# Keep the VRhythm going

## A musician-centred study investigating how Virtual Reality can support creative musical practice


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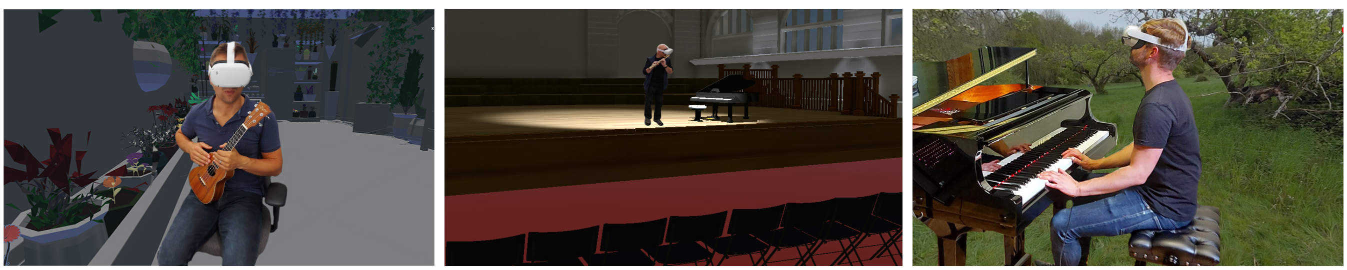

**Figure 1: In *VR Rehearse & Perform*, musicians have the opportunity to play music in a variety of creative virtual spaces – a flat with magical plants (left), an iconic performance venue (middle), a peaceful orchard (right)**


## ABSTRACT

The acoustic and visual experiences of musicians in the spaces they perform in are complex and organic in nature, entailing a continuous interaction with the environment. With this project, we leverage the power of Virtual Reality (VR) to support musicians in their creative practice by transporting them to novel sonic and visual worlds. For this, we developed a musician-centred VR system, featuring various acoustic and visual virtual environments, *VR Rehearse & Perform*, based on design requirements gathered with musicians and performance experts. To investigate how VR can be designed to support music-makers in their creative musical practice, we performed iterative tests with 19 musicians followed by semi-structured interviews. Our findings suggest that VR has the potential to support different aspects of the creative musical practice, such as rehearsing, performing and improvising. Our research provides insights and inspirations toward designing musician-centred VR experiences for various musical activities.



## CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

## KEYWORDS

Virtual Reality, Music, Musical practice, Rehearsing, Performing, Improvisation, Creativity

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# 1 INTRODUCTION

Musicians continuously react and adapt to the environments they play in. The acoustic and visual feedback they receive from the space impacts their performance [77], and provides musicians with different forums to exercise creativity that pertain to both: 1) the expressive playing of a pre-determined piece of music; and 2) improvisation (i.e., the playing of music pieces not specified in advance) [28]. While the room itself shapes and changes the music being played, musicians rarely have the ability to rehearse in the spaces they ultimately perform in. Access to performing venues for rehearsing purposes is limited in time and often comes with a prohibitive financial cost. Therefore, musicians have to settle for rehearsal rooms with varying qualities, where the acoustic parameters are often not ideally designed [52, 54]. The COVID-19 pandemic brought additional challenges (e.g., in terms of access to physical spaces, time management, entering proper mindsets) that further affected and transformed the creative practices of musicians as pointed out by Cai et al. [20] in their insightful analysis.

Virtual Reality (VR) is used in a variety of contexts [67], because of its ability to change the way we experience the world fundamentally. Performance and the performing arts are one of the VR application areas, however, research is often focused on the experience of the audiences attending performances rather than on the performers themselves [21, 45, 47]. Moreover, these applications tend to rely mostly on visuals, while the rendering of realistic sound effects remains an overlooked component. Audio-first VR experiences with authentic acoustic reproductions could elicit new possibilities for challenges faced by musicians [19], by granting them access to interactive music production environments and the opportunity to create engaging, personalised, richer performances. In addition, by combining immersive visuals with spatial audio compositions, VR could exert a powerful effect and lead to new forms of expression, including more meaningful relationships with musical content [11].

In this paper, we propose *VR Rehearse & Perform*, a platform for rehearsing and creating music in VR [44], which resulted from a user-centred iterative design process. Our solution builds on the power of VR to transport users in new visual and acoustic environments and aims to serve as a complementary tool for artists to develop their performance skills. Our goal is to understand how VR can support the creative musical practice and how practitioners create and interpret in immersive settings. Our research was led by the following research questions:

- **RQ1:** In what ways can VR support the creative musical practice? What are the barriers and challenges in achieving that?
- **RQ2:** What key characteristics of VR add value to musician-centred experiences and how?
- **RQ3:** How do musicians themselves perceive the application opportunities afforded by VR for their creative musical practice?

