XRMusic4VIP: Enabling Simultaneous Sheet Music Reading and Playing for Visually Impaired Musicians through Extended Reality

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Abstract

The use of assistive technologies for visually impaired musicians has been well documented, but the ability to visually read music and play simultaneously is still largely unexplored. Extended Reality (XR) could offer promising technology to support visually impaired people in this area. We address this research gap by examining the effectiveness of XR as a tool to read and play music at the same time, specifically for keyboard instruments. To achieve this, we chose a dual-phase human-centered approach that involved user participation. First, we conducted need-finding interviews with ten visually impaired participants to gather information about persisting challenges and their ideas on how to improve sheet music reading. Based on the results of these interviews, we then developed the XRMusic4VIP prototype. In the second phase, we conducted a user study with the same participants to evaluate the effectiveness of the prototype. Our findings indicate that the XRMusic4VIP prototype successfully enables the simultaneous reading of music and the playing of a keyboard instrument. Participants reported regaining their joy in making music and some of those who stopped playing because of their visual impairment can even imagine starting again.

CCS Concepts

• **Human-centered computing** → **Accessibility**; **Interactive systems and tools**; **User studies**.

Keywords

Visually impaired musicians, XR, keyboard instrument, assistive technology, user studies

ACM Reference Format:
Julia Anken, Delia Blaess, and Karin Müller. 2025. XRMusic4VIP: Enabling Simultaneous Sheet Music Reading and Playing for Visually Impaired Musicians through Extended Reality. In *The 27th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '25), October 26–29, 2025, Denver, CO, USA.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3663547.3746339

ACM ISBN 979-8-4007-0676-9/25/10
https://doi.org/10.1145/3663547.3746339

1 Introduction

Music plays a crucial role in culture, education and professional domains, encompassing both the experience of musical performances and the process of making music [16]. Many people derive joy from playing music, for leisure or as a profession [21]. Among the most popular instruments worldwide are keyboard instruments such as the piano and electronic keyboard [47]. The foundation for playing any musical instrument, including keyboards, lies in the ability to read music. Music reading is defined as "the act of decoding the symbols of staff notation using a musical instrument" [26]. This definition highlights two components: reading the music and simultaneously playing it. But reading music, which is the basis for playing instruments, becomes increasingly difficult as eyesight deteriorates. Usually visually impaired people[1]use assistive technologies, such as magnification, in their daily activities to facilitate text reading. However, reading text is distinct from reading music as each requires different visual skills. The visual representation of text differs from that of sheet music [46]. Musical notation more closely resembles a graphical depiction, utilizing both horizontal and vertical information, thus demanding a detailed vision to recognize individual notes and a global vision to understand the overall composition [31]. Furthermore, for keyboard instruments, two staves — one for the left hand and another for the right hand — are placed above each other and must be read simultaneously to perform the notes together.

The increasing popularity of emerging technologies introduces new opportunities to improve accessibility. Extended Reality (XR) is one such innovation that provides multimodal user interactions, including hands-free options that can be used to access and navigate sheet music [45]. Although XR has been explored as an assistive technology in various domains, its potential for visually impaired musicians is still largely unexplored. Hence, our aim is to fill this research gap by examining XR's efficacy as an assistive tool for concurrent music reading and playing, with a focus on keyboard instruments.

We begin by identifying the prevailing challenges faced by visually impaired individuals when sight-reading sheet music and playing keyboard instruments despite the widespread adoption of

[1]We aim at writing respectfully about people with disability. As language use differs in various countries and between individuals, we decided to use identify-first language as Sharif et al. reported this as a slight preference of visually impaired people [59]. However, we are aware of personal and cultural preferences for person-first language.

assistive technology. Subsequently, our approach addresses two primary research questions:

- RQ1: What are the necessary design concepts and technical requirements to address the challenges with sight-reading of sheet music for visually impaired musicians?
- RQ2: To what extent can XR technologies mitigate these challenges and serve as an aid to visually impaired musicians to read and play music simultaneously?

To address these questions, we employed a user-centered methodology: we started with investigating participants' needs and ideas, developed based on their suggestions a suitable tool, and subsequently evaluated its effectiveness. In our approach, we worked with a uniform group of participants throughout the studies. Hence, our research contributes in the following ways: it emphasizes key issues of sight-reading of sheet music for visually impaired musicians and establishes essential requirements for systems that support this, and it demonstrates that XR technology is a suitable solution to overcome identified challenges and facilitate simultaneous reading and playing of music.

2 Related Work

In the field of music, several terms are frequently used to describe the process and specific aspects of interpreting written music. Music reading is often used as a general term for deciphering musical notes. More specifically, sheet music reading refers to the action of interpreting notated music on sheets. In classical music or when reading polyphonic scores, score reading is commonly referenced [36, 38].

2.1 Musical Notations

Classical music notation employs standardized stave dimensions with black notes against a white background [31]. This fixed format poses difficulties for visually impaired musicians [45], because it lacks customization options to the respective user needs. Furthermore, the notation is built solely on graphical details to denote meaning, for example, the vertical position of a note on the stave indicating pitch [31].

Consequently, there is large-print notation, requiring a conversion process to generate these distinct measures [31]. However, this resource is scarce, with only select libraries, such as the Library of Congress [28], offering a repertoire of large-print materials. In Germany, musicians can access the braille music notation of a library that also performs commissions for large-print productions [18]. Given the limited availability of large-print music, digital sheet music is gaining popularity, with both paid and free alternatives, such as MusicReader [8], forScore [19], or Dorico [62]. These tools facilitate the viewing of sheet music digitally and some are designed specifically for visually impaired musicians, such as Lime Lighter [17], which offers extensive customization features. Open-source software such as MuseScore [41] also incorporates limited accessibility options, providing sheet music in varied styles, and supporting braille output. These applications either lack options for size and color customization altogether or depend on magnification for enlarging the sheet music. Although magnification supports reading details, getting an overview requires zooming out, which requires additional hardware such as foot pedals in the case of Lime Lighter [17] or manual adjustments, thus hindering hands-free practice.

Moreover, audio representations present an alternative that bypasses the need to read the sheet music visually. Visually impaired musicians may benefit from learning by ear through online audio resources or teacher-provided recordings. Yet, memorization of the musical composition is essential before performance [11]. Compared to visual music reading, auditory learning accelerates the acquisition of a new piece. However, the proficiency in playing by ear requires substantial preparatory training [1]. Therefore, a solution that enables visual reading during play would be more promising.

Braille music notation serves as another format for musical representation. Similarly to literary braille, this system employs a 6-dot configuration to denote both the pitch and the rhythmic duration of the notes [60]. However, learning strategies differ significantly. Braille music notes cannot be interpreted concurrently with playing. There must be pauses to take the hands away from an instrument and read braille notes, leading to the argument that braille alone is often insufficient for the acquisition of new musical pieces [55]. Moreover, many visually impaired people do not know literary braille at all, which is a prerequisite and thus cannot utilize this solution.

In summary, current musical notation systems do not support seamless concurrent navigation of sheet music during practice sessions. However, digital sheet music appears to offer potential solutions given its wide availability and customization options.

