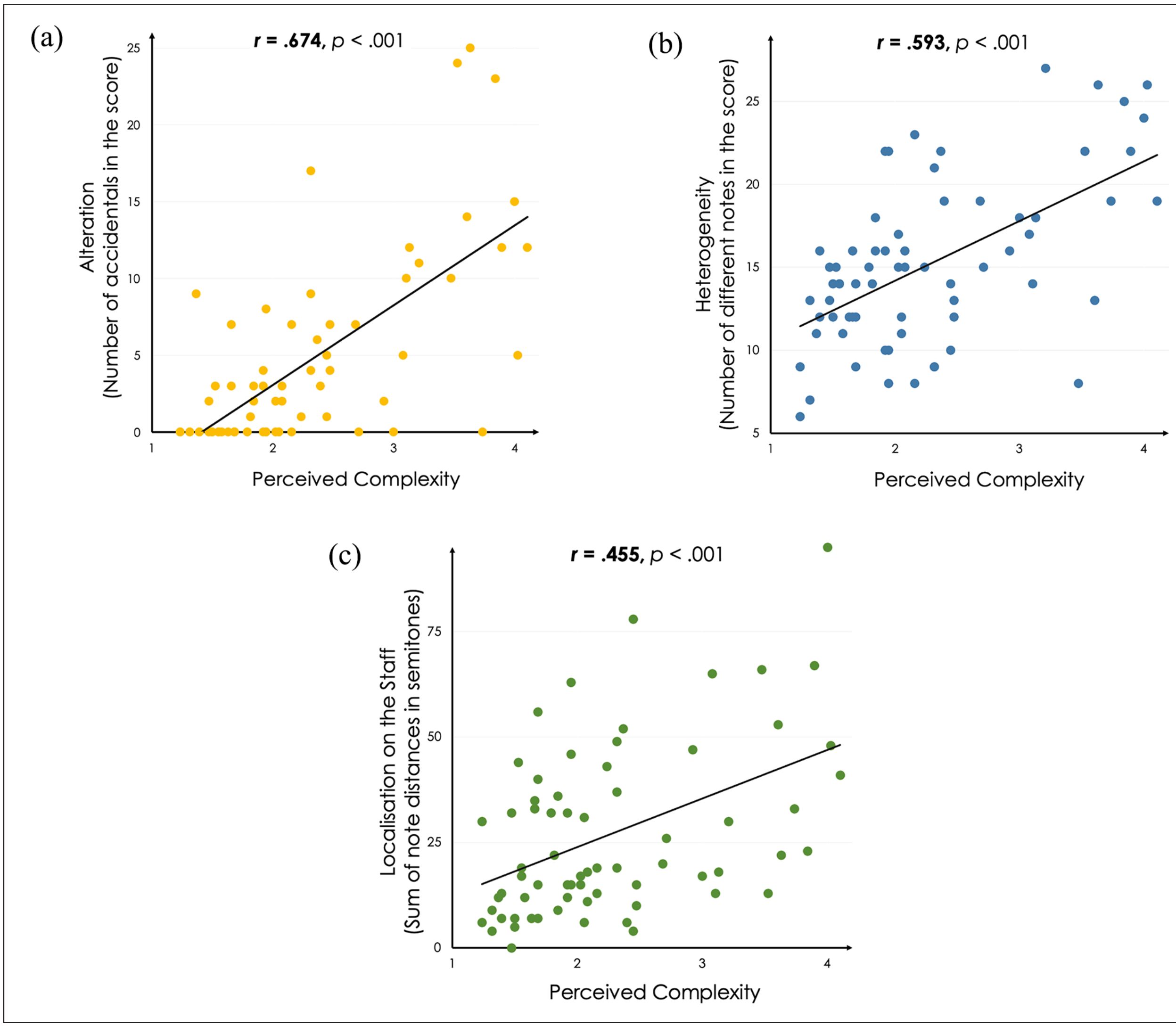

Figure 3. Alteration (a), heterogeneity (b), and location of the staff (c) as a function of perceived complexity.

Table 2. Correlations between the perceived complexity and characteristics of the score.

Score characteristics	PC	ALT	HTG	LS	NC
PC	—				
ALT	.674***	—			
HTG	.593***	.384**	—		
LS	.455***	.250*	.200	—	
NC	.194	.188	.540***	.112	—

Note. PC: perceived complexity; ALT: alteration; LS: location of the staff; HTG: heterogeneity; NC: note count.
*$p < .05$. **$p < .01$. ***$p < .001$.

characteristics on the FPF. **Alteration:** The FPF was significantly longer in the accidental condition ($M = 456$ ms, $SD = 88.6$) than in the no accidental condition ($M = 368$ ms, $SD = 73.9$), $\beta = 53.2$, 95% CI [43.2, 63.2], $SE = 5.10$, $p < .001$. **Location of the staff:** The FPF was significantly longer in the distant condition ($M = 419$ ms, $SD = 84.2$) than in the on-staff condition ($M = 355$ ms, $SD = 68.9$), $\beta = 25.4$, 95% CI [18.1, 32.7], $SE = 3.71$, $p < .001$. **Note count:** The FPF was significantly longer in the more-than-two notes condition ($M = 504$ ms, $SD = 115$) than that in the less-than-three notes condition ($M = 356$ ms, $SD = 68.1$), $\beta = 135$, 95% CI [125, 145], $SE = 5.17$, $p < .001$. **Heterogeneity:** The FPF was significantly longer in the new-note condition ($M = 395$ ms, $SD = 77.7$) than that in the repeated-note condition ($M = 375$ ms, $SD = 74.5$), $\beta = 17.5$, 95% CI [10.8, 24.2], $SE = 3.43$, $p < .001$.

Moreover, there was a significant Expertise × Note Count interaction effect on the FPF, $\beta = -48.3$, 95% CI [−64.8, −31.7], $SE = 8.43$, $p < .001$. Post hoc analyses with Bonferroni corrections revealed that among the less-expert musicians, the FPF was significantly longer in the more than two notes condition ($M = 561$ ms, $SD = 84.7$) than that in the less than three notes condition ($M = 388$ ms,

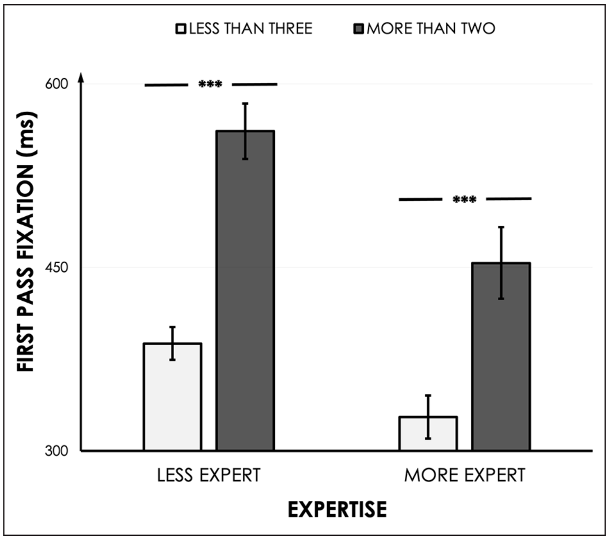

Figure 4. First-pass fixation as a function of expertise and note count.
Error bars represent standard errors.
$^{***}p < .001$.

Figure 5. Second-pass fixation as a function of expertise and alteration.
Note. Error bars represent standard errors. NS: nonsignificant.
$^{***}p < .001$.

SD=50.3, β=159, 95% CI [146, 172], *SE*=6.78, *p* < .001). The more-expert musicians also allocated a significantly longer FPF in the more than two notes condition (*M*=454 ms, *SD*=117) than in the less than three notes condition (*M*=328 ms, *SD*=70.5), but this difference was less pronounced, (β=111, 95% CI [97.8, 124], *SE*=6.56, *p* < .001, Figure 4).

Second-pass fixations. There was a significant main effect of Expertise on the SPF, β=−383, 95% CI [−550, −216], *SE*=85.0, *p* < .001. The more-expert musicians allocated significantly shorter SPF (*M*=227 ms, *SD*=110) compared to the less-expert musicians (*M*=520 ms, *SD*=305).

In addition, we observed significant main effects of three of the four score characteristics on the SPF. **Alteration:** The SPF was significantly longer in the accidental condition (*M*=521 ms, *SD*=359) than in the no accidental condition (*M*=321 ms, *SD*=253), β=49.8, 95% CI [30.9, 68.6], *SE*=9.62, *p* < .001. **Note Count:** The SPF was significantly longer in the more than two notes condition (*M*=563 ms, *SD*=439) than in the less than three notes condition (*M*=309 ms, *SD*=234), β=195, 95% CI [176, 214], *SE*=9.74, *p* < .001. **Heterogeneity:** The SPF was significantly longer in the new-note condition (*M*=462 ms, *SD*=364) than in the repeated-note condition (*M*=242 ms, *SD*=173), β=157, 95% CI [144, 170], *SE*=6.41, *p* < .001.