Our results indicate that musician-centred VR is a promising medium to support the creative musical practice, alongside more traditional ways of rehearsing, compositing and performing. Our participants reported that VR has the potential to enable music-makers to practice and improvise in venues that they would typically not have access to, as well as places that can become a source of inspiration for new music. Our work makes the following contributions: first, we identify a set of design requirements for musician-centred VR experiences, informed by 15 performance scientists representing a broad range of musical expertise and 11 musicians. Second, we introduce a novel prototype VR system and we evaluate the use of VR for creative music practice with 19 musicians. Third, we discuss the implications of our work and provide insights for developing VR experiences specifically tailored to the unique demands of the musicians based on the qualitative analysis of our evaluation of *VR Rehearse & Perform.*

# 2 RELATED WORK

## 2.1 Musical space as an instrument

Rehearsal and performance venues set the tone for music-makers and performers. The acoustic and visual experiences of musicians in the spaces they perform in are complex and organic in nature, entailing a continuous interaction with the environment. Schärer and Weinzierl [57] describe how the environment is an instrument in itself for music-makers. As shown by Ueno et al. [75], objective differences identified in the tempo and extent of vibrato employed demonstrate that musicians relate to the physical characteristics of concert halls and adjust their playing technique subconsciously. Ueno and Tachibana [76] proposed a cognitive model of musicians' performing action and showed that to generate the desired musical image during a performance, music-makers extend their physical sensation into the sound field of the concert hall to sense all its characteristics.

The complex subjective experience musicians have with the stage acoustics enables them to form a musical representation through insight (i.e., an "aha!" moment or a string of insightful realisations), implicit learning [27] (i.e., the acquisition of knowledge about a complex stimulus domain in an incidental manner) and deliberate practice [33]. These cause a sense of intuition, spontaneity, and skill acquisition based on procedural learning, and therefore are closely tied to musical practice components including intuitive creativity, composition, expressive playing of music, and improvisation [27]. The dynamic coupling between the sonic world and the individual action of music-makers is further necessary for flow [81] – the mental state of complete absorption in activities or performances [24] that allows artists to tap into an abundant stream of inspiration. These processes show that the importance of continuously savouring, reacting and adapting to diverse sonic worlds cannot be overstated in the context of musicians' creative practice.

Despite this, the differences in character between a typical practice or composition venue and the performance space are often stark. Music-makers have to settle for rehearsal rooms with varying qualities, often poor, where the acoustic parameters are not ideally designed [52, 54]. Therefore, they cannot account for the complexity of the perceptual effects involved in the musical practice. Furthermore, rehearsal spaces are not representative of the large, high-pressure environments musicians aspire to perform in. This situation was further exacerbated by the COVID-19 pandemic [69], which imposed severe restrictions on the use of physical spaces. The ongoing trend of relocating work to home contexts continues to affect performers' unconscious adjustment to source levels [15, 34], severely limiting rehearsing effectiveness.

## 2.2 Musical space as a creative medium

The experience musicians have with the space is complex and can be examined *"both at the level of the reception and performance of music, and at the level of internal processing"* [28]. Musicians do not simply play an instrument; they play a room [43], and the 'room' they play is both a physical space as well as a mental model of the sonic world they form in their imagination. The room in this context is not simply the sonic and visual environment, but includes the cognitive processes being stimulated in relation to making the music. The perception of space relies on complex sensory information provided by all perceptual systems: visual, auditory, haptic, olfactory-gustatory. Sound is only one component, as each place has its acoustics and arouses specific expectations associated with it – for instance, we expect to hear the sound of birds in a forest [49]. The visual dimension of spaces is always carefully considered in purpose-built halls, where significant attention is given not only to the acoustic design but also to the visual impression [52]. This is also true in VR, and Bargum et al. [9] stressed the importance of visuals for musicians perceiving and recognising sounds in simulated concert halls.

In a recent study observing music-makers' responses to the Covid-19 pandemic, participants identified three key ways creativity was affected by the physical location of performance *"as a creative trigger to encourage one to start making music; as a creative input and creative prompt; as a means to create psychological safe spaces to support creative risk taking"* [20]. For example, the authors showed that interstitial spaces (e.g., elevators) could be perceived as a trigger for creative experimentation while being outside provides inspiration, connecting musicians to new ideas. This demonstrates how visual and acoustic spaces can be used as complex tools for injecting variety during music-making, fostering new waves of creativity. This recursive play between perceiving the external environment and musical imagination reflects how musicologist Mark M. Reybrouck describes musical creativity as a *"process of sensory– motor integration, with a gradual shift from presentational immediacy to symbolic representation."* 'Presentational immediacy' here refers to the immediate physical (acoustic and visual) environment being played in, and 'symbolic representation' refers to the mental or psychic formulations the musician is experiencing (which are independent of the sensory data being processed). Reybrouck describes these simultaneously active creative processes holistically as *"coping with the sonic world"* which is always both part of the physical environment and part of the imagination [56]. Whether looking at the creative products or the creative experience, musicians are continuously reacting and adapting to these sonic worlds which impacts their performance [77].

## 2.3 Virtual reality for creative musical practice

VR has the power to break down the walls of our daily living spaces and to transport us to simulated or novel fictional environments [67]. It does so by replacing physical sense perceptions with computer-generated ones, which can feel as real. When this substitution is effective, the brain appears to infer its perceptual model from the virtual world, corresponding to the actual sensory data stream. However, effective substitution is an ideal, and depends on the sensory systems being included. Our initial survey of research around VR and music indicated that VR applications have been most often centred around vision. At the same time, the rendering of realistic sound effects appears to be an often overlooked component. Although modelling realistic sound propagation in VR is possible through the spatialisation of the Room Impulse Response (RIR, the room's transfer function between the sound source and microphone), this is challenging to achieve in real time as it involves a large computational overhead of the convolution operation.