2.2 Assistive Technologies and Tools

Some visually impaired and blind musicians focus on braille music as described by Baker [3]. There are various aspects that need to be addressed to make music accessible to visually impaired people: individual playing, playing in a group, and using digital or multimodal tools. For example, Ahmed et al. [2] suggests a tool for the creation of music for blind people, which automatically generates both braille and audio outputs. Baker and Green [5] recognize technology as a means of leveling the playing field between musicians with and without visual impairment. The research by Frid [20] explores the field of digital music instruments, emphasizing the need for accessible instruments by providing an overview of the literature in this area, which highlights the importance of tangible and haptic controllers. Lu and others [42, 43] designed and tested applications that use haptic and audio feedback to practice music in groups or with a teacher. Turchet et al. [64] identifies the requirements for tools that aid ensembles and groups, focusing on synchronization between choir members and instruments. Although a wearable solution with tactile feedback was highly rated, it primarily focused on playing together rather than reading music and playing simultaneously. Recognizing this need, Lu et al. [44] considers tools for simultaneous reading and playing of music, albeit limiting them to audio and haptic feedback. The potential of other technologies, such as XR, is still underexplored in this context.

Dang et al. [14, 15] leverages Virtual Reality (VR) to enhance access to musical performances through omnidirectional audio descriptions, focusing primarily on audio and performances rather than reading music. Payne and Hurst [56] points to the vast repository of visual music notation and suggests a transformation tool utilizing MusicXML for more accessible music, converting visual music to non-visual formats such as audio and braille or providing customizable formats such as large-print with adaptations. Furthermore, Housley et al. [31] offers a tablet solution that allows customization options for visual sheet music for visually impaired musicians. Lussier-Dalpé et al. [45] proposes a head-mounted display (HMD) solution to magnify sheet music, facilitating simultaneous reading and interpretation. Although initial studies indicate that this is feasible, challenges remain concerning the control of head movements while magnifying the entire field of view.

2.3 XR as an Assistive Technology for People with Visual Impairments

As noted by Mott et al. [52], accessibility is often considered an afterthought, and the status of XR technology has not yet reached full commercialization. To improve the quality of XR experiences, it is crucial to integrate accessibility from the beginning using established standards and guidelines. This integration not only ensures better experiences, but also promotes a diverse range of applications. Moreover, XR holds the potential to improve various tasks, both digital and non-digital, by enhancing accessibility features. Creed et al. [12], highlights numerous accessibility barriers within XR, offering collected recommendations for improvement. Specific considerations for visually impaired people include providing accessible menus, avoiding sensory or information overload, and offering customization options.

Furthermore, Kasowski et al. [34] discusses the potential of XR to improve visual accessibility and emphasizes the importance of real-world validation and participatory design involving end-users. These steps are essential in ensuring that XR technologies are truly inclusive and effective for all users. In the study conducted by Naikar et al. [53], the accessibility of free VR applications for Meta Quest 2 was inspected. 36.8% of the apps were found to not include any accessibility features at all. Furthermore, only 10% of the applications offered a magnification feature and none provided options to adjust colors, which could aid users with color blindness or other visual impairments.

Various applications address different tasks. In a literature review by Hamash et al. [27], it was observed that XR can potentially improve the inclusion of visually impaired people in educational settings and offer enriching experiences in various fields. Although music is among those fields mentioned, the review only examined educational games and none related to music reading. Outside of the educational domain, Hoppe et al. [30] explored the role of VR in the context of work and learning, presenting an interaction concept and tools designed to support visually impaired people. The evaluation of the proposed system demonstrates that VR can effectively address the needs of users with visual impairments.

Previous studies have applied XR technologies, notably Augmented Reality (AR), to enhance the visual abilities of individuals with visual impairments [24] and those with color vision deficiencies [48]. A case study by Powell et al. [58], involving a visually impaired participant, was carried out using a commercially available head-mounted display. The HMD featured increased display brightness, which facilitated better recognition of objects, faces, and colors.

In recent years, several tools and frameworks have been developed to support vision rehabilitation and enhance the accessibility of VR experiences for visually impaired people. FlexiSee is an AR tool that aims to assist in vision rehabilitation and also provides a Web tool for customization [54]. MagniVR facilitates magnification through a user interface that allows customization of camera and display positions [35]. SeeingVR offers multiple tools designed to enhance VR experiences for visually impaired people, providing developers with easy-to-use features. This set of tools not only enables users to enjoy VR content more thoroughly, but also to perform tasks with greater speed and precision [70].

Furthermore, Valakou et al. [65] proposed a framework that empowers developers to create inclusive XR applications. It offers guidelines that specifically focus on visually impaired people and provides various tools for developers to follow. Furthermore, there are multiple guidelines for XR Accessibility:

- XR Accessibility User Requirements (XAUR) [66] provides accessibility guidelines for XR applications
- Meta Platforms, Inc. presents a set of guidelines [49]
- Meta Platforms, Inc. provides Virtual Reality Check (VRC) Accessibility [51]
- A collection of VR game guidelines by Heilemann et al. [29] summarizes best practices for creating accessible VR games.

The above approaches show that XR is used in various areas as an assistive technology to improve accessibility, which could also be promising for visually impaired musicians when reading sheet music.

2.4 XR in Keyboard Instrument Learning

XR technology offers promising applications for learning keyboard instruments, as seen in commercial applications such as Soundela [61], PianoVision [33], and Pianogram [57]. These applications employ AR to integrate the user's real keyboard with virtual sheet music overlays. However, they do not prioritize learning the notation of music or enhance readability. Instead, they used colored beams and symbols for a more engaging learning experience. Furthermore, the absence of customization options for adjusting sheet music display makes these apps less accessible to visually impaired musicians. These applications demonstrate that the usage of XR for keyboard practice is viable. However, integrating accessibility features is essential for visually impaired musicians.

3 Phase I: Need-finding Interviews

We conducted need-finding interviews to investigate the challenges for visually impaired musicians in sight-reading sheet music despite the available assistive technologies. In addition, we detail on which functionality an XR assistive tool should include to address these challenges (RQ1) and to support the development of future systems for more effective support of visually impaired musicians.

3.1 Participants

We recruited ten participants, four women and six men, between the age of 18 and 69 years using email lists and postings within relevant institutions. Four participants had visual impairments, while six were severely visually impaired[2], each with different onset conditions. We present more detailed information on the participants in Table 1. Participants in the study were required to have visual impairment and work visually. In addition, participants should have a background in regularly playing or having played a keyboard instrument. All participants received a compensation of 30 €. Ethical considerations were prioritized throughout the study; a data protection statement was provided and informed consent was obtained from all participants before participation.

3.2 Procedure

The study consisted of two parts: (i) an online questionnaire and (ii) a semi-structured online interview, which lasted approximately 90 minutes. We sent the online questionnaire to the participants prior to the interview. The interviews were conducted online, allowing participants to use their own technology setups.