Moreover, there was a significant Expertise × Alteration interaction effect on the SPF, β=−67.0, 95% CI [−97.2, −36.8], *SE*=15.4, *p* < .001. Post hoc analyses with Bonferroni corrections revealed that among the less-expert musicians, the allocated SPF in the accidental condition (*M*=743 ms, *SD*=399) was significantly longer than that in the no accidental condition (*M*=467 ms, *SD*=297, β=83.2, 95% CI [58.7, 108], *SE*=12.5, *p* < .001). There was no significant difference between the two conditions in more-expert musicians (β=16.3, 95% CI [−7.44, 40.0], *SE*=12.1, *p*=1, Figure 5). There was also a significant Expertise × Location of the Staff interaction effect on the SPF, β=−36.7, 95% CI [−61.3, −12.2], *SE*=12.5, *p*=.003. Post hoc analyses with Bonferroni corrections indicated that among the more-expert musicians, the allocated SPF was marginally longer in the distant condition (*M*=244 ms, *SD*=121) than in the on-staff condition (*M*=195 ms, *SD*=103, β=24.0, 95% CI [5.84, 42.1], *SE*=9.24, *p*=.057). There was no significant difference between the two conditions in the less-expert musicians (β=−12.8, 95% CI [−31.4, 5.78], *SE*=9.47, *p*=1). In addition, there was a significant Expertise × Note Count interaction effect on the SPF, β=−196, 95% CI [−226, −165], *SE*=15.7, *p* < .001. Post hoc analyses with Bonferroni corrections revealed that among the less-expert musicians, the allocated SPF was significantly longer in the more than two notes condition (*M*=832 ms, *SD*=499) than in the less than three notes condition (*M*=444 ms, *SD*=273, β=293, 95% CI [268, 318], *SE*=12.7, *p* < .001). The more-expert musicians also allocated a significantly longer SPF in the more than two notes condition (*M*=328 ms, *SD*=191) than in the less than three notes condition (*M*=191 ms, *SD*=96.5), but this difference was less pronounced (β=97.8, 95% CI [73.6, 122], *SE*=12.3, *p* < .001). Finally, there was a significant Expertise × Heterogeneity interaction effect on the SPF, β=−168, 95% CI [−192, −144], *SE*=12.2, *p* < .001. Post hoc analyses with Bonferroni corrections revealed that among the less-expert musicians, the allocated SPF was significantly longer in the new-note condition (*M*=674 ms, *SD*=427) than in the repeated-note

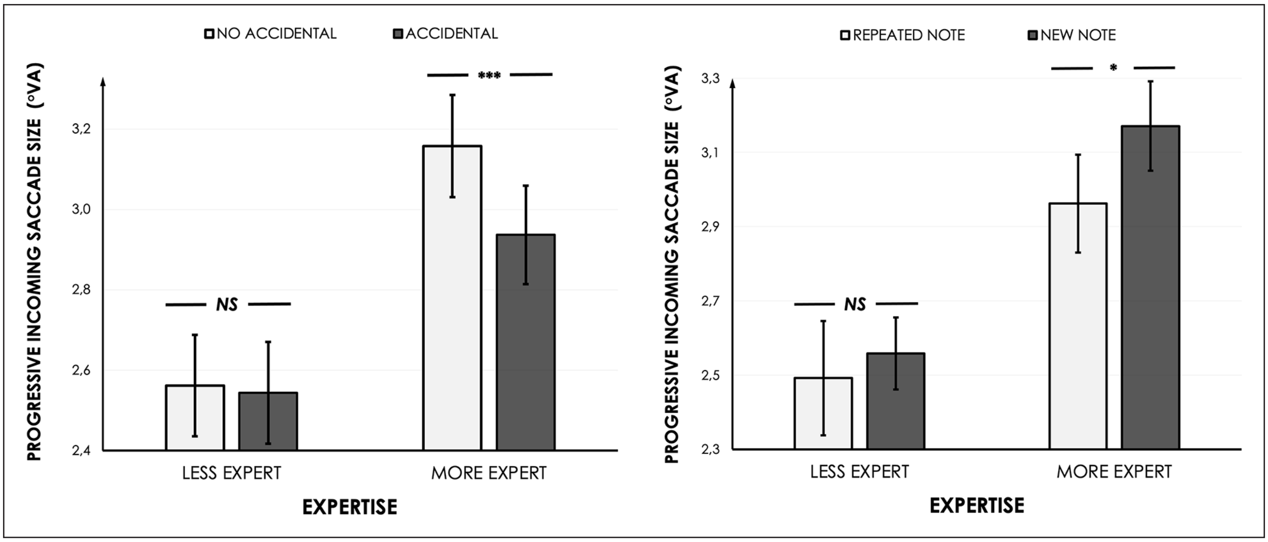

Figure 6. Progressive incoming saccade size as a function of expertise and (a) alteration and (b) heterogeneity.
Note. Error bars represent standard errors. NS: nonsignificant, $^*p < .05$, $^{***}p < .001$.

condition (M=346 ms, SD=191, β=241, 95% CI [224, 259], SE=8.95, $p < .001$). The more-expert musicians also allocated a significantly longer SPF in the new-note condition (M=277 ms, SD=137) than in the repeated-note condition, but this difference was less pronounced (M=150 ms, SD=83.2, β=72.8, 95% CI [55.7, 89.9], SE=8.72, $p < .001$).

Progressive incoming saccade size. There was a significant main effect of Expertise on the PISS, β=.483, 95% CI [0.137, 0.829], SE=0.176, p=.01. The PISS was significantly larger in more-expert musicians (M=3.07 °VA, SD=0.501) than in less-expert musicians (M=2.55 °VA, SD=0.459).

In addition, significant main effects were found for the four score characteristics on the PISS. **Alteration**: The PISS was significantly shorter in the accidental condition (M=2.72 °VA, SD=0.514) than in the no accidental condition (M=2.85 °VA, SD=0.570), β=−.144, 95% CI [−0.247, −0.042], SE=0.052, p=.006. **Location of the Staff**: The PISS was significantly larger in the distant condition (M=2.93 °VA, SD=0.567) than that in the on-staff condition (M=2.72 °VA, SD=0.534), β=.103, 95% CI [0.026, 0.181], SE=0.040, p=.009. **Note Count**: The PISS was significantly larger in the more than two notes condition (M=3.02 °VA, SD=0.582) than in less than three notes condition (M=2.77 °VA, SD=0.542), β=.143, 95% CI [0.039, 0.247], SE=0.053, p=.007. **Heterogeneity**: The PISS was significantly larger in the new-note condition (M=2.89 °VA, SD=0.526) than in the repeated-note condition (M=2.74 °VA, SD=0.591), β=.089, 95% CI [0.018, 0.160], SE=0.036, p=.014.

Moreover, there was a significant Expertise × Alteration interaction effect on the PISS, β=–.251, 95% CI [–0.416, –0.086], SE=0.084, p=.003. Post hoc analyses with Bonferroni corrections revealed that among the more-expert musicians, the PISS was significantly shorter in the accidental condition (M=2.91 °VA, SD=0.489) than that in the no accidental condition (M=3.13 °VA, SD=0.507, β=–.270, 95% CI [–0.402, –0.138], SE=0.067, $p < .001$), while there was no significant difference in the less-expert musicians (β=–.019, 95% CI [–0.149, 0.112], SE=0.067, p=1, Figure 6). In addition, there was a significant Expertise × Heterogeneity interaction effect on the PISS, β=.140, 95% CI [0.005, 0.275], SE=0.069, p=.043. Post hoc analyses with Bonferroni corrections revealed that among more-expert musicians, the PISS was significantly longer in the new-note condition (M=3.17 °VA, SD=0.483) than in the repeated-note condition (M=2.96 °VA, SD=0.528, β=.159, 95% CI [0.059, 0.259], SE=0.051, p=.011), while there was no significant difference in the less-expert musicians, β=–.019, 95% CI [–0.115, 0.077], SE=0.049, p=1.

Eye-hand span. There was a significant main effect of Expertise on the EHS, β=.412, 95% CI [0.086, 0.739], SE=0.166, p=.020. The more-expert musicians exhibited significantly larger EHS (M=1.68 AOIs, SD=0.499) than less-expert musicians (M=1.22 AOIs, SD=0.343).

In addition, significant main effects were found for three of the four score characteristics on the EHS. Alteration: The EHS was significantly shorter in the accidental condition (M=1.11, SD=0.341) compared to the no accidental condition (M=1.53 AOIs, SD=0.520), β=−.099, 95% CI

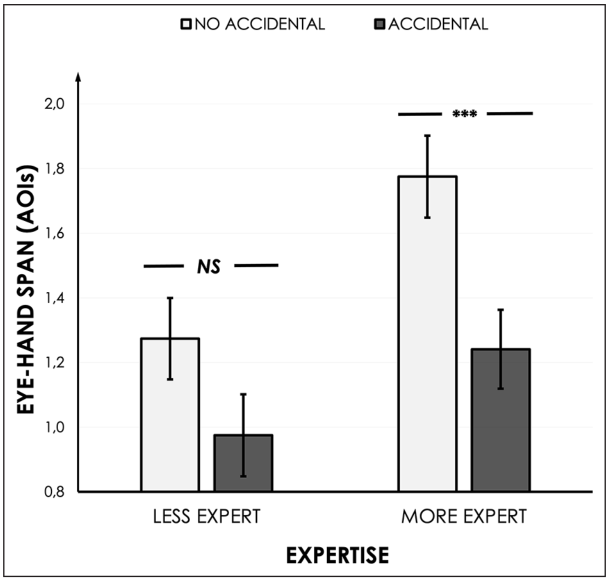

Figure 7. Eye-hand span as a function of expertise and alteration.
Error bars represent standard errors. NS: nonsignificant.
***$p < .001$.