Nevertheless, recent technological developments enabled the emergence of immersive, interactive sound-rendering experiences, which can represent a solution for music-makers by offering new ways of composing, performing and experiencing music [60]. Research has shown the potential of the auralisation of immersive environments in applications, including: the development of computational acoustic models for the reproduction of the acoustics of historical sites such as the Théâtre de l'Athénée [39] or Notre-Dame Cathedral [42]; the evaluation of audiences' experience [61]; providing solutions for music performance anxiety [13, 14]; and developing virtual musical instruments [59]. Surprisingly, the complex facets of creative musical practice have not been thoroughly examined in immersive spaces.

To our knowledge, one of the only attempts to address this gap was made by Aufegger et al. [3], who proposed a performance simulator[1] where musicians can be exposed repeatedly to realistic performance situations through a process of sequential simulation. This simulator consists of a physical rehearsal room where key features of the recital ritual and its environment are manipulated (e.g., the audience is video projected on the walls of the room, the lights are adjusted to correspond to stage lights, auditory cues such as coughs or applause can be enabled). Evaluation results with music students showed that this performance space facilitates an immersive experience that benefits musicians' performance and reduces their anxiety [3, 4]. It is important to note here some of the significant limitations of this technology: i) the lack of portability (users cannot experience the system in their own homes); ii) the overall acoustic impression of musicians is limited, as the sound does not simulate that of a concert hall – musicians only experience the acoustics of the simulator room; iii) users are not tracked; therefore natural sensorimotor contingencies cannot be experienced [67], and musicians' sense of 'being there' is affected. Overall, although music-makers saw potential for such simulators to be used as a form of intervention that can help them overcome challenges impacting their performance quality, there remains an uncharted territory about how virtual visual and sonic worlds can be used to support musicians in their practice.

# 3 ITERATIVE DESIGN PROCESS AND EVALUATION

Our experimental design was aimed primarily at discovering insights related to the use of VR for creative musical practice that could inspire innovative ways to design VR for supporting musicians. We took a musician-centred iterative design approach, to

[1] https://www.rcm.ac.uk/research/projects/performancesimulator/

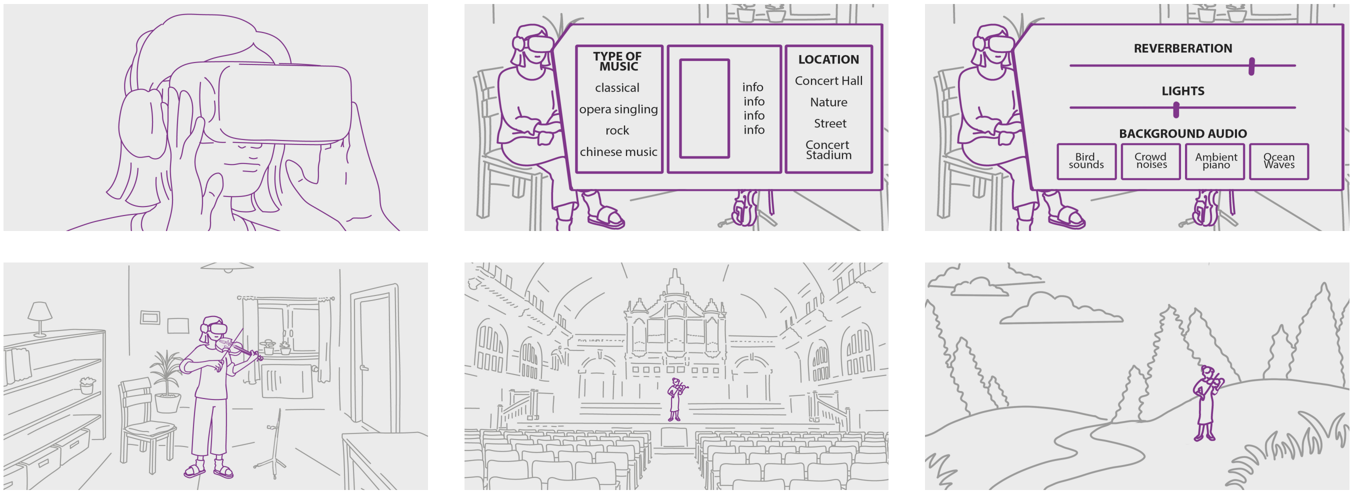



**Figure 2: A storyboard of the musician's experience based on the design requirements – the musician is able to wear a headset and headphones, select a location and type of music, adjust audio and visual parameters, and be transported to their selected location where they are able to play their instrument.**

capture from music-makers a broad range of experiences related to how immersive spaces can support different facets of their work. For this, we engaged with professional musicians and performance science researchers to design *VR Rehearse & Perform* – a VR system prototype aimed to support musicians' needs.

## 3.1 Gathering design requirements

We defined the core design requirements of the prototype through a musician-centred approach, where we actively involved different types of music-makers in a series of activities – see Figure 3, left.

In this initial phase, we sought to: (1) gather insights from performance science researchers into the features and limitations of current solutions (such as the simulator in [3]) for developing musical practice; (2) expose leading experts in music performance and musicians to immersive technologies that could support musical practice; (3) spark ideas for prototyping a VR tool that could improve performance preparation through an ideation workshop; (4) gather acoustic requirements by exposing musicians to audio spatialisation solutions (i.e., the 3DTi Toolkit – an open-source system for designing and rendering realistic audio spatialisation and reverberation models [25]); and (5) understand the repertoire of strategies used by music-makers in music practice and discuss how immersive technologies might support them. In the various activities we carried out as part of this phase, we involved 11 musicians, 15 performance researchers and two researchers specialised in building experiences for immersive technologies – see details in Figure 3. We worked with video-prompts to facilitate discussions on immersive technologies inspired by the invisible design concept [16] and we carried out design tasks where we asked participants to sketch their ideas and to act them out. Based on this, we formulated six core design requirements for immersive musical practice, which we detail below (see Figure 3 for how they emerged from each activity and Figure 2 for a storyboard of the experience based on the design requirements).