Online questionnaire. We conducted the online questionnaire using SoSciSurvey [22] prior to the interview. It focused on collecting demographic information, including age, gender, and details related to visual impairment and its changes over time. It also explored the use of assistive technologies by participants to read content, their ability to play keyboard instruments, and prior experience with XR.

Semi-structured Interview. The interviews consisted of open-ended questions and an assessment of the importance of some aspects on a Likert scale of 1 to 5 to learn about the desired functionality of a future XR system. Although the Likert scale items support comparability among participants, each rating was followed by open-ended questions that allowed and encouraged participants to elaborate on their responses. These questions were categorized into inquiries about current practices in the play of the keyboard instrument, possible challenges, and desired system functionality. In particular, we asked the following main questions:

- Could you talk about your current practice routine? How do you learn a new piece? How do you practice pieces you already know?
- What functions and features should technology have to really help you?
- Can you imagine how VR or AR technology could help you read sheet music? What functions or support options would you like to have?

See the complete list of questions in the study guide in Appendix A. We conducted and recorded the interviews on BigBlueButton [32].

3.3 Data Collection and Analysis

Data were gathered during the above described questionnaire and semi-structured online interviews. The interviews were recorded in audio.

The audio recordings of the interviews were transcribed using the Whisper tool for automatic transcription. Later, we manually corrected the transcripts to ensure an accurate basis for content analysis. For this a qualitative deductive content analysis was performed according to Kuckartz [37] using the MAXQDA software [23]. This method was chosen because of it's suitability also for smaller sample sizes and the advised close text work. After a first familiarization with the data through close reading of all transcribed interviews, one of the researchers deductively developed a first category structure based on the structure and questions of the interview. In a second step, the same researcher assigned all relevant text passages to these categories. Finally, all identified text passages of the categories were summarized and are reported in the results.

3.4 Results

This section outlines the main themes identified from the need-finding interviews on existing playing practices, associated challenges, and the desired system functionalities mentioned by the participants.

3.4.1 Current Playing Practices. Five participants regularly play a keyboard instrument, while another five have stopped doing so, primarily due to visual impairment. Among those who stopped playing, three have transitioned to other instruments, one has joined a choir, and one has completely stopped their musical activities. In Table 2, we present more details on the playing practice and experience of the participants.

Some participants opted to lower the difficulty of the pieces they played. However, this change made their experience less successful and technically demanding. Others switched to monophonic instruments before transitioning to singing. P03 mentioned that spontaneous playing is not possible due to the need for optimal lighting and environmental conditions, which restricts flexibility when changing locations. Table 3 presents the tools and methods used by the participants along with the challenges they face.

Memorization as Part of the Learning Process. In summary, the study participants described their approach to practice as partial learning, focusing on small sections at a time. This involved reading, playing, and memorizing music in bits rather than reading through continuous passages while playing.

Access to Printed Sheet Music. P02 noted the simplicity of older printed music sheets, which are often easier to read due to their closer print style than the newer versions. P02 also described a specially developed frame that helps maintain a consistent reading distance of 2 cm, while other participants (P05, P06) use telescopic magnifying glasses combined with a tablet. This necessity for close viewing distances can lead to health problems due to poor posture (P08) and may result in a lack of motivation to learn new pieces or play music regularly (P02, P06, P10).

P07 added to the usage of such magnifying tools that *"the overall view of the sheet music is lost."* Furthermore, participants mentioned that their learning process differs greatly from that of people without visual impairments, making simultaneous reading and playing unfeasible even at advanced levels (P02, P08).

Access to Digital Sheet Music. Many participants rely on digital aids, such as PDF viewers, that allow magnification, inverted presentation, and color adjustments. P04 specifically mentioned an app called Mobile Sheets [71] that is used to display scanned lyrics

[2] The categories for the degrees of visual impairments (VI) are applied according to German law defining VI as visual acuity less than or equal to 30%, severe VI less than or equal to 5% and blindness less than or equal to 2%

Table 1: Demographic data on study participants (P01-P10)

Code	Age	Gender	Visual Acuity	Onset of VI	Visual Field affected	Color Vision affected	Glare sensitivity
P01	40-49	m	10% on both eyes	Birth	yes, entire	no	yes, severe degree
P02	60-69	m	2% on left eye	Birth	yes, central	no	no
P03	18-29	f	8-12% on both eyes	age 6-20	yes, central	yes	yes, severe degree
P04	30-39	f	2% on both eyes	age 6-20	yes, peripheral	yes	yes, mild degree
P05	40-49	m	15% on left eye, 0% on right eye	Birth	yes, entire	no	yes, mild degree
P06	30-39	m	30% on left eye, 20% on right eye	Birth	yes, entire	no	yes, severe degree
P07	18-29	m	10% on both eyes	Birth	no	yes	yes, severe degree
P08	40-49	f	2-5% on both eyes	Birth	yes, peripheral	yes	yes, severe degree
P09	50-59	f	unaffected	age 21-60	yes, peripheral	no	no
P10	50-59	m	25% on both eyes	age 21-60	yes, right eye	yes	yes, mild degree

Table 2: Data on the playing practice of the participants; the knowledge in instrument playing was rated self reported on the scale 1 = None, 2 = Little, 3 = Some, 4 = Comprehensive

Code	Instrument	Knowledge Instrument Playing	Currently Playing	VI	Change of VI	Change of Playing Practice
P01	Keyboard	Comprehensive	no	Severe VI	yes	yes, slightly
P02	Organ	Comprehensive	yes	Severe VI	no	-
P03	Piano	Little	yes	Severe VI	no	-
P04	Piano	Some	no	Severe VI	yes	yes, significantly
P05	Piano, Organ	Comprehensive	yes	Severe VI	no	-
P06	Piano	Comprehensive	yes	VI	no	-
P07	Piano	Comprehensive	yes	VI	no	-
P08	Piano	Some	no	Severe VI	yes	yes, slightly
P09	Piano	Some	no	VI	yes	yes, significantly
P10	Organ	Some	no	VI	yes	unsure

from a songbook, allowing users to add digital notes directly to the music.

Some participants found it helpful to enlarge the notes on their iPad using the magnification feature. However, especially zooming in or moving through the music can be challenging. They observed that constant back-and-forth movement while navigating the screen could be frustrating (P10) and therefore disrupt fluid reading (P06). P08 reported difficulty maintaining focus at their playing speed, often resulting in recognizable notes only for one hand. P07 expressed frustration with the relationship between zooming and visible area. *"It always comes down to memorizing and learning step by step, which is very time consuming and tedious. It is not fun, and it is very difficult,"* P07 noted.

3.4.2 *Desired System Functionality.* As apparent from current playing practice and the challenges mentioned by the participants, the process of reading the sheet music was described as essential to them. Therefore, there is a clear priority to improve the readability of the notes.

Customizable Sheet Music Display and Environment. The customization options requested included the option to adjust the colors and contrast of the score music display. However, customizations also affect the environment. For example, the participants wanted to adjust the brightness and contrast of the environment around them as well. The participants rated the importance of a customizable sheet music display including size and color adjustments as the most important feature, with an average rating of 4.5 (out of 5, SD = 0.71). Additionally, P04 highlighted a particular emphasis on certain note types, which would be helpful as they are usually displayed smaller and are more challenging to grasp.