[−0.159, −0.039], *SE* = 0.031, *p* = .001. Location of the staff: The EHS was significantly shorter in the distant condition (*M* = 1.39 AOIs, *SD* = 0.416) than in the on-staff condition (*M* = 1.51 AOIs, *SD* = 0.543), β = −.048, 95% CI [−0.091, −0.005], *SE* = 0.022, *p* = .027. Heterogeneity: The EHS was significantly shorter in the new-note condition (*M* = 1.44 AOIs, *SD* = 0.474) than in the repeated-note condition (*M* = 1.47 AOIs, *SD* = 0.498), β = −.145, 95% CI [−0.185, −0.106], *SE* = 0.020, *p* < .001.

Moreover, there was a significant Expertise × Alteration interaction effect on the EHS, β = −.225, 95% CI [–0.323, –0.128], *SE* = 0.050, *p* < .001. Post hoc analyses with Bonferroni corrections revealed that among the more-expert musicians, the EHS in the accidental condition (*M* = 1.24 AOIs, *SD* = 0.336) was significantly shorter than that in the no accidental condition (*M* = 1.78 AOIs, *SD* = 0.547, β = –.212, 95% CI [–0.288, –0.136], *SE* = 0.039, *p* < .001), while there was no significant difference between the two conditions in the less-expert musicians (β = .013, 95% CI [–0.065, 0.092], *SE* = 0.040, *p* = 1, Figure 7). There was a significant Expertise × Location of the Staff interaction effect on the EHS, β = −.100, 95% CI [–0.176, –0.023], *SE* = 0.039, *p* = .010. Post hoc analyses with Bonferroni corrections revealed that among the more-expert musicians, the EHS was significantly shorter in the distant condition (*M* = 1.57 AOIs, *SD* = 0.435) than in the on-staff condition (*M* = 1.77 AOIs, *SD* = 0.572), β = –.098, 95% CI [–0.155, –0.041], *SE* = 0.029, *p* = .005, while there was no significant difference between the two conditions in the less-expert musicians, β = .002, 95% CI [–0.055, 0.059], *SE* = 0.029, *p* = 1.

Accuracy (%). There was a significant main effect of **Expertise** on the accuracy, β = 10.3, 95% CI [6.01, 14.6], *SE* = 2.18, *p* < .001. The more-expert musicians were significantly more accurate (*M* = 90.8%, *SD* = 2.11) than the less-expert musicians (*M* = 83.1%, *SD* = 7.60).

In addition, significant main effects were found for three of the four score characteristics on the accuracy. Location of the staff: The accuracy was significantly lower in the distant condition (*M* = 82.5%, *SD* = 8.93) than in the on-staff condition (*M* = 91.1%, *SD* = 4.96), β = –3.28, 95% CI [–4.08, –2.48], *SE* = 0.409, *p* < .001. Note count: The accuracy was significantly lower in the more than two notes condition (*M* = 73.2%, *SD* = 11.4) than in the less than three notes condition (*M* = 90.4%, *SD* = 5.80), β = –13.1, 95% CI [–14.2, –11.9], *SE* = 0.574, *p* < .001. Heterogeneity: The accuracy was significantly lower in the new-note condition (*M* = 85.5%, *SD* = 7.28) than in the repeated-note condition (*M* = 88.7%, *SD* = 6.30), β = –1.17, 95% CI [–1.91, –0.436], *SE* = 0.376, *p* = .002.

Moreover, there was a significant Expertise × Location of the Staff interaction effect on the accuracy, β = 3.49, 95% CI [2.05, 4.93], *SE* = 0.734, *p* < .001. Post hoc analyses with Bonferroni corrections revealed that among the less-expert musicians, the accuracy was significantly lower in the distant condition (*M* = 73.9%, *SD* = 9.60) than in the on-staff condition (*M* = 85.3%, *SD* = 7.34), β = –5.02, 95% CI [–6.08, –3.97], *SE* = 0.540, *p* < .001. More-expert musicians were also significantly less accurate in the distant condition (*M* = 87.6%, *SD* = 2.66) than in the on-staff condition (*M* = 93.8%, *SD* = 1.88), but this difference was less pronounced (β = –1.53, 95% CI [–2.63, –0.439], *SE* = 0.559, *p* = .036). There was also a significant Expertise × Note Count interaction effect on the accuracy, β = 5.47, 95% CI [3.67, 7.27], *SE* = 0.009, *p* < .001. Post hoc analyses with Bonferroni corrections revealed that among the less-expert musicians, the accuracy was significantly lower in the more than two notes condition (*M* = 66.4%, *SD* = 12.5) than in the less than three notes condition (*M* = 87.2%, *SD* = 6.58), β = –15.8, 95% CI [–17.2, –14.4], *SE* = 0.730, *p* < .001. The more-expert musicians were also significantly less accurate in the more than two notes condition (*M* = 80.0%, *SD* = 3.99) than the less than three notes condition (*M* = 93.6%, *SD* = 2.06), but this difference was less pronounced, β = –10.3, 95% CI [–11.8, −8.87], *SE* = 0.742, *p* < .001 (Figure 8).

Discussion

The aim of this study was to determine the extent to which expertise in music reading impacts eye movements and performance in a sight-reading task as a function of different local characteristics of the score such as the presence of accidentals, the note count, the location of the notes on the staff, or the note heterogeneity. In this experiment, musicians of two expertise levels (less expert vs. more

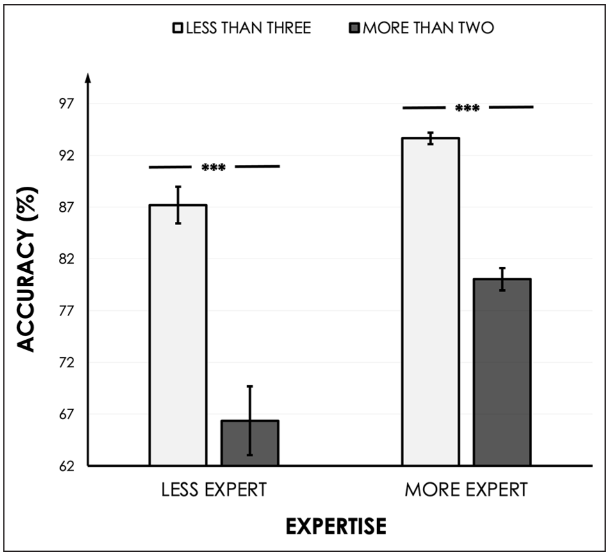

Figure 8. Accuracy as a function of expertise and note count. Error bars represent standard errors.
$^{***}p < .001$.

expert) were asked to sight read double-staff scores of similar complexities to what a musician encounters in their daily practice. We assumed interaction effects between expertise and complexity that would highlight the more-expert task-related visual processing. We hypothesised both the more-expert ability to deal with the foveal load induced by local complexities and to benefit and adjust their eye movements to the information projected onto the parafoveal area. The results showed that (1) more-expert musicians were less affected by heterogeneity and note count, showing a smaller accuracy difference between complex and noncomplex features. More-expert musicians were less affected by the foveal load induced by a local complexity, showing a lower increase in FPF on the AOIs that contained the more notes, and a lower increase in SPF on AOIs containing an accidental, the more notes, and new notes compared to less-expert musicians. (2) Musicians showed a saccadic flexibility with respect to the local characteristics of the score, exhibiting an increase in the PISS that landed on AOIs containing more notes or a distant note from the staff. These findings suggest that musicians can use the information projected onto the parafoveal area to adjust their saccade programming to the score characteristics. Moreover, the saccadic flexibility was even greater in the more-expert musicians, who were the only group to show a decrease in the PISS that landed on AOIs containing an accidental, and to show an increase of the PISS that landed on AOIs containing a new note. These results indicate that more-expert musicians are the ones who most adjust their saccadic programming to score characteristics, and that the direction of this adjustment varies, increasing or decreasing as a function of the local complexity. (3) Finally, musicians showed a visuo-motor flexibility with respect to the local characteristics of the score, showing a shorter EHS when playing AOIs containing new notes tan when playing AOIs containing repeated notes. Furthermore, the visuo-motor flexibility was even greater in the more-expert musicians, who were the only group to show a shorter EHS when playing AOIs that contained accidentals or distant notes from the staff compared to noncomplex AOIs. These results indicate that more-expert musicians are the ones who most adjust their EHS to the played score characteristics during sight reading.