While experimenting with various headsets, performance science researchers observed that interacting with the user interface via hand controllers could impact their flow during a performance. Motivated by their concerns, we formulated DR1 to ensure a seamless experience within the virtual world.

- **DR1:** *Natural user interactions* that enable musicians to switch between playing their instruments and interacting with the user interface.

Performance science researchers indicated as an important limitation of existent simulators the fact that they do not enable musicians to experiment with the real, accurate acoustics of spaces they ultimately perform in. This challenge was also mentioned by music-makers during the *Ideation workshop* (3) and the *Gathering acoustic requirements* (4) activities, where they expressed the importance of entering a performance mindset as part of their training. The elements deemed important to enable this were: the accurate acoustics of the space and light intensity as visual cue of the *performance time*, captured in DR2-DR3.

- **DR2:** *Accurate acoustics* of the environments the musicians are in.
- **DR3:** *Customisation of the visual features* of the environment (e.g., lights) that can be used to set up the atmosphere for different types of performances.

Music-makers emphasised that musical practice has various nuances – from performing to composing and improvising – that require producing different mindsets through sources of inspiration and creative triggers. To initiate and maintain their creative pursuits, musicians mentioned the need for various elements as sources for inspiration. These elements (i.e., acoustic and spatial variety, psychologically safe spaces) are the building blocks of DR4-DR6.

- **DR4:** *Customisation of the acoustic features of the environment* (e.g., reverberation levels). This would enable musicians to change the acoustic parameters depending on their instruments and the type of music they wanted to play.

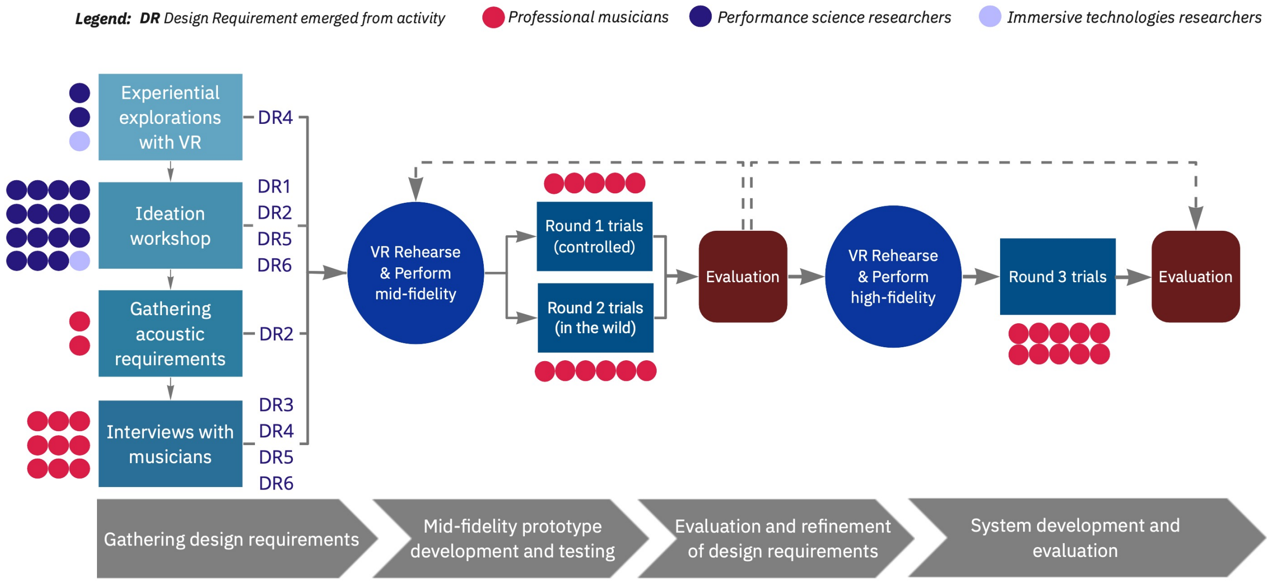



**Figure 3: Developing *VR Rehearse & Perform* – a user-centred iterative process**

- **DR5:** *Spaces that can be used as creative triggers.* This requirement is also supported by findings reported in [20] stating that music-makers mentally associate certain physical spaces with creativity.
- **DR6:** *Immersive spaces that regulate emotions.* For example spaces that prompt emotions similar to those of a performance.

## 3.2 Medium-fidelity prototype development and testing (Round 1 and Round 2)

Based on insights from Section 2 and the design requirements that emerged from the activities with the music-makers, we developed a medium-fidelity prototype and we used this in our experiential design research to refine our understanding of the musicians' needs.

*Game engine and VR platform.* To deploy *VR Rehearse & Perform*, we used the Oculus Quest 1 VR headset and the Unity 3D game engine, combined with the Oculus Integration Package SDK. The Oculus Quest platform was chosen because of its ease of use, portability and low cost, all indicating the potential for a more inclusive technology, accessible to many musicians [30]. To address **DR1**, we used Mixed Reality Toolkit [2] to enable hand-tracking and design for an intuitive interaction with the user interface – see Figures 4a, 4b, 4c for details on the types of interaction we implemented.