Highlighting Currently Played Section. In order to support orientation in the displayed sheet music, we asked participants to rate the importance of specifically highlighting the currently played part through, for example, markers. The participants rated this with an average rating of 4.0 (out of 5, SD = 1.33). During the interview, P01 imagined a system to minimize the visual search required for the current section of the sheet music. Therefore, the sheet music should be displayed as an endless loop that shows the staves currently played in the center of the view. This display would then be controllable via hand or finger gestures, for example, providing functionality for rewinding or pausing. Complementing this idea, P09 added that sections should fade in when they become relevant

Table 3: Tools used by the participants for reading sheet music and the existing challenges using them

Tools & Strategies Used	Challenges encountered
Tablet and digital PDF viewer	Limited excerpt of the score; frequent manual scrolling hinders fluent playing; slow learning process.
Self-built devices	Poor posture; high costs due to individual customization; not very flexible.
Telescope magnifier glasses	Poor posture; loss of focus when looking away; outdated technology.
Adaptation of the room environment	Limited flexibility when changing locations; technical requirements must be met.

and fade out later on. Another idea described by P09 was to display two bars before and after the currently played section. In addition, by turning the head to both sides, the rest of the sheet music could be captured (P08).

Seeing Own Hands in XR. In general, the participants rated the importance of seeing the hands on the keyboard instrument as less important, with an average rating of 2.9 (out of 5, SD = 1.60). The given reasons mainly focused on the fact that players should not look at their hands. One participant compared it to 10-finger writing, where one also does not look at the hands. Looking down to the hands was mentioned only for practice, especially for jumps in the piece.

Additional Audio Feedback. The participants rated additional acoustic feedback with an average rating of 2.1 (out of 5, SD = 1.20) as the majority of the participants were concerned that this would be rather annoying or confusing while playing.

3.4.3 Summary of Findings. The need-finding interviews indicated the importance of sight-reading sheet music. When this was not possible, the participants stopped playing keyboard instruments or instruments in general. Although participants devised various strategies and tools to assist in reading sheet music, none allowed simultaneous reading of music and keyboard playing. This underscores the necessity for a system that emphasizes note visibility and hands-free operation.

4 The XRMusic4VIP Prototype

In this section, we describe the design of the XRMusic4VIP prototype, which is based on the results of the need-finding interviews. For the prototype, we chose a keyboard as an instrument because it is a middle ground, as it shares characteristics with pianos and organs but avoids complexities such as weighted keys or foot pedals. The design of the prototype involves the user sitting in front of a real keyboard while wearing the Meta Quest 3 headset and seeing a virtual representation of sheet music that is adaptable in color, position, and scale to enhance readability. This dynamic display supports the continuous movement of the notes, allowing hands-free interaction during practice sessions. The prototype allows hand gesture interactions with sheet music, as well as playing music in two different contexts: (i) getting to know a musical piece in VR as an overview and (ii) playing music on a real keyboard while reading virtual sheet music.

4.1 Implementation

For the prototypical implementation, we focused on standard hardware as these are more affordable than assistive technology, which facilitates accessibility even further. We chose the Meta Quest 3 headset to reflect the current state of technology. The development was carried out using Unity 2022 LTS [63] and built on the MetaXR SDK [50] to create an XR application that runs solely on the headset.

In general, the design referred to XR Accessibility User Requirements (XAUR) [66] and Web Content Accessibility Guidelines (WCAG) [67] to ensure accessibility. For example, to select colors, interactive elements were designed with a black background and white letters for maximum contrast while reading. When the element is activated or hovered, it changes to a blue color that conforms to the WCAG 2.1 AAA standards [67].

The following sections describe how a user can interact with the prototype, as well as the two different XR scenes: the preview scene to get an overview of a musical piece entirely in VR, and the main practice scene in AR, which shows the virtual music sheet and the real keyboard.

4.2 Interaction with the Prototype

The prototype allows for intuitive interaction without requiring additional hardware by using hand tracking to keep the users' hands free for uninterrupted play. The user can utilize direct touch buttons similar to the operation of a tablet or employ pinch gestures at a distance to interact with the settings menu. The distance grab is consistent with the standard pinch gesture of the Meta SDK, which facilitates the learning process. Additional hand gestures allow for the initiation or stop of notes' movements and make interactions faster, eliminating the need for a visual search for buttons. For example, executing a stop pose with one hand will pause the movement of the sheet music display, while a thumbs-up gesture initiates the movement. Both gestures are available at any time within the main practice scene. An overview of all gestures utilized in the prototype is presented in Table 4.

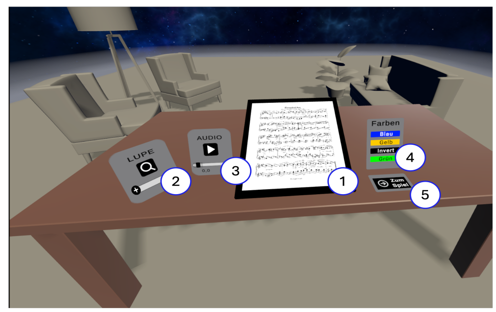
4.3 Preview Scene

The preview scene is designed to provide an overview of the whole musical piece. In addition, the **audio playback function** lets users listen to the musical piece. This audio feedback is restricted to the preview scene due to interview findings, indicating that extra audio might distract during play. The scene is designed in VR. Therefore, the real environment is invisible, enabling the user to focus solely on sheet music reading. The virtual scene has a dark background to reduce brightness and visual details. A virtual table is shown at the

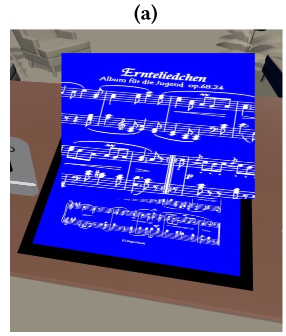
Table 4: Overview of the hand gestures and their usage in the XRMusic4VIP prototype

Hand Gesture	Description	Usage in the Prototype
Direct Touch	Touch with the index finger on virtual interaction elements	Click button
Pinch	Bringing tips of thumb and index finger together	Click button on distance
Grab	Closing fingers toward the palm, as if grasping an object	Grab virtual objects
Thumbs-up	Extending thumb upward while keeping the other fingers curled into the palm	Start movement of sheet music display
Stop	Raising hand with the palm facing outward and fingers extended	Stop movement of the sheet music display

same height as the real keyboard instrument in front of the user to avoid any unintended collision with the real instrument. The sheet music display and the interaction elements are designed in high-contrast colors for better readability. On top of the virtual table, an **enlarged sheet music display** is shown, simulating the appearance of a tablet. Similarly to interacting with real objects with the hand, the virtual sheet music display can be grabbed, moved, and positioned freely with a hand gesture. Additional interaction elements for magnification, audio playback, and **color adjustment** of the sheet music are placed on the left and right sides of the sheet music display, which can also be interacted with hand gestures. These modification options align with the desired customizable sheet music display and environment features identified in the interview. In the preview scene, a **magnification feature** provides an overlay that moves in sync with the user's head movements, offering an enlarged view. This magnification that leaves the periphery unmagnified for spatial orientation was inspired by [71]. The user can manually adjust the level of magnification in the respective settings panel. Figure 1 shows the preview scene with the mentioned elements. A virtual button on top of the table takes the user directly to the main practice scene to start playing.