Lower impact of local complexity on accuracy

First, we hypothesised that the induced perceived complexity when sight reading complex features would be higher than for noncomplex features, causing a decrease in accuracy. Except for the note count per score, musicians perceived an increasing complexity as the number of accidentals, the number of different notes, and the distance of the notes from the staff increased. In addition, musicians were less accurate when sight reading complex compared to noncomplex features. Although the note count per score did not correlate with the musicians' perceived complexity, these results suggest that except for the note count per score, each of the other score feature can predict the sight-reading complexity as suggested by previous studies (Cara, 2018; Gilman & Underwood, 2003; Qi & Adachi, 2022; Wurtz et al., 2009; Zhukov et al., 2019). Furthermore, we assumed that musicians would be increasingly accurate as expertise develops. This was confirmed with a significant difference in accuracy between the less-expert and more-expert musicians. Finally, we expected that the decrease in accuracy when sight reading complex features would be less pronounced with the development of expertise. The results concerning the evolution of the accuracy as a function of expertise and complexity confirmed our assumption. Both accuracy differences between sight reading AOIs containing new notes compared to repeated notes and AOIs containing distant notes from the staff and on-staff notes were smaller for the more-expert than for the less-expert musicians, indicating that the less-expert musicians were more affected by local complexity than the more-expert musicians.

Efficient management of the foveal load induced by local complexity

First, consistent with the decrease in accuracy rate with local complexity and its increase with expertise, we assumed an increase in both FPF and SPF on local complexity and a decrease of both FPF and SPF across expertise levels. In line with our assumption, on the one hand, musicians allocated longer FPF and SPF on each complex compared to noncomplex features (except for the main effect of the location of the staff on SPF, which was nonsignificant), indicating a higher induced foveal load when sight reading complex compared to noncomplex features. Moreover, the more-expert musicians allocated significantly shorter FPF and SPF than less-expert musicians, indicating an increased ability to deal with the foveal load with expertise. These results are consistent both with studies investigating the effect of complexity on eye movements in music reading on stimulus complexity (Cara, 2018; Qi & Adachi, 2022; Wurtz et al., 2009; Zhukov et al., 2019) or local complexity (Chitalkina et al., 2021; Penttinen et al., 2015; Rosemann et al., 2016), and with studies having investigated the effect of music reading expertise on fixation durations (Drai-Zerbib & Baccino, 2005, 2014, 2018; 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).

Second, and as one of the major assumptions of this study, we expected that the increase in FPF and SPF on complex compared to noncomplex features would be less pronounced as expertise develops. Our assumptions were partially confirmed. There was a significant Expertise × Note Count interaction effect on the FPF. The difference in FPF between the more than two notes condition and the less than three notes condition was less pronounced in the less-expert than in the more-expert musicians. In addition, concerning the SPF, we observed significant interactions between expertise and the four local complexities.

In three out of the four score characteristics, namely the alteration, the heterogeneity, and the note count, there was a less pronounced difference in SPF between the complex AOIs and the noncomplex AOIs in the less experts compared to the more-expert musicians. These results indicate that the complexity effect on the time taken to extract visual information and to plan an adequate motor response is less impactful in the more experts than in the less-expert musicians. For example, in the case of the Expertise × Note count interaction effects, the more-expert musicians might have been able to chunk groups of notes together allowing them to be less impacted by the foveal load induced by AOIs containing more than two notes than the less-expert musicians. First, these results emphasise the structured processing skills developed with music reading expertise (Aiello, 2001; Burman & Booth, 2009; Chaffin & Imreh, 1997; Halpern & Bower, 1982; Sheridan & Kleinsmith, 2022; Waters et al., 1998; Williamon & Valentine, 2002). Second, these results suggest that the lowering difference in fixation durations between complex and noncomplex features can be a marker of sight-reading expertise: the foveal load induced by a local complexity is lowering with expertise.

However, contrary to our expectations, the Expertise × Location of the Staff interaction effect indicated that the SPF allocated to AOIs containing distant notes from the staff was marginally higher than AOIs containing on-staff notes among the more expert, and the difference was not significant among the less expert. This result runs counter to our hypotheses. It could indicate that the more-expert musicians are the only musicians needing to revisit AOIs containing distant notes for a longer duration than other AOIs. However, if we look at the mean values of the two expertise groups, we can see that the more-expert musicians show a shorter SPF than the less-expert ones, whatever the modality of the factor (distant vs. on-staff), and second, the variance of the SPF is quite large among the less-expert musicians, who therefore seem to show greater inter-individual differences, which is not the case among the more-expert musicians, who all show very little need to return to the AOI during sight-reading, although it is marginally higher in the case of complex AOIs. Thus, the fact that the difference is only marginal among the more-expert users could be due to this phenomenon, which has a fairly moderate impact on our interpretations regarding the SPF variable.

Finally, in this study, more-expert musicians differ from less-expert musicians more often in terms of SPF than FPF. These results indicate that for the more experts, most of the visuo-motor information is already extracted during the FPF, regardless of whether the AOI is complex or not. By contrast, in less-expert musicians, there is most often a need to come back to the AOI to extract the associated visuo-motor information, especially when the AOI is complex (Figure 9).

Visuo-motor flexibility depending on the played complexity

We assumed a shorter EHS when playing complex compared to noncomplex features and an increase in EHS with expertise. These assumptions were confirmed. Musicians' EHS was shorter when fixating complex compared to noncomplex features, and the more-expert musicians showed significantly larger EHS than the less-expert musicians. These results are consistent with those observed in the literature (for a review, see Perra et al., 2021) and indicate that the complexity requires musicians to reduce their average EHS (Cara, 2018; Chitalkina et al., 2021; Gilman & Underwood, 2003; Penttinen et al., 2015; Rosemann et al., 2016; Sloboda, 1977; Truitt et al., 1997; Wurtz et al., 2009) and that the amount of information that is held active in WM at a given time between a fixated note and a played note increases with expertise (Cara, 2018; Furneaux & Land, 1999; Gilman & Underwood, 2003; Huovinen et al., 2018; Imai-Matsumura & Mutou, 2021; Penttinen et al., 2015; Qi & Adachi, 2022; Sloboda, 1974; Truitt et al., 1997). Overall, these results indicate that EHS is a marker of the ability to deal with the cognitive load involved in note deciphering. Furthermore, we expected that the reduction in EHS on complex compared to noncomplex features would be less pronounced as expertise develops, suggesting better expert

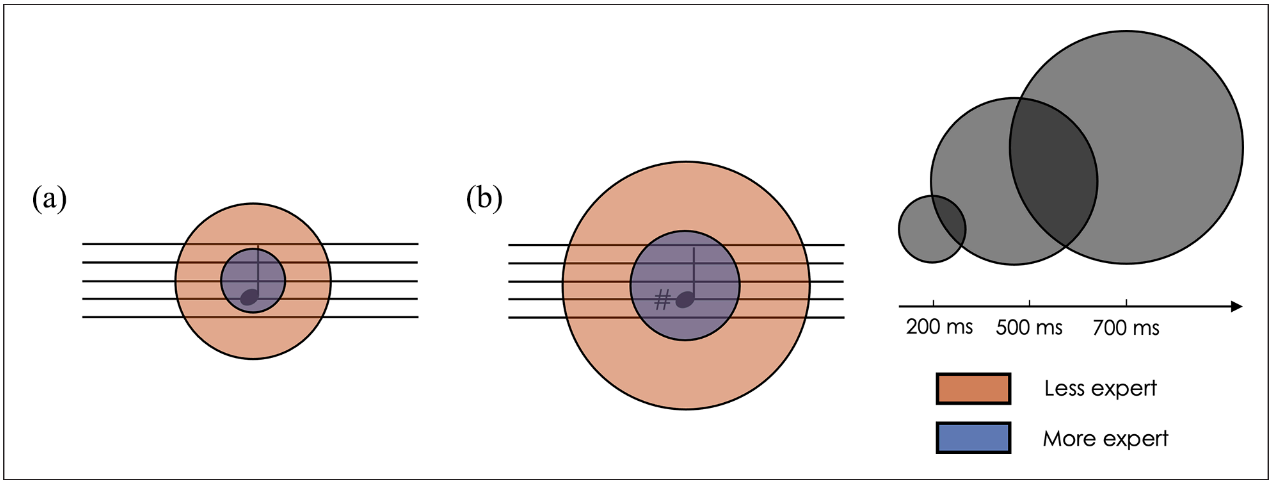

Figure 9. Differences in the allocated SPF on noncomplex features (a) and accidentals (b) in the less- and more-expert musicians.