*Sound.* To meet **DR2** and ensure accurate spatialisation and reverberation of the sound, we adapted the 3DTi toolkit [25] into a plugin for Unity. We chose to use 3DTi because of its accuracy in simulating human hearing – other similar tools (for example Resonance audio[3]) focus on efficiency and performance rather than on accuracy and quality, therefore do not allow for the creation of authentic acoustic reproductions. The spatialisation and 3D reverberation features of the toolkit mean that the audio output is directly correlated to the user's head position and direction in the space. This feature not only supports immersion and improves users' experience [17], but it can be used as a musical tool [35]. According to Harley [37], sound ideals are influenced by the *"musical spatiality relating to the acoustic conditions of performance (types of enclosures, outdoor environments)"* and by the location of musicians and sound sources within the performance space.

Existing Unity libraries do not handle real-time audio[4] well, and induce noticeable latency. This problem is aggravated on the operating system used by Oculus Quest (i.e., a version of Android)[50, 53], as well as the headset's limited processing power. To overcome this and optimise our software we used the Juce platform [5] to write a native audio plugin which processed the audio outside of Unity's audio loop, hence significantly reducing (but not fully eliminating) the latency to 20ms and improving performance without compromising the headset's ability to run the application untethered.

*Performing space.* The virtual environment we chose for this version of the prototype was a 3D representation of the *the Royal College of Music's Amaryllis Fleming Concert Hall*[6] (Figure 6, first image). A low-polygon 3D model was developed using Maya 2020, based on a high quality point cloud of the venue that included

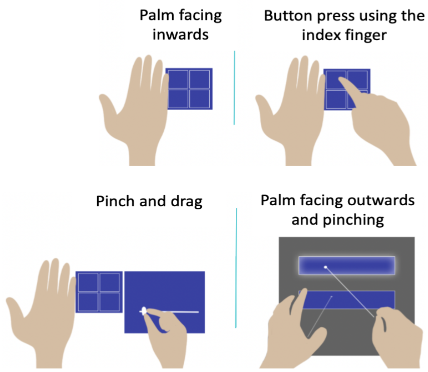
[2]https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/

[3]https://resonance-audio.github.io/resonance-audio/

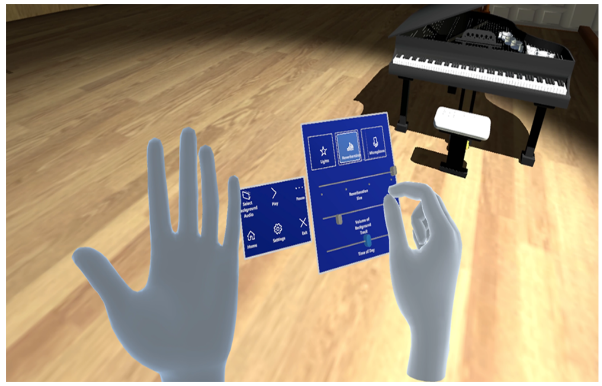
[4]https://gametorrahod.com/android-native-audio-primer-for-unity-developers/

[5]https://juce.com

[6]https://www.rcm.ac.uk/hire/hirethercmforanevent/amaryllisflemingconcerthall/




**(a) Gesture-based interactions available in *VR Rehearse & Perform***



**(b) Menu gets enabled when palm faces inwards**

**(c) User interacting with *VR Rehearse & Perform***

**Figure 4: User interaction in *VR Rehearse & Perform***

texture information (Figure 6, second image). We chose this environment due to its versatile features, which make it a good fit for both **DR5** and **DR6**.

*Functionality.* When the application starts, musicians are positioned in the middle of the concert hall's stage. The real-time microphone input feature of *VR Rehearse & Perform* enables the performer to speak, sing or play an instrument and listen to real-time audio feedback from the virtual environment. At this stage, because of the national lockdown imposed by the pandemic, we did not have access to capture the acoustics of the performance hall we modelled. Therefore, for this version of the software, we offered musicians the possibility to choose between *approximate* acoustics emulating a small (shorter decay), medium and big auditorium (longer decay) (we note here that because of this, **DR2** was not accurately met in the medium-fidelity prototype, but later on with the high-fidelity prototype in Section 3.4). Given the need for customisation expressed through **DR3** and **DR4**, we enabled users to interact with the lights of the auditorium – adjusting their intensity – and to choose between the three types of acoustics available for this version. Users also have the option to turn off the acoustics and listen to the natural sound of their instrument in the physical room they are in.

*Testing protocol: Round 1 and Round 2.* To assess the implementation of the design requirements gathered in the first phase and to evaluate the functionality of *VR Rehearse & Perform*, we carried out two rounds of tests (controlled and in-the-wild) with 11 music-makers, taking advantage of their domain-specific experience to identify infeasible and missing functions or interactions [80]. In *Round 1*, five musicians (P1-P5; 4 males and 1 female; ages 40-69 – see Table 1) experimented with playing different musical compositions while immersed in our software. These experiments took place in person, in one of our research labs and lasted between 1 and 2 hours. They were followed by semi-structured interviews that were audio recorded. *Round 2*, involving six vocalists from different musical backgrounds (P6-P11; 2 males and 4 females; ages 20-40 – see Table 1), was designed as an in-the-wild experiment. Given that it took place under national lockdown, the in-person contact between researchers and participants was minimal (i.e., the researcher was not present when the musicians used the software). Participants were given an Oculus Quest 2[7] with a standalone version of *VR Rehearse & Perform* installed, for several days, and were instructed to use it for their musical practice at home or at a location of their convenience. This was followed by an online questionnaire covering the topics of comfort, ease of use and operation, and the impact of the quality of visuals and audio on singing. A semi-structured online interview lasting 25-30 minutes was conducted post questionnaires to give participants an opportunity to expand on their responses, as well as discuss with the researcher the potential of VR to support their practice.