(a)



(b)

Figure 1: Preview Scene of the XRMusic4VIP prototype: (a) Overview of the preview scene with numbered functionality; 1 = sheet music display, 2 = magnification settings, 3 = audio playback, 4 = color adjustment settings, 5 = switch to main practice scene (top image); (b) Magnified view of the sheet music display with adapted colors (bottom image)

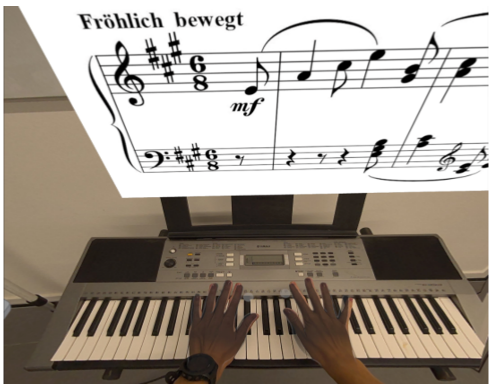
4.4 Main Practice Scene

The main practice scene contains the core functionality of the prototype and focuses on playing the musical piece. Various settings support this function to facilitate note reading and the practice process. In order to see the real keyboard instrument in front of the user, the scene is designed in video-passthrough AR. The real-world setting with the keyboard is enhanced with virtual elements for the sheet music display and settings. The sheet music is displayed as staves next to each other like a horizontal band at head level (Fig. 2a) which aligns with the imagined system design provided by P01 in the interviews. When starting to play, this band moves continuously from right to left, keeping the next bar in focus right in front of the user. The speed of this movement can be manually controlled so that the user can slow it down for practice.

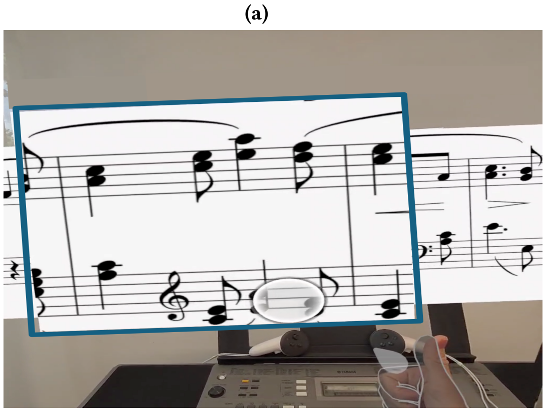
In addition, three control panels are located on the right, left, and front of the instrument. The right control panel contains the **environmental settings** mentioned above. Since the real environment is captured through a video-passthrough and displayed in a VR headset, it could also be adapted. Therefore, the advantages of XR can be utilized to adjust the brightness, contrast, and saturation of the captured real environment around the user fulfilling the desired functionality of the conducted interview to also customize the environment. The **music control panel** is shown on the left side of the instrument. This panel contains the option to activate a metronome. Additionally, the representation of the sheet music can be adapted in size and color in this panel.

The preset settings are located in the middle, right in front of the instrument. These settings guide the user through the initial setup.

The first step is to choose whether to **invert the colors** of the sheet music display. Changes in this setup are immediately applied to test them and directly see the changes in action. After clicking on the next button, the **position of the sheet music** can be adapted by providing arrow keys to move it. In the last step, **magnification** can be set. Magnification is implemented analogously with a magnification lens. Therefore, an additional layer is displayed in front of the sheet music, where a part of the stave is enlarged, which can also be seen in Figure 2. Additionally, this layer is fixated in the 3D space and does not move with the user's head movement, allowing a seamless reorientation after, for example, looking down to the hands. This allows the user to choose their preferred way of enlarging the sheet music either by positioning the sheet music closer to them or by using a magnification lens.



(a)



(b)

Figure 2: Main Practice Scene of the XRMusic4VIP prototype: (a) Overview of the practice scene showing the virtual sheet music display above the real keyboard (top image); (b) Thumbs-up gesture in the main practice scene including a magnified overlay over the sheet music display (bottom image)

5 Phase II: User Study

This study aims to evaluate whether the XRMusic4VIP prototype enables simultaneous reading and playing of score music for visually impaired musicians and, therefore, to validate the usage of XR technology as an assistive technology to improve sight reading of sheet music, and to collect further ideas for improvements.

5.1 Participants

As described above, we used a two-phase process and, therefore, recruited the same participants as in the need-finding interviews via email. All participants, except two (P06, P07), participated. See Table 1 above for demographic information. The study was carried out in our local laboratory.

5.2 Procedure

The evaluation consisted of four parts: (i) an introductory session, (ii) a walk-through with a member of our team and testing combined with a think-aloud session, (iii) a quantitative evaluation, including System Usability Score (SUS), and questions about usability and satisfaction, and (iv) a semi-structured interview.

Introductory Session. The session began with an oral introduction to the prototype, where we went through the different settings and scenes with the participants until they understood the different settings and functions. In addition, we introduced the distinct hand gestures to control the prototype and encouraged participants to practice them. Taking into account the previous experience and practice of the participants, we selected a moderately easy music piece. Based on difficulty ratings from IMSLP users [39], we chose *Ernteliedchen* from Robert Schumann's *Album für die Jugend* [40].

Walk-through. The testing session started with a step-by-step guided walk-through of the prototype that lasted approximately 30 minutes. The participants had the opportunity to get to know the different functions and configure their practice setup.

Testing. This was followed by an approximately 30 minute exploration session in which participants could interact freely while playing the musical piece. Throughout the walk-through and test session, participants were encouraged to verbalize their thoughts, emotions, and experiences as part of the think-aloud session.

Quantitative Evaluation. Once they finished this session, the participants removed the headset and participated in the quantitative evaluation by answering a SUS questionnaire [7]. This was followed by additional statements about usability and satisfaction with the prototype, which were rated on a Likert scale from 1 (completely disagree) to 5 (completely agree).

(1) The customizability of the sheet music display has improved the legibility of the notes.
(2) The magnification function has improved the legibility of the notes.
(3) The continuous movement of the notes made it easier to play.
(4) The polyphony of the notes was well captured.
(5) How satisfied are you overall with the prototype on a scale from 1 (very dissatisfied) to 5 (very satisfied)?

Semi-structured Interview with Open-ended Questions. The participants gave feedback on their general impressions of the XRMusic4VIP prototype answering the following questions in an interview.

(1) Were there certain functions that you particularly liked? If so, why?
(2) Were there certain moments or functions that you found rather difficult? If so, why?
(3) Did you miss a function that you would have liked to have in the prototype? If so, what function are you missing?
(4) Do you have general suggestions for improvement?