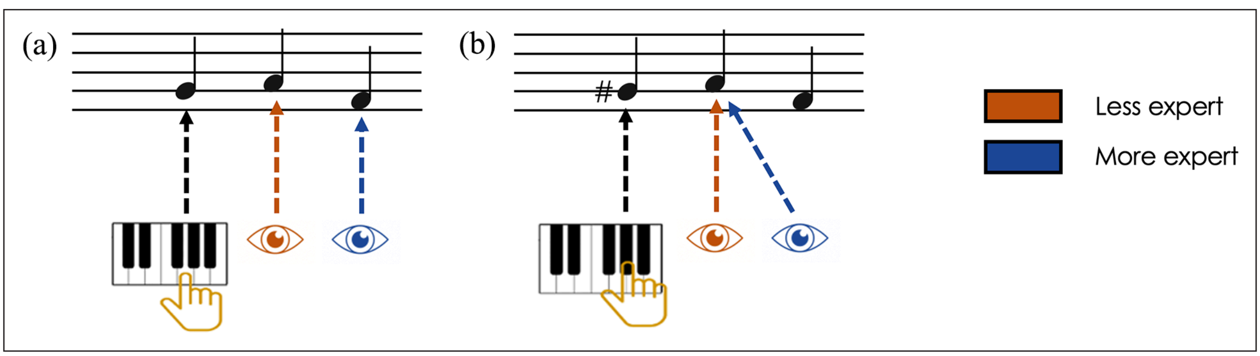

Figure 10. Differences in EHS when playing a noncomplex feature (a) and when playing an accidental (b) in less- and more-expert musicians.

handling of sight-reading local complexity. We did observe significant Expertise × Alteration and Expertise × Location of the Staff interaction effects on EHS. In both these interaction effects, the EHS was significantly shorter in the complex condition than in the noncomplex condition among the more-expert musicians, while there was no significant difference between the two conditions in less-expert musicians. Our assumptions were confirmed. These results indicate that more-expert musicians demonstrate a visuomotor flexibility, by being able to adjust their EHS with respect to the features they sight read. This phenomenon is consistent with the results observed by Lim et al. (2019). In their study, more-proficient musicians showed a negative correlation between EHS and score complexity, which was not observed in less-proficient musicians. The authors interpretated these results by stating that the EHS could reflect a dynamic adjustment to the score complexity. Our findings are in line with this assumption, indicating that expertise is associated with the ability to adjust the EHS to the score characteristics. Among the more experts, EHS is longer when the played AOI is noncomplex than when it is complex (Figure 10).

Saccadic flexibility towards local parafoveal complexity

We assumed that the PISS would be larger as expertise increased. Our assumption was confirmed. The more-expert musicians showed significantly larger PISS than the less-expert musicians. These results are consistent with studies on the effect of music reading expertise (Drai-Zerbib & Baccino, 2005; Penttinen et al., 2013; Sheridan & Kleinsmith, 2022; Waters & Underwood, 1998) or skill (Polanka, 1995) on saccade size. These results indicate that expertise is associated with an increase of the perceptual span. Moreover, we hypothesised an increase of the PISS on local complexities compared to the other features. This assumption was confirmed on three out of the four score characteristics. On the one hand, the PISS increased on AOIs containing more than two notes, a distant note from the staff and a new note compared to noncomplex features. As suggested in the Huovinen et al.'s (2018) study, in which musicians showed distant attraction of the gaze to the note following an intervallic skip (increases of ETS and incoming saccade size), our results indicate that

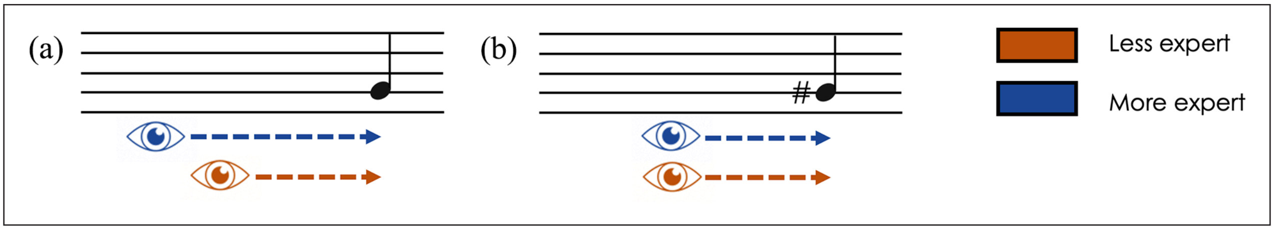

Figure 11. Differences in the progressive incoming saccade size on a noncomplex feature (a) and an accidental (b) in less- and more-expert musicians.

local complex features undergo parafoveal processing that allows musicians to tailor their eye movements to cope with it. This ability may be a great skill developed with sight-reading training. From another point of view, the fact that saccade sizes were larger on these three features for all expertise groups could have been due to visual properties of the score. For instance, in the case of distant notes from the staff, the fact that the incoming saccade sizes were larger on these specific elements could have been due to their distance from the other element (Goolsby, 1994b) rather than to a distant attraction of the eye. However, the fact that this effect was also observed on new notes and on AOIs containing the more notes may indicate a distant attraction effect of these local complexities. It would be interesting to further investigate this issue with finer grained staff-characteristic manipulated factors.

On the other hand, the PISS was shorter on AOIs containing an accidental compared to noncomplex features, and there was a significant Expertise × Alteration interaction on the PISS. Among the more-expert musicians, the PISS was significantly shorter in the accidental condition than in the no accidental condition, while there was no significant difference in less-expert musicians. These results indicate a greater saccadic flexibility in the more-expert musicians as a function of the score characteristics projected onto the parafoveal area. However, contrary to what we expected, the PISS was smaller on AOIs containing an accidental compared to noncomplex features. By linking these results to the theoretical holistic model of image perception (Kundel et al., 2007), more-expert musicians might be able to decipher larger groups of notes per fixation thanks to a larger perceptual span (global processing), explaining their larger average progressive saccades than less experts, and as a second step, to make a focal fixation on accidentals to facilitate their deciphering (local processing). In fact, since accidentals are particularly salient features that can be recognised in the parafoveal area (shape recognition) and since it was the most correlated feature with the perceived complexity, accidentals might be recognised even earlier than other local complexities in the expert sight-reading process. It would require a distant dynamic adjustment of the eye on accidentals to facilitate their deciphering, which would result in shorter PISS on AOIs containing accidentals compared to noncomplex features in the more-expert musicians (Figure 11). Interestingly, there was also an Expertise × Heterogeneity interaction effect on the PISS, but post hoc analyses revealed that among the more-expert musicians, the PISS was significantly longer in the new-note condition than in the repeated-note condition, while there was no significant difference in less-expert musicians. These results go in an opposite direction from the Expertise × Alteration interaction effect. Our findings indicate that more-expert musicians were able tailor their saccadic programming to the heterogeneity of the notes, by being "attracted" to a new note compared to a repeated note in the score.

Overall, although this question might require further investigations, these results highlight the fact that, as observed in text-reading studies (Brysbaert et al., 2005; Hyönä, 1995; Rayner et al., 2011), it seems to be a preview-benefit effect in more-expert musicians, who could benefit from their high-level knowledge to present a greater perceptual span and consequently to adjust their saccade size to the upcoming features projected onto the parafoveal area. Therefore, as in other domain such as medicine (Donovan & Litchfield, 2013), chess (Sheridan & Reingold, 2014), or sports (Vansteenkiste et al., 2014), the saccadic flexibility in regards to local "disturbances" that reflects the expert knowledge-driven approach when scanning a visual stimulus (Kundel et al., 2007), music reading expertise could also be reflected by saccadic flexibility as a function of the upcoming features in the score, although it could be reflected in different results (larger or shorter saccade size as a function of the type of visual "disturbances").

Conclusion

This study emphasises the usefulness of granularising performance and eye-movement analysis according to the local characteristics of a score to investigate foveal and parafoveal processing skills during music reading. It seems that the well-known domain-specific knowledge-driven processing effect of expertise results in a perceptual and visuo-motor flexibility during music reading, which enables more-expert musicians to anticipate and efficiently manage local complexity. As a result, more-expert musicians are less affected by the foveal load induced by local complexity, showing a lower increase in fixation durations between noncomplex features and local complexity compared to the less experts. They present a saccadic flexibility towards the local complexity projected onto the parafoveal area, being the only group to exhibit shorter PISS on accidentals and larger PISS on new notes compared to noncomplex features. Finally, they present a visuo-motor flexibility depending on the played complexity, being the only group to exhibit a shorter EHS when playing accidentals or distant notes compared to noncomplex features.

Limitations

Insofar as we chose to use "naturalistic" material with scores that musicians might encounter in their daily practice, the four complexity factors (alteration, location of the staff, note count, and heterogeneity) were not present in a balanced way in the material. While this method maintains the ecological validity of the scores, it opens the possibility for confounds between complex and noncomplex AOIs. For instance, the average location of complex AOIs within the excerpts might differ systematically from noncomplex AOIs, potentially introducing unintended biases. Furthermore, we observed that the presence of some of the features was correlated with each other. Therefore, some of the results we observe may not be due to a particular complexity factor, but to the sum of the effects of several local features, or to the position of a local feature in the score. We have chosen LMMs as statistical analyses to overcome this limitation as far as possible, both to isolate the effect of each factor and to take into account the characteristics of each partition as random effects. It would be interesting to develop a study that controls the quantity and distribution of each feature in the scores, to isolate even better the effect of each score characteristic on eye movements. Furthermore, since a few participants recognised a few scores (never more than 10% of the whole material), small effects could have been driven by a subset of the stimuli. We tested score recognition as a covariate in our analyses. As a result, none of the effects were qualitatively modified, and score recognition had no significant effect on any of the dependent variables (all $ps > .160$).