## 3.3 User evaluation of the medium-fidelity prototype and refinement of the design requirements

In general, musicians in *Round 1* and *Round 2* were overwhelmingly positive about the potential of VR to support their practice, connecting the immersive space with an enhanced ability to perform. All music-makers reported enthusiasm about having the possibility to perform in spaces that recreate, both visually and acoustically, famous venues. The three reverberation options provided were perceived as being very similar to an emptier and fuller (with audience) auditorium, and musicians played around with them, with no specific option being preferred. The sound quality was found satisfactory and the quality of the 3D reverberation was something musicians commented positively about. Participants who had performed previously in the real Amaryllis Fleming Concert Hall provided mixed feedback - two found the sound and reverberation as they remembered it, one thought the reverberation was slightly different from the what they experienced in the physical venue. This showcases that the acoustic expectations of musicians might vary depending on various factors such as their experience of playing in similar spaces. Furthermore, although in this round of

[7] As Oculus Quest 2 became available on the market, we decided to port our prototype to this headset. This came with significant improvements to visual and audio performance, due to its much faster processor, better display, and more RAM.

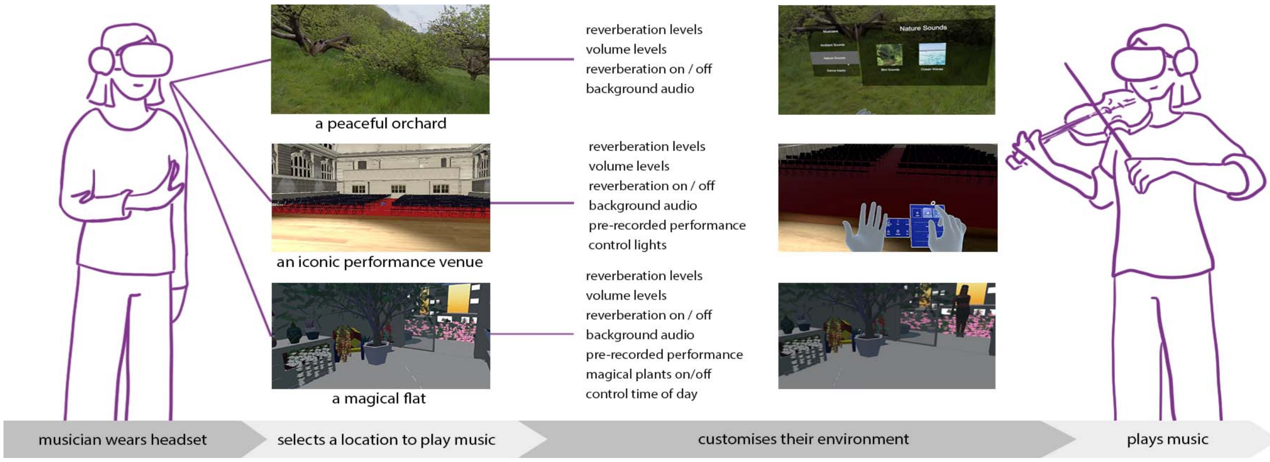



**Figure 5: *VR Rehearse & Perform* system overview.**

evaluations, most feedback focused on the sound, the visuals cues provided by the virtual environment were also deemed important. Music-makers identified some inaccuracies when comparing the virtual environment and the physical hall (e.g., comments were made about the lighting, the absence of chairs and of the piano from the stage). Additionally, musicians reinforced their interest in being transported to other realities where they could interact with other types of sonic worlds (e.g., forest, cave) and improvise with environmental sounds. At the same time, they emphasised that making music is often a collaborative process, therefore having the possibility to play with others in these immersive worlds, would have a significant impact on their practice.

## 3.4 High-fidelity prototype

The insights emerging from the evaluation allowed us to revisit and refine different design features of our solution, to ensure they best meet the needs of music-makers. Based on this, we enhanced *VR Rehearse & Perform* by adding new features (see Figure 5 for all the included features):

- To fulfil **DR2**, we added the RIR of the Amaryllis Fleming Hall as one of the reverberation options musicians can choose from. We captured impulse responses from various locations in the auditorium using an ambisonic microphone. For the prototype we used the RIR captured from the front of the stage, the same location the performer is located when in the virtual environment. The addition of the RIR of the concert hall as a reverberation option, increased the latency of the real-time audio playback to an average of 250 ms due to the complex real-time processing needed combined with the limited processing of the Oculus Quest 2 standalone headset.
- Based on participants' feedback, we increased the visual realism of the concert hall by improving the lights setup and the design of the space – see Figure 6 for the evolution of the room design.
- Given the interest expressed by musicians involved in the evaluation rounds to experiment and improvise with different environmental audio cues, we expanded **DR4**, allowing users to customise not only the reverberation of the virtual environments, but also the addition of various audio triggers. Informed by musical practice, as resulted from the interviews we carried out in the previous stage, we added a library of background audio (e.g., crowd noises, nature sounds, orchard sounds, ambient music) that could be enabled in any of the performance spaces. We chose to have a common library of audio effects for all the environments to observe whether musicians tend to experiment with sounds that are not necessarily semantically congruent with the visual information they are presented with in the chosen setting. This approach was inspired by Cytowic and Eagleman [26], who highlighted that one of the measures of creativity is a certain flexibility to inconsistency, contradiction, and paradox. We therefore aimed to understand musicians' choice of sounds, their flexibility for experimentation and how this might influence their musical practice by inducing desired emotional and behavioural effects [58].
- To allow music-makers access to spaces that could support different dimensions of their practice (**DR5** and **DR6**), we added two more environments depicting a natural setting (a 360-degree video of an orchard) and a magical flat (where musicians can change the time of the day and make an abundance of imaginary plants appear). The choice of environments is motivated by the insights from the interviews. The audio captured from the orchard was added as an option in the library of background audio.
- To enable musicians to improvise with other artistic acts, we added a library of performances pre-recorded in front of a green screen (e.g., musical and dance performances).