5.3 Data Collection and Analysis

We recorded all the interactions of the participants on an audio tape and subsequently transcribed them. Transcriptions were manually reviewed to ensure their accuracy. Then, we performed a qualitative content analysis following Kuckartz's approach of evaluative content analysis [37] using the MAXQDA software. After the first step of familiarization by reading all the transcribed interviews, one of the researchers generated aligned categories to allow the evaluation of the materials based on selected dimensions. The initial coding was performed deductively based on the structure of the interview and the specific guiding questions. In a later step, the same researcher carried out an inductive analysis approach in which the codes emerged directly from the data itself. Each code was analyzed to identify observations and patterns, focusing on how the prototype affected the experience of reading sheet music by visually impaired musicians. This approach enabled the extraction of detailed insights into user experiences, including specific challenges, important features, and overall impressions of the prototype within the target group.

5.4 Results

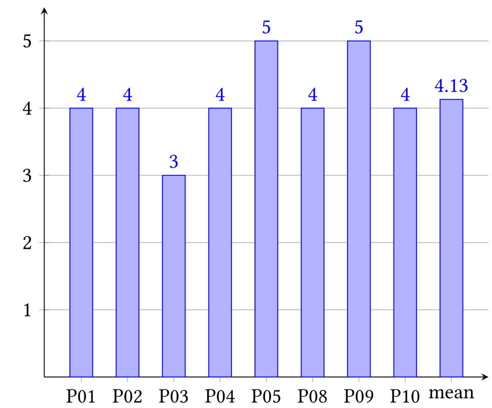
In this section, we first report the quantitative results of the user study by discussing the overall impression ratings of the prototype and then describe the qualitative results by the main themes identified through content analysis.

5.4.1 Quantitative Results. As quantitative measures, we calculated the SUS values as well as the ratings for the specific functionalities of the prototype and overall satisfaction.

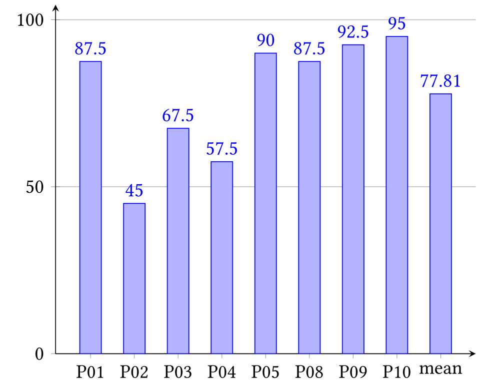
System Usability Score. The SUS evaluation resulted in an average score of 77.81, indicating good overall usability as described by Bangor[6]. Figure 3 shows the detailed values. Only participants P02 and P04, who were using an XR headset for the first time, exhibited lower SUS values. Their lack of experience with XR environments initially led to uncertainty in interaction, and therefore both expressed that at this stage they could not yet envision integrating the application into daily practice and consequently adapting their learning strategies.

Figure 4 shows a box plot for further insight into the specific items of the SUS questionnaire. High levels of agreement with Items 3, 5 and 7 suggest that participants found the system well-integrated and easy to use and learn. Additionally, string agreement with item 1 (frequent use) and low agreement with negatively worded items (e.g., 2, 4, 6, 8, 10) indicate that the system was perceived as intuitive and non-cumbersome.

Usability and Satisfaction. The primary characteristics of the prototype were evaluated using a 5-point Likert scale, where higher



(a) Overall satisfaction rating on a scale from 1 (very dissatisfied) to 5 (very satisfied)



(b) SUS values

Figure 3: Quantitative measures for each participant including the mean over all participants

scores signified stronger agreement. These findings are further discussed with the qualitative results, incorporating additional feedback related to these features.

- In general, the agreement on customizability improving the legibility of the notes was highly rated with M = 4.63 (SD = 0.48).
- Regarding magnification to increase the legibility of the notes, the participants rather agreed with the statement with M = 4.13 (SD = 1.36).
- The importance of continuous movement making playing easier was rated undecided with M = 3.75 (SD = 1.29).
- The statement on the perception of polyphonic reading was seen as indecisive with M = 3.75 (SD = 1.29).

The user satisfaction with the prototype, which ranged from 1 (very dissatisfied) to 5 (very satisfied), resulted in an average score of M = 4.13 (SD = 0.60). The concrete rating for each participant can be found in Figure 3.

5.4.2 Qualitative Results of the Content Analysis. As qualitative measures, we present the main eight themes and categories identified in the content analysis performed.

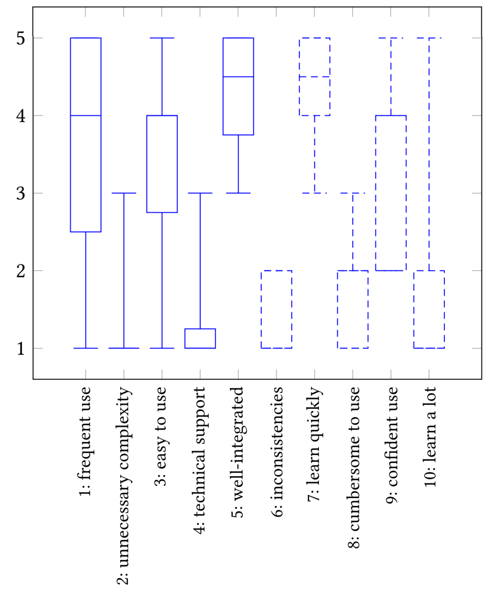


Figure 4: Box Plot of SUS values per Statement over all participants

Customizability of the Sheet Music Display. Seven out of eight participants (P01-P05, P08, P10) positively mentioned the high degree of visual customizability of the sheet music display. In particular, the ability to individually adjust the size and position of the score within the 3D environment was considered highly beneficial to improve readability. The color inversion feature was highlighted as especially effective in enhancing the contrast between the score and background. Several participants also noted that these adjustments supported a more upright and ergonomic playing posture, as the sheet music display could be positioned according to the user's body position. P02 summarized this: *"A surprisingly large number of parameters can be adjusted, which is important for individual practice routines. Basically, all the problems are solved."* The linear and continuous layout of the sheet music display was especially mentioned by P01, P04, and P08, who found it beneficial to apply an appropriate magnification and therefore enable a smooth reading, which is also supported by the high rating of visual adaptability. P01 noted in this context: *"It is clearly visible - one note is on the line, the other is between the lines."*

Customizability of the Environment. Additional settings were used selectively to adapt the environment around the participants, such as contrast, brightness, and saturation, but the participants generally agreed on their importance. P04 noted: *"That is crucial for me because often I cannot even see where the keys are."* P09 completely darkened the environment to remove any visual details that could distract.

Magnification. The magnification feature was frequently mentioned as helpful in improving readability, which was generally rated satisfactory by the participants. P05 added: *"It is much easier to read because the size can be adjusted so well"*. However, several participants noted that the chosen layout of the sheet music as a horizontal band already provided sufficient clarity, making additional magnification unnecessary in their case. For example, P03 commented: *"The layout was already enlarged enough to be readable."* P05 did not agree at all that the magnification feature improved the readability because this feature was not needed at all for them. P08 proposed an additional magnification mode that would allow temporary zooming into a section, followed by a return to full view, similar to pinch-and-zoom gestures on touchscreen devices.