Moreover, given that the workload assigned to WM has been shown to positively correlate with pupil size (Beatty, 1982; Granholm et al., 1996; Sibley et al., 2020), and as suggested by studies examining the effect of expertise on pupil size in fields other than music (Castner et al., 2020; Szulewski et al., 2015; Tien et al., 2015), we could have explored how musical expertise and how score characteristics affect pupil size in a sight-reading task. However, to maintain ecological validity in the experimental setup, we used an eye tracker that allowed for free head movement (i.e., the musicians were not constrained by a chinrest). We observed significant variations in the distance between the musician's face and the eye tracker during the task, which would be susceptible to have affected the accuracy of pupil size measurements. For this reason, we decided not to include this measure in the analyses. It would be interesting to test local variations in pupil size as a function of score characteristics in future studies.

Acknowledgements

We thank the administrative staffs and the musicians of the conservatories Maurice Ravel (Paris, 75013), Charles Münch (Paris, 75011), and the Conservatoire du Grand-Chalon (Chalon-sur-Saône, 71100) for their collaboration in the realisation of this study.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the French Agence Nationale de la Recherche (ANR JCJC MUREA project, grant ANR-18-CE38-0006-0).

ORCID iD

Joris Perra https://orcid.org/0000-0003-3075-2556

Data accessibility statement

The data from the present experiment are publicly available at the Open Science Framework website: https://osf.io/473mb/

Supplemental material

The supplementary material is available at qjep.sagepub.com.

References

Ahken, S., Comeau, G., Hébert, S., & Balasubramaniam, R. (2012). Eye movement patterns during the processing of musical and linguistic syntactic incongruities. *Psychomusicology: Music, Mind & Brain*, *22*(1), 18–25. https://doi.org/10.1037/a0026751

Aiello, R. (2001). Playing the piano by heart. From behavior to cognition. *Annals of the New York Academy of Sciences*, *930*(1), 389–393. https://doi.org/10.1111/j.1749-6632.2001.tb05749.x

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*, *91*(2), 276–292. https://doi.org/10.1037/0033-2909.91.2.276

Bennett, D., Gobet, F., & Lane, P. C. (2020). Forming concepts of Mozart and Homer using short-term and long-term memory: A computational model based on chunking. *Proceedings of the 42nd Annual Meeting of the Cognitive Science Society*, 178–184.

Bilalić, M., Kiesel, A., Pohl, C., Erb, M., & Grodd, W. (2011). It takes two-skilled recognition of objects engages lateral areas in both hemispheres. *PLOS ONE*, *6*, e16202. https://doi.org/10.1371/journal.pone.0016202

Boshuizen, H. P. A., Gruber, H., & Strasser, J. (2020). Knowledge restructuring through case processing: The key to generalise expertise development theory across domains? *Educational Research Review*, *29*, 100310. https://doi.org/10.1016/j.edurev.2020.100310

Brams, S., Ziv, G., Levin, O., Spitz, J., Wagemans, J., Williams, A. M., & Helsen, W. F. (2019). The relationship between gaze behavior, expertise, and performance: A systematic review. *Psychological Bulletin*, *145*(10), 980–1027. https://doi.org/10.1037/bul0000207

Breland, H. M. (1996). Word frequency and word difficulty: A comparison of counts in four corpora. *Psychological Science*, *7*(2), 96–99. https://doi.org/10.1111/j.1467-9280.1996.tb00336.x

Brysbaert, M., Drieghe, D., & Vitu, F. (2005). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Cognitive processes in eye guidance* (pp. 53–77). Oxford University Press. http://eprints.soton.ac.uk/id/eprint/145103

Burman, D. D., & Booth, J. R. (2009). Music rehearsal increases the perceptual span for notation. *Music Perception*, *26*(4), 303–320. https://doi.org/10.1525/mp.2009.26.4.303

Cara, M. A. (2018). Anticipation awareness and visual monitoring in reading contemporary music. *Musicae Scientiae*, *22*(3), 322–343. https://doi.org/10.1177/1029864916687601

Castner, N., Appel, T. M., Eder, T., Richter, J., Scheiter, K., Keutel, C., Huettig, F., Duchowski, A. T., & Kasneci, E. (2020). Pupil diameter differentiates expertise in dental radiography visual search. *PLOS ONE*, *15*(5), e0223941. https://doi.org/10.1371/journal.pone.0223941

Chaffin, R. (2007). Learning Clair de Lune: Retrieval practice and expert memorization. *Music Perception*, *24*(4), 377–393. https://doi.org/10.1525/mp.2007.24.4.377

Chaffin, R., & Imreh, G. (1997). "Pulling teeth and torture": Musical memory and problem solving. *Thinking & Reasoning*, *3*(4), 315–336. https://doi.org/10.1080/135467897394310

Chaffin, R., & Imreh, G. (2002). Practicing perfection: Piano performance as expert memory. *Psychological Science*, *13*(4), 342–349. https://doi.org/10.1111/j.0956-7976.2002.00462.x

Charness, N., Reingold, E. M., Pomplun, M., & Stampe, D. M. (2001). The perceptual aspect of skilled performance in chess: Evidence from eye movements. *Memory & Cognition*, *29*(8), 1146–1152. https://doi.org/10.3758/BF03206384

Chase, W. G., & Ericsson, K. A. (1982). Skill and working memory. *Psychology of Learning and Motivation*, *1*, 58. https://doi.org/10.1016/s0079-7421(08)60546-0

Chase, W. G., & Simon, H. A. (1973a). Perception in chess. *Cognitive Psychology*, *4*(1), 55–81. https://doi.org/10.1016/0010-0285(73)90004-2

Chase, W. G., & Simon, H. A. (1973b). The mind's eye in chess. In *Visual information processing* (pp. 215–281). Academic Press. https://doi.org/10.1016/B978-0-12-170150-5.50011-1

Chitalkina, N., Puurtinen, M., Gruber, H., & Bednarik, R. (2021). Handling of incongruences in music notation during singing or playing. *International Journal of Music Education*, *39*(1), 18–38. https://doi.org/10.1177/0255761420944036

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587

de Groot, A. D., Gobet, F., & Jongman, R. W. (1996). *Perception and memory in chess: Studies in the heuristics of the professional eye*. Van Gorcum & Co. https://psycnet.apa.org/record/1996-98853-000

Donovan, T., & Litchfield, D. (2013). Looking for cancer: Expertise related differences in searching and decision making. *Applied Cognitive Psychology*, *27*(1), 43–49. https://doi.org/10.1002/acp.2869

Drai-Zerbib, V., Ansart, M., Grenot, C., Poulin-Charronnat, B., Perra, J., & Baccino, T. (2024). Classifying musical reading expertise by eye-movement analysis using machine learning. *Frontiers in Cognition*, *3*, 1417011. https://doi.org/10.3389/fcogn.2024.1417011

Drai-Zerbib, V., & Baccino, T. (2005). L'expertise dans la lecture musicale: Intégration intermodale. *L'Année Psychologique*, *105*(3), 387–422. https://doi.org/10.3406/psy.2005.29702

Drai-Zerbib, V., & Baccino, T. (2014). The effect of expertise in music reading: Cross-modal competence. *Journal of Eye Movement Research*, *6*(5).

Drai-Zerbib, V., & Baccino, T. (2018). Cross-modal music integration in expert memory: Evidence from eye movements. *Journal of Eye Movement Research*, *11*(2). https://doi.org/10.16910/jemr.11.2.4

Drai-Zerbib, V., Baccino, T., & Bigand, E. (2012). Sight-reading expertise: Cross-modality integration investigated using eye tracking. *Psychology of Music*, *40*(2), 216–235. https://doi.org/10.1177/0305735610394710

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, *102*(2), 211–245. https://doi.org/10.1037/0033-295X.102.2.211

Ericsson, K. A., & Kintsch, W. (2000). Shortcomings of generic retrieval structures with slots of the type that Gobet (1993) proposed and modelled. *British Journal of Psychology*, *91*(4), 571–590. https://doi.org/10.1348/000712600161998

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Fox, J., Merwin, D., Marsh, R., McConkie, G., & Kramer, A. (1996). Information extraction during instrument flight: An evaluation of the validity of the eye-mind hypothesis. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *40*, 77–81. https://doi.org/10.1177/154193129604000215

Furneaux, S., & Land, M. F. (1999). The effects of skill on the eye–hand span during musical sight-reading. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *266*(1436), 2435–2440. https://doi.org/10.1098/rspb.1999.0943

Gegenfurtner, A., Gruber, H., Holzberger, D., Keskin, Ö., Lehtinen, E., Seidel, T., Stürmer, K., & Säljö, R. (2022). Towards a cognitive theory of visual expertise: Methods of inquiry. In C. Damşa, A. Rajala, G. Ritella, & J. Brouwer (Eds.), *Re-theorizing learning and research methods in learning research*. Routledge. https://opus.bibliothek.uni-augsburg.de/opus4/95654

Gegenfurtner, A., Lehtinen, E., & Säljö, R. (2011). Expertise differences in the comprehension of visualizations: A meta-analysis of eye-tracking research in professional domains. *Educational Psychology Review*, *23*, 523–552. https://doi.org/10.1007/s10648-011-9174-7

Gilis, B., Helsen, W., Catteeuw, P., & Wagemans, J. (2008). Offside decisions by expert assistant referees in association football: Perception and recall of spatial positions in complex dynamic events. *Journal of Experimental Psychology: Applied*, *14*(1), 21–35. https://doi.org/10.1037/1076-898X.14.1.21