## 3.5 User evaluation of the high-fidelity prototype (Round 3)

*Participants.* Ten musicians of various backgrounds (P1,P2, P12-P19; 8 males and 2 females; ages 21-69 – Table 1) took part in the *Round 3* user evaluations. All participants had previous experience with VR.

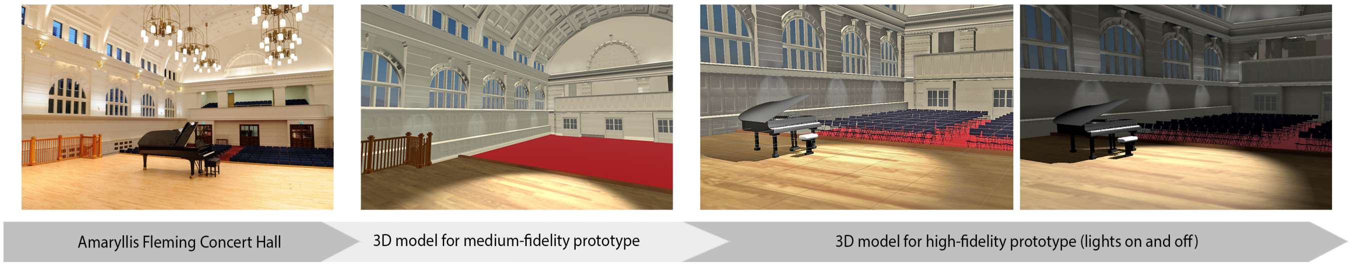



**Figure 6: The Amaryllis Fleming Concert Hall - from a physical space for musical practice to its 3D representation in *VR Rehearse & Perform***

*Software.* Participants experimented with the high-fidelity version of *VR Rehearse & Perform*.

*Hardware.* We used the Oculus Quest 2 headset for this round of evaluations. To reduce the latency introduced by the RIR of the hall (average 250 ms), we tethered the headset to a laptop and the instruments to an external audio interface connected to the laptop. These measures minimised the latency induced by the authentic acoustics of the hall to an average of 40 ms. As audio renderers, musicians were able to choose between using: 1) the built-in speakers of the headset – these provide good quality spatial audio, while allowing users to listen to the sound of their surroundings at the same time, and 2) noise cancelling headphones, which provide better audio quality, louder, more targeted sound and complete isolation from the surroundings.

*Testing protocol: Round 3.* The sessions took place in person, in a research lab and lasted between 1 and 2 hours. They consisted of the following phases: a) a brief introduction from the researcher about the project followed by musicians signing consent forms; b) 5-10 minutes of semi-structured interviews on the musicians' backgrounds and their experience with technology and VR; c) engagement in musical practice without VR; d) after a brief introduction of the system and its functionalities, experimentation and engagement in musical practice with their chosen features (e.g., environments, environmental sounds, reverberation levels, etc.) of *VR Rehearse & Perform*; e) semi-structured interviews on their experience and the potential of using VR for their musical practice, carried out at the end of their experimentation.

### 3.6 Data and analysis

Prior to their participation in our study, all participants were given a participant information sheet and signed consent and photography/video release forms, approved by the ethics committee at our institutions. These gave permission for the interviews to be audio recorded and the software tests to be photographed, screen-captured and video recorded (This was not done for the *Round* in-the-wild evaluations). The audio recordings of the interviews in *Round 1, Round 2 and Round 3* were transcribed. The transcripts were coded and labelled by three researchers independently, using a combination of thematic and inductive analysis [18, 72]. Initial codes were assigned based on our guiding research questions regarding 'presence', 'creativity', 'space' 'relationship with the instrument', 'performance mindset'. Subsequent codes were added based on the frequency of sentiments shared by multiple participants. The observational data from the video recordings complimented the interview data during the analysis. The following themes emerged as salient for the broadest range of participants and useful for guiding further research and practice: *Presence as an antecedent of flow*, *The sound of being "here and there"*, *Relationship with the instrument*, *Facilitating creative musical practice.*

## 4 RESULTS

***"I wasn't sure if I was inspired or intimidated, which was really cool. Because that could be a feeling that a performer could tap into to further their practice or their creativity and come up with new material (P17)".***