Continuous Movement of the Sheet Music Display. Participants P04 and P08 emphasized the value of continuous horizontal scrolling of the sheet music display to maintain focus and readability throughout the practice. P09 and P10 noted that this allowed for more fluent practice. In contrast, P03 who was accustomed to memorizing static notation found this functionality difficult to use, explaining: *"I am generally used to memorizing the music score while they're static and then playing them. This way of playing while the music score scrolls is something completely different."* These different opinions were also reflected in the quantitative results, where the rating was rather in-between and undecided. In addition, adjustable speed settings were particularly mentioned, as they allowed participants to tailor the speed to individual skill levels, practice progress, and familiarity with the system.

Music-Related Functionalities. Most of the participants (P01-P03, P08, and P10) used available music-specific features, such as navigation in the sheet music display, tempo control of the continuous movement, and marking sections in the sheet music display extensively during free play time. Furthermore, P04 highlighted the usefulness of listening to the musical piece in the preview scene before playing, as it improved the orientation within the sheet music in the main practice scene. The suggested improvements included a broader library of music pieces (P03). Some participants expressed the wish for more specific music control features, such as automatic handling of repeat signs and dynamic tempo adjustments (P04, P10).

Interaction in XR. Over time, participants increasingly preferred gesture controls over physical buttons. P01 appreciated the reliability of gesture recognition, while P04 and P09 highlighted the benefits of gesture-based interaction for visually impaired users. P09 added that the use of hand gestures to start and stop continuous movement was especially effective and helpful, which was also described by P01, P04, and P08.

Based on this positive experience, the participants suggested additional gestures, such as swiping actions to rewind or fast forward the music score (P01, P08-P10). However, some challenges were also reported. P02 found that the icons used in the prototype were in general unclear, which highlights the need for standardized icons in this domain. P03 criticized the precision of the sliders, while P04 and P08 struggled to grab and target items. Acoustic control options, such as voice commands, were suggested as a potential improvement to omit any precise targeting needed in the interaction (P03, P04).

Perception of Polyphony. Most of the participants successfully described that they could perceive and follow two staves simultaneously. P02 noted: *"It is easy to follow. I found a good size that allows me to read both staves."*. However, P01 and P04 only found a configuration to perceive one stave at a time which they attributed to their own reduced field of view. Furthermore, they mentioned that the distance between the staves for each hand was rather large and hindered the further adaption to fit the view. This was also reflected in the quantitative results as being rather satisfactory.

Simultaneous Music Reading and Playing. Compared with the current playing practice of the participants, simultaneous reading and playing of music introduces a new learning strategy. Among the participants, P04, P05, P08, P09, and P10 had prior experience with this technique, while others were using it for the first time. Especially for first-time users, time is required to familiarize with the new strategy and adapt to it. As an example of this process, P02 initially remarked: *"Just to even begin practicing at a basic level, I would need a few days. [...] This is a different learning strategy for me."* However, P02 became more familiar during the study period and later stated: *"I am really impressed by what is built here. [...] I am truly amazed that I can actually read the music. That is incredibly impressive."* Overall, we could observe fast learning progress and most participants reported a successful and relatively fast adaption to the new system.

Despite these initial challenges, such as the mental load of simultaneous reading and playing mentioned by P10, the prototype was perceived as a significant improvement over traditional assistive tools. P05 commented: *"Compared to the conventional option of using a telescope magnifier, this is a real improvement. I am not used to seeing this level of detail."* Similarly, P10 described the prototype as: *"Already much better than regular sheet music with magnifier glasses."*

6 Discussion

In the subsequent section, we discuss our findings concerning the research questions, highlighting how these results correlate with the existing literature on music reading and playing for visually impaired musicians, and the role of XR as an assistive tool. Our methodology followed a dual-phase approach, beginning with need-finding interviews to gain a comprehensive understanding of the problem at hand and the desired system functionality of a solution. In the subsequent phase, we engaged the same participants to evaluate a prototype developed based on the insights from the interviews. This user participation facilitated both the definition of the problem space and the validation of the prototype, resulting in highly positive feedback from the participants also regarding the process in general and the perceived added value of contributing in the studies. Previous research underscored the necessity of validation with end users and their participation in XR-based interventions [34]. Our studies met this requirement, demonstrating its critical importance.

6.1 Persistent Challenges for Visually Impaired Musicians.

Our initial phase focused on identifying the persistent challenges experienced by visually impaired musicians. Given the extensive body of literature addressing this broad theme, we focused specifically on keyboard instruments because of their widespread use. Moreover, our attention was directed to the dual task of music reading and concurrent instrument performance, as outlined in the definition by Gudmundsdottir [26]. To gain an initial understanding of the techniques and tools used by our participants in need-finding interviews, we requested them to describe their current practice routines and identify their main challenges. Consistent with the findings of [4, 5, 9, 13], 50% of our participants stopped playing keyboard instruments, predominantly due to a decrease in vision. In line with Baker and Green [5], a reduction in music reading ability directly influenced the discontinuation of playing keyboard instruments or, in certain cases, playing instruments altogether. This underlines the crucial role of accessible music reading, as noted in [3].

In particular, classical music notation, with its fixed visual standards and spacing, creates considerable challenges for visually impaired musicians. Most strategies involved enlarging the visual music notation. However, as noted in earlier studies [31, 45], magnification can intensify the issue by restricting the visible area of the music. Consequently, these obstacles require additional learning time for musical pieces, making participants feel less accomplished in their practice, which aligns with the findings in [5, 31, 43]. Participants reported that simultaneous reading and playing is currently unfeasible, even with the assistive technologies or custom-made tools they use. As a result, their learning process heavily involves memorization, described as "tedious" and not enjoyable, causing significant frustration. The memorization process and its associated challenges are also documented in [4, 5, 44, 45, 55, 56]. A less frequently discussed issue is poor posture due to the necessity of close reading proximity. This concern is addressed similarly in [45], where, as in our study, a head-mounted display (HMD) was employed. This suggests that head-worn devices could introduce new opportunities by allowing users to select comfortable body postures without compromising reading distance. All identified challenges and practice routines align with previous research, highlighting the need for developments to address these issues effectively.

6.2 Requirements to Solve Challenges

In our first research question, we address enduring challenges and how a system could be developed to allow visually impaired musicians to read and play music simultaneously. Responding to the main obstacle identified by participants in need-finding interviews, the predominant requirement emphasized improving the clarity of the sheet music. To achieve this, the visual display of the sheet music must be adjustable, offering a range of customization options to cater to diverse user needs. These requirements were also reflected in [12], which investigated barriers in XR.