Gilman, E., & Underwood, G. (2003). Restricting the field of view to investigate the perceptual spans of pianists. *Visual Cognition*, *10*(2), 201–232. https://doi.org/10.1080/713756679

Gobet, F., Lane, P. C. R., Croker, S., Cheng, P. C.-H., Jones, G., Oliver, I., & Pine, J. M. (2001). Chunking mechanisms in human learning. *Trends in Cognitive Sciences*, *5*(6), 236–243. https://doi.org/10.1016/S1364-6613(00)01662-4

Gobet, F., & Simon, H. A. (1996). Templates in chess memory: A mechanism for recalling several boards. *Cognitive Psychology*, *31*(1), 1–40. https://doi.org/10.1006/cogp.1996.0011

Gobet, F., & Simon, H. A. (2000). Five seconds or sixty? Presentation time in expert memory. *Cognitive Science*, *24*(4), 651–682. https://doi.org/10.1016/S0364-0213(00)00031-8

Goolsby, T. W. (1994a). Eye movement in music reading: Effects of reading ability, notational complexity, and encounters. *Music Perception*, *12*(1), 77–96. https://doi.org/10.2307/40285756

Goolsby, T. W. (1994b). Profiles of processing: Eye movements during sightreading. *Music Perception*, *12*(1), 97–123. https://doi.org/10.2307/40285757

Granholm, E., Asarnow, R. F., Sarkin, A. J., & Dykes, K. L. (1996). Pupillary responses index cognitive resource limitations. *Psychophysiology*, *33*(4), 457–461. https://doi.org/10.1111/j.1469-8986.1996.tb01071.x

Hadley, L. V., Sturt, P., Eerola, T., & Pickering, M. J. (2018). Incremental comprehension of pitch relationships in written music: Evidence from eye movements. *Quarterly Journal of Experimental Psychology*, *71*(1), 211–219. https://doi.org/10.1080/17470218.2017.1307861

Halpern, A. R., & Bower, G. H. (1982). Musical expertise and melodic structure in memory for musical notation. *The American Journal of Psychology*, *95*(1), 31–50. https://doi.org/10.2307/1422658

Helsen, W. F., & Starkes, J. L. (1999). A multidimensional approach to skilled perception and performance in sport. *Applied Cognitive Psychology*, *13*(1), 1–27. https://doi.org/10.1002/(SICI)1099-0720(199902)13:1<1::AID-ACP540>3.0.CO;2-T

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*(3), 417–429. https://doi.org/10.1037/0278-7393.16.3.417

Huovinen, E., Ylitalo, A.-K., & Puurtinen, M. (2018). Early attraction in temporally controlled sight reading of music. *Journal of Eye Movement Research*, *11*(2). https://doi.org/10.16910/jemr.11.2.3

Hyönä, J. (1995). Do irregular letter combinations attract readers' attention? Evidence from fixation locations in words. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 68–81. https://doi.org/10.1037/0096-1523.21.1.68

Hyönä, J., & Bertram, R. (2004). Do frequency characteristics of nonfixated words influence the processing of fixated words during reading? *European Journal of Cognitive Psychology*, *16*(1–2), 104–127. https://doi.org/10.1080/09541440340000132

Imai-Matsumura, K., & Mutou, M. (2021). Gaze analysis of pianists' sight-reading: Comparison between expert pianists and students training to be pianists. *Music & Science*, *4*, 20592043211061106. https://doi.org/10.1177/20592043211061106

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, *40*(6), 431–439. https://doi.org/10.3758/BF03208203

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, *87*(4), 329–354. https://doi.org/10.1037/0033-295X.87.4.329

Kennedy, A., & Pynte, J. (2005). Parafoveal-on-foveal effects in normal reading. *Vision Research*, *45*(2), 153–168. https://doi.org/10.1016/j.visres.2004.07.037

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General*, *135*(1), 12–35. https://doi.org/10.1037/0096-3445.135.1.12

Krupinski, E. A. (1996). Visual scanning patterns of radiologists searching mammograms. *Academic Radiology*, *3*, 137–144. https://doi.org/10.1016/s1076-6332(05)80381-2

Kundel, H. L., Nodine, C. F., Conant, E. F., & Weinstein, S. P. (2007). Holistic component of image perception in mammogram interpretation: Gaze-tracking study. *Radiology*, *242*(2), 396–402. https://doi.org/10.1148/radiol.2422051997

Lim, Y., Park, J. M., Rhyu, S.-Y., Chung, C. K., Kim, Y., & Yi, S. W. (2019). Eye-hand span is not an indicator of but a strategy for proficient sight-reading in piano performance. *Scientific Reports*, *9*(1), 17906. https://doi.org/10.1038/s41598-019-54364-y

Madell, J., & Hébert, S. (2008). Eye movements and music reading: Where do we look next? *Music Perception*, *26*(2), 157–170. https://doi.org/10.1525/mp.2008.26.2.157

Mallett, S., Phillips, P., Fanshawe, T. R., Helbren, E., Boone, D., Gale, A., & Halligan, S. (2014). Tracking eye gaze during interpretation of endoluminal three-dimensional CT colonography: Visual perception of experienced and inexperienced readers. *Radiology*, *273*(3), 783–792. https://doi.org/10.1148/radiol.14132896

Manning, D., Ethell, S., Donovan, T., & Crawford, T. (2006). How do radiologists do it? The influence of experience and training on searching for chest nodules. *Radiography*, *12*(2), 134–142. https://doi.org/10.1016/j.radi.2005.02.003

Maturi, K. S., & Sheridan, H. (2020). Expertise effects on attention and eye-movement control during visual search: Evidence from the domain of music reading. *Attention, perception & psychophysics*, *82*(5), 2201–2208. https://doi.org/10.3758/s13414-020-01979-3

Meixner, J. M., Nixon, J. S., & Laubrock, J. (2022). The perceptual span is dynamically adjusted in response to foveal load by beginning readers. *Journal of Experimental Psychology: General*, *151*(6), 1219–1232. https://doi.org/10.1037/xge0001140

Neto, P. A. S. O., & de Oliveira, G. A. D. (2019). Differences between scale steps and absolute interval sizes: A new test for intervallic awareness. *Psychology of Music*, *49*(3), 413–425. https://doi.org/10.1177/0305735619869456

Penttinen, M., & Huovinen, E. (2011). The early development of sight-reading skills in adulthood: A study of eye movements. *Journal of Research in Music Education*, *59*(2), 196–220. https://doi.org/10.1177/0022429411405339

Penttinen, M., Huovinen, E., & Ylitalo, A. K. (2013). Silent music reading: Amateur musicians' visual processing and descriptive skill. *Musicae Scientiae*, *17*(2), 198–216. https://doi.org/10.1177/1029864912474288

Penttinen, M., Huovinen, E., & Ylitalo, A.-K. (2015). Reading ahead: Adult music students' eye movements in temporally controlled performances of a children's song. *International Journal of Music Education*, *33*(1), 36–50. https://doi.org/10.1177/0255761413515813

Perra, J., Latimier, A., Poulin-Charronnat, B., Baccino, T., & Drai-Zerbib, V. (2022). A meta-analysis on the effect of expertise on eye movements during music reading. *Journal of Eye Movement Research*, *15*(4). https://doi.org/10.16910/jemr.15.4.1

Perra, J., Poulin-Charronnat, B., Baccino, T., Bard, P., Pfister, P., Lalitte, P., Zerbib, M., & Drai-Zerbib, V. (2024). Markers of musical expertise in a sight-reading task: An eye-tracking study. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. Advance online publication. https://doi.org/10.1037/xlm0001358

Perra, J., Poulin-Charronnat, B., Baccino, T., & Drai-Zerbib, V. (2021). Review on eye-hand span in sight-reading of music. *Journal of Eye Movement Research*, *14*(4). https://doi.org/10.16910/jemr.14.4.4

Piras, A., Lobietti, R., & Squatrito, S. (2014). Response time, visual search strategy, and anticipatory skills in volleyball players. *Journal of Ophthalmology*, *2014*, 189268. https://doi.org/10.1155/2014/189268

Polanka, M. (1995). Research note: Factors affecting eye movements during the reading of short melodies. *Psychology of Music*, *23*(2), 177–183. https://doi.org/10.1177/0305735695232005

Prytz, E. G., Norén, C., & Jonson, C. O. (2018). Fixation differences in visual search of accident scenes by novices and expert emergency responders. *Human Factors*, *60*, 1219–1227. https://doi.org/10.1177/0018720818788142

Puurtinen, M. (2018). Eye on music reading: A methodological review of studies from 1994 to 2017. *Journal of Eye Movement Research*, *11*(2), 1–16. https://doi.org/10.16910/jemr.11.2.2

Qi, J., & Adachi, M. (2022). The influence of modality on input, visuo-motor coordination, and execution in the advanced pianist's sight-reading processes. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.933106

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. https://doi.org/10.1037/0033-2909.124.3.372

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, *14*(3), 191–201. https://doi.org/10.3758/BF03197692

Rayner, K., & Pollatsek, A. (1997). Eye movements, the eye-hand span, and the perceptual span during sight reading of music. *Current Directions in Psychological Science*, *6*(2), 49–53. https://doi.org/10.1111/1467-8721.ep11512647