A key element in reading music is to enable detailed focus while providing a complete view of the entire composition, as stated in [31]. To enhance focus and detail perception, a participant suggested a concept during need-finding interviews in which the entire piece is displayed on a horizontal band that continuously moves from right to left. This band presents the section currently being played directly in front of the user, including the two staves necessary to maintain polyphony, one for each hand. This approach retains the traditional visual music notation for each segment, minimizing additional learning requirements. Conversely, it helps to concentrate on individual bars and notes, and facilitates reorientation within the composition after momentarily looking away, such as to monitor one's playing hand on the instrument. Consequently, this design was selected for integration into our prototype as it effectively addresses the main challenges of music reading identified by our visually impaired participants.

In contrast to the findings in Creed et al. [12], the significance of the audio feedback differed. Although they considered it essential for visually impaired people, in our study, additional audio feedback was considered less critical. This can be attributed to the context of the instrument playing, where additional audio could distract from the music. Furthermore, this underscores the participants' distinct emphasis on reading sheet music visually. It indicates that barriers in XR applications are highly context dependent and influenced by specific tasks, determining whether something is regarded as an obstacle.

6.3 XR as Assistive Technology for Simultaneous Music Reading and Playing

Our second research question aimed to examine how XR can serve as an assistive tool, allowing visually impaired musicians to simultaneously read and perform music. In the user study, the prototype was evaluated as a proof-of-concept. Most of the participants reported that the polyphonic aspects were understood through the XR design and features. Additionally, many participants noted being able to read around two to four bars concurrently, aligning with the designed focus section displayed on the horizontal band of the sheet music. These findings suggest that our prototype and proposed design successfully enabled concurrent reading and playing of music. As this simultaneous process was novel to many participants, it requires time and practice. However, first learning effects were already observed during the study. Approximately 50% of the participants had prior access to a similar technique and could easily anticipate its use, reporting clear improvements over their current methods (e.g. P05 and P10). For others, the approach was entirely new and required more time to become familiar. However, even short usage periods showed promising signs of adoption. For example, P02 began to benefit after only a brief trial. Participants with little or no prior XR experience faced more challenges, but greater familiarity is expected to ease use over time, in line with broader trends in technological adoption [10, 69]. The desired improvements identified during the study focused on expanding musical features and offering a wider selection of pieces, while the readability of the sheet music display was not raised as a concern. In general, the prototype confirmed the suitability of XR as an assistive technology for visually impaired musicians, supporting simultaneous sheet music reading and performance. This emphasizes the potential of such an application.

Lussier-Dalpé et al. [45] confirmed these findings by indicating that simultaneous reading and playing is feasible with an HMD. However, magnifying the entire field of view proved difficult, making the control of head movement more complicated. Thus, our prototype incorporated two distinct magnification strategies: for preview scenes, a head-controlled magnification that leaves peripheral vision unmagnified for spatial orientation, inspired by [70]; and in the main practice scene, a fixed magnification on the horizontal band showing sheet music. This magnification remains static, aiding in reorientation after looking down to the hands as the magnified area does not shift. These challenges described in [45] were addressed in our prototype without recurrence. Furthermore, unlike [45], we applied commercial standard hardware (Meta Quest 3), which is more affordable compared to the eSight HMD in their study.

In general, the XRMusic4VIP prototype demonstrated the potential of XR as an assistive technology for simultaneous reading and playing of music, which is supported by the feedback of P10 who said: *"It could make playing the piano fun again. Honestly, I had given up because you had to learn everything by heart."*

7 Limitations and Future Work

The research prototype discussed here exhibited restricted functionality compared to a fully developed system. Its primary objective was to validate concepts that support the concurrent reading and playing of music. Future efforts should be directed towards refining the prototype and integrating additional functionalities desired by the participants. We also note that the study involved participants with minimal or no experience with XR technology, which could have influenced the XR-specific desired system functionality stated in the need-finding interviews. Furthermore, no dedicated familiarization period with the prototype was established in the user study, affecting the participants' evaluations of its utility during the study itself. Although first familiarization effects could be observed, longer-term effects, potentially noticeable with prolonged use, have not yet been investigated. Future plans include extended use of the enhanced prototype to gain further insight into the simultaneous reading and playing of music as well as exploring input alternatives, such as speech, to keep hands on the instrument at all times.

8 Conclusion

We developed an XRMusic4VIP prototype based on suggestions from visually impaired musicians during need-finding interviews. Our study demonstrates the potential of XR technology as an effective assistive tool for visually impaired musicians for sight-reading sheet music. By engaging ten participants in a dual-phase user-centered approach, our findings reveal the critical importance of adaptability in music notation display. The developed prototype successfully enabled concurrent music reading and playing, addressing persistent challenges. The feedback of the participants reflected the regaining of enjoyment while playing, as well as the feasibility of music reading and playing the keyboard instrument with the support of XR. Some of those who stopped playing a keyboard instrument due to visual impairment can even imagine starting to play again. In conclusion, our approach points to the potential of XR to overcome existing problems and facilitate the accessibility of sight-reading of sheet music for visually impaired users.

Acknowledgments

The InclusiveVR@Work project is funded by the German Federal Ministry of Labor and Social Affairs (BMAS) under grant number AGF.00.00002.22. We acknowledge the use of Grammarly [25] and Writefull [68] in some cases to adjust the grammar of the paper.

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A Questions of Need-Finding Interviews

We conducted the need-finding interviews in German. The questions here are translated into English. The tag *<instrument>* is used as a placeholder for the respective instrument participants stated in the previous online questionnaire.

A.1 Introductory Question

You have already mentioned in the questionnaire that you regularly play/played *<instrument>*. How would you summarize your experiences with *<instrument>* playing so far?

A.2 Current Practice Routine

(1) Could you talk about your current practice routine? How do you learn a new piece? How do you practice pieces you already know?
(2) What goal do you aim to achieve practicing on the *<instrument>*?
(3) Are there any challenges that you face when playing *<instrument>*?
(4) Do you use tools when playing *<instrument>*? Is it a conventional tool or have you personally developed your own strategy?
(5) You have indicated that your visual impairment was/was not present at the time of learning the *<instrument>*. Did you have to adapt your strategies and tools accordingly? If so, in what way?

A.3 System Functionality

General system functionality:

(1) What functions and features would a technology need to have to really help you?
(2) How important is it to you that the new system helps make notes easier to read and thus improves the current presentation of notes? On a scale from 1 (not at all important) to 5 (very important), indicate to what extent the above applies.
(3) How important is it to you that the system supports you in learning a piece, e.g. through a tutorial? On a scale from 1 (not at all important) to 5 (very important), indicate to what extent the above applies.

XR-specific functionality:

(1) Can you imagine how VR or AR technology could help you read sheet music? What functions or support options would you like to have?
(2) How important would it be for you to be able to recognize your own hands? On a scale from 1 (not at all important) to 5 (very important), indicate to what extent the above applies.
(3) How important would it be for you to be able to see where you are in the sheet music, e.g. by marking it? On a scale from 1 (not at all important) to 5 (very important), indicate to what extent the above applies.
(4) Could additional acoustic feedback be helpful? If so, how?
(5) How should notes be designed so that you can easily recognize them?

A.4 Final Question

Are there any other ideas about what the system should be able to do or do you have any comments on the technological means that the system should implement?