Rayner, K., Slattery, T. J., Drieghe, D., & Liversedge, S. P. (2011). Eye movements and word skipping during reading: Effects of word length and predictability. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(2), 514–528. https://doi.org/10.1037/a0020990

Reingold, E. M., & Charness, N. (2005). Perception in chess: Evidence from eye movements. In G. Underwood (Ed.), *Cognitive processes in eye guidance* (pp. 325–354). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198566816.003.0014

Reingold, E. M., Charness, N., Pomplun, M., & Stampe, D. M. (2001). Visual span in expert chessplayers: Evidence from eye movements. *Psychological Science*, *12*(1), 48–55. https://doi.org/10.1111/1467-9280.00309

Reingold, E. M., & Sheridan, H. (2011). Eye movements and visual expertise in chess and medicine. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 523–550). Oxford University Press. https://doi.org/10.1093/OXFORDHB/9780199539789.013.0029

Roca, A., Ford, P. R., McRobert, A. P., & Williams, A. M. (2013). Perceptual-cognitive skills and their interaction as a function of task constraints in soccer. *Journal of Sport & Exercise Psychology*, *35*, 144–155. https://doi.org/10.1123/jsep.35.2.144

Rosemann, S., Altenmüller, E., & Fahle, M. (2016). The art of sight-reading: Influence of practice, playing tempo, complexity and cognitive skills on the eye–hand span in pianists. *Psychology of Music*, *44*(4), 658–673. https://doi.org/10.1177/0305735615585398

Ryu, D., Abernethy, B., Mann, D. L., & Poolton, J. M. (2015). The contributions of central and peripheral vision to expertise in basketball: How blur helps to provide a clearer picture. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(1), 167–185. https://doi.org/10.1037/a0038306

Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception & Psychophysics*, *74*(1), 5–35. https://doi.org/10.3758/s13414-011-0219-2

Schroyens, W., Vitu, F., Brysbaert, M., & d'Ydewalle, G. (1999). Eye movement control during reading: Foveal load and parafoveal processing. *The Quarterly Journal of Experimental Psychology: Section A*, *52*(4), 1021–1046. https://doi.org/10.1080/713755859

Sheridan, H., & Kleinsmith, A. L. (2022). Music reading expertise affects visual change detection: Evidence from a music-related flicker paradigm. *Quarterly Journal of*

Experimental Psychology, *75*(9), 1643–1652. https://doi.org/10.1177/17470218211056924
Sheridan, H., Maturi, K. S., & Kleinsmith, A. L. (2020). Eye movements during music reading: Toward a unified understanding of visual expertise. In K. D. Federmeier & E. R. Schotter (Eds.), *The psychology of learning and motivation: Gaze toward the future: Advances in eye movement theory and applications* (pp. 119–156). Elsevier Academic Press. https://doi.org/10.1016/bs.plm.2020.07.002
Sheridan, H., & Reingold, E. M. (2014). Expert vs. novice differences in the detection of relevant information during a chess game: Evidence from eye movements. *Frontiers in Psychology*, *5*, Article 941. https://doi.org/10.3389/fpsyg.2014.00941
Sibley, C., Foroughi, C. K., Brown, N. L., Phillips, H., Drollinger, S., Eagle, M., & Coyne, J. T. (2020). More than means: Characterizing individual differences in pupillary dilations. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *64*(1), 57–61. https://doi.org/10.1177/1071181320641017
Sloboda, J. (1974). The eye-hand span: An approach to the study of sight reading. *Psychology of Music*, *2*(2), 4–10. https://doi.org/10.1177/030573567422001
Sloboda, J. A. (1976). The effect of item position on the likelihood of identification by inference in prose reading and music reading. *Canadian Journal of Psychology/Revue Canadienne de Psychologie*, *30*(4), 228–237. https://doi.org/10.1037/h0082064
Sloboda, J. A. (1977). Phrase units as determinants of visual processing in music reading. *British Journal of Psychology*, *68*(1), 117–124. https://doi.org/10.1111/j.2044-8295.1977.tb01566.x
Spitz, J., Put, K., Wagemans, J., Williams, A. M., & Helsen, W. F. (2016). Visual search behaviors of association football referees during assessment of foul play situations. *Cognitive Research: Principles and Implications*, *1*, 12. https://doi.org/10.1186/s41235-016-0013-8
Stewart, L., Henson, R., Kampe, K., Walsh, V., Turner, R., & Frith, U. (2003). Brain changes after learning to read and play music. *NeuroImage*, *20*(1), 71–83. https://doi.org/10.1016/S1053-8119(03)00248-9
Szulewski, A., Roth, N., & Howes, D. (2015). The use of task-evoked pupillary response as an objective measure of cognitive load in novices and trained physicians. *Academic Medicine*, *90*(7), 981–987. https://doi.org/10.1097/acm.0000000000000677
Thalmann, M., Souza, A. S., & Oberauer, K. (2019). How does chunking help working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(1), 37–55. https://doi.org/10.1037/xlm0000578
Tien, T., Pucher, P. H., Sodergren, M. H., Sriskandarajah, K., Yang, G., & Darzi, A. (2015). Differences in gaze behaviour of expert and junior surgeons performing open inguinal hernia repair. *Surgical Endoscopy and Other Interventional Techniques*, *29*(2), 405–413. https://doi.org/10.1007/s00464-014-3683-7
Truitt, F. E., Clifton, C., Jr., A., & Rayner, K. (1997). The perceptual span and eye-hand span in sight reading music. *Visual Cognition*, *4*(2), 143–161. https://doi.org/10.1080/713756756
van Meeuwen, L. W., Jarodzka, H., Brand-Gruwel, S., Kirschner, P. A., de Bock, J., & van Merrienboer, J. J. G. (2014). Identification of effective visual problem solving strategies in a complex visual domain. *Learning and Instruction*, *32*, 10–21. https://doi.org/10.1016/j.learninstruc.2014.01.004
Vansteenkiste, P., Vaeyens, R., Zeuwts, L., Philippaerts, R., & Lenoir, M. (2014). Cue usage in volleyball: A time course comparison of elite, intermediate and novice female players. *Biology of Sport*, *31*, 295–302. https://doi.org/10.5604/20831862.1127288
Waters, A. J., Townsend, E., & Underwood, G. (1998). Expertise in musical sight reading: A study of pianists. *British Journal of Psychology*, *89*(1), 123–149. https://doi.org/10.1111/j.2044-8295.1998.tb02676.x
Waters, A. J., & Underwood, G. (1998). Eye movements in a simple music reading task: A study of expert and novice musicians. *Psychology of Music*, *26*(1), 46–60. https://doi.org/10.1177/0305735698261005
White, S. J., Rayner, K., & Liversedge, S. P. (2005). The influence of parafoveal word length and contextual constraint on fixation durations and word skipping in reading. *Psychonomic Bulletin & Review*, *12*(3), 466–471. https://doi.org/10.3758/BF03193789
Williamon, A., & Valentine, E. (2002). The role of retrieval structures in memorizing music. *Cognitive Psychology*, *44*(1), 1–32. https://doi.org/10.1006/cogp.2001.0759
Williams, A. M., & Davids, K. (1998). Visual search strategy, selective attention, and expertise in soccer. *Research Quarterly for Exercise and Sport*, *69*, 111–128. https://doi.org/10.1080/02701367.1998.10607677
Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1994). Visual search strategies in experienced and inexperienced soccer players. *Research Quarterly for Exercise and Sport*, *65*, 127–135. https://doi.org/10.1080/02701367.1994.10607607
Williams, A. M., Ward, P., Knowles, J. M., & Smeeton, N. J. (2002). Anticipation skill in a real-world task: Measurement, training, and transfer in tennis. *Journal of Experimental Psychology: Applied*, *8*(4), 259–270. https://doi.org/10.1037/1076-898X.8.4.259
Wolf, T. (1976). A cognitive model of musical sight-reading. *Journal of Psycholinguistic Research*, *5*(2), 143–171. https://doi.org/10.1007/bf01067255
Wood, G., Batt, J., Appelboam, A., Harris, A., & Wilson, M. R. (2014). Exploring the impact of expertise, clinical history, and visual search on electrocardiogram interpretation. *Medical Decision Making*, *34*(1), 75–83. https://doi.org/10.1177/0272989X13492016
Wood, G., Knapp, K. M., Rock, B., Cousens, C., Roobottom, C., & Wilson, M. R. (2013). Visual expertise in detecting and diagnosing skeletal fractures. *Skeletal Radiology*, *42*, 165–172. https://doi.org/10.1007/s00256-012-1503-5
Wurtz, P., Mueri, R. M., & Wiesendanger, M. (2009). Sight reading of violinists: Eye movements anticipate the musical flow. *Experimental Brain Research*, *194*(3), 445–450. https://doi.org/10.1007/s00221-009-1719-3
Zhukov, K., Khuu, S., & McPherson, G. E. (2019). Eye-movement efficiency and sight-reading expertise in woodwind players. *Journal of Eye Movement Research*, *12*(2). https://doi.org/10.16910/jemr.12.2.6