### 4.1 Presence as an antecedent of flow

*4.1.1 Presence and mes-mersion.* We observed throughout our study that, when interacting with *VR Rehearse & Perform*, participants were ready to suspend disbelief and perform: *"I didn't actually think I was in an orchard. If I was actually in an orchard, the sky is grey, I'd be thinking, I hope it doesn't rain. And that didn't even occur to me. [..] It's like you kind of suspend your disbelief [..] and play along with the environment (P19)"*. The sense of 'being there' – in the virtual environment – and the emotions associated with it were amplified in settings associated with traditional spaces that musicians play in. For example, the concert hall environment, while being a traditional performance venue, also inspired some of the strongest emotional reactions, with participants experiencing a sense of awe and reverence, *"when I first got into it, and it was this big hall, it kind of made me feel better than I was (P16)"*. Another participant commented *"I would have happily hammered away the piano for hours, because it's quite a nice way to play in that concert hall (P13)"*. Participants paid particular attention to how they sounded in the hall, *"I was more immersed in hearing the acoustic in that space (P16)"*, and some participants also commented on their openness to being influenced by the realism of the virtual environment :*"Just tricking yourself that you are in a performance space usually makes you sing better because then your subconscious, or your body says, 'oh now it's for real' (P9)"*. The visual and acoustic accuracy of the hall in particular appears to have had a transformational effect on the way musicians perceived themselves, one participant describing *"I felt like more of a musician, because I was in the place, you know, with the instruments and all of that in that grand concert hall (P16)"*.

**Table 1: participants details: ID, occupation, instrument played while in *VR Rehearse & Perform*, type of music performed, evaluation round they participated in.**

| PID | Occupation | Instrument in VR | Type of music played in VR | Eval. round |
|---|---|---|---|---|
| **P1** | Professional flute player and music teacher | Base flute | Improvisation based on the environment | 1 + 3 |
| **P2** | Multi-instrumentalist professional musician and music teacher | Yukalele + singing | Own music + Improvisation based on the environment | 1 + 3 |
| **P3** | Professional Japanese drum player | Japanese drums | Improvised | 1 |
| **P4** | Professional guitarist and vocalist(band member) | Singing | Improvised | 1 |
| **P5** | Professional keyboard player (band member) | Keyboard | Random Notes | 1 |
| **P6** | Postgraduate and professional opera singer | Singing | Known musical piece | 2 |
| **P7** | Postgraduate musician | Singing | Known musical piece | 2 |
| **P8** | Postgraduate and professional opera singer | Singing | Known musical piece | 2 |
| **P9** | Postgraduate and professional opera singer | Singing | Known musical piece | 2 |
| **P10** | Undergraduate musician, vocal principal study | Singing | Known musical piece | 2 |
| **P11** | Former professional jazz singer | Singing | Known musical piece | 2 |
| **P12** | Professional classical pianist | Piano | Random notes | 3 |
| **P13** | Formerly professional bass player, classically trained on piano. Postgraduate performance science student | Piano | Known musical piece | 3 |
| **P14** | Multi-instrumentalist professional musician and music teacher | Keyboard + singing | Own music | 3 |
| **P15** | Multi-instrumentalist professional musician and music teacher | Resonator guitar + singing | Improvised | 3 |
| **P16** | Hobbyist, student musician | Electric guitar | Known musical piece | 3 |
| **P17** | Professional vocalist and postgraduate performance science student | Singing | Improvisation based on the environment | 3 |
| **P18** | Multi-instrumentalist professional musician and music teacher | Acoustic guitar | Known piece | 3 |
| **P19** | Professional composer, improviser and music lecturer | Vibraphone | Improvisation based on the environment | 3 |

The transformational, almost magical power of the space was experienced by another participant who referred to the concert hall as *"sacred (P19)"*, showing the intense meaning attributed to this space. This relates to the concept of a *sacred sphere*, or special place where the significance and meaning of certain social actions become amplified. According to Spychiger [70], the function of a sacred sphere (related in its most obvious materialisation to spaces and location) is to connect the factual world with an *otherworld* that can "take on multiple nonreligious qualities, which may play out in all kinds of artistic narratives, film, music, literature, sculpture and so on." Although fully independent of the religious world, sacred artistic spaces (e.g., iconic buildings with outstanding visuals and acoustics) might feel similar to religion itself, unleashing feelings difficult to articulate. We use *mes-mersion* to describe the feelings of magnetic pull a musician experiences when making music in accurate simulations of such "sacred" spaces. This suggests the power virtual iconic venues might have not only on inducing the right creative mindset – cited as one of more important factors in musical practice [20] – but also on unleashing musical performances that go beyond the everyday.

The orchard environment, for example, was perceived as less immersive than the concert hall (endowed with 'sacred' significance) by most musicians: *"The concert hall was much more immersive. In the outdoors one, at first, before I started playing, I felt like I was outdoors. As soon as I started playing, it took it away. Because I was, I think my brain had sort of figured out « oh okay this is just a photo» (P14)"*; *"I felt more immersed in the virtual flat than I did in the orchard. I can't explain why that is. Maybe because in the orchard, there's so many more other sensory experiences like heat and breeze and the sound of the birds, whereas in a flat you're used to not having all the other senses (P2)"*. One explanation for this could be that the sense of presence is enhanced in more immersive, computer generated settings that are 1) surrounding – the sensory signals (i.e., sound) approached participants from any virtual direction; 2) matching – the participants' proprioceptive feedback about body movements matched the information rendered on the display [68]. This confirms and extends recent findings reported by Yeo et al. [83], who showed that computer-generated virtual content (i.e, nature) performs better than 360-degree videos when it comes to the experienced feelings of presence. In pursuit of presence, improved sensory realism and quality might exert a powerful effect, but it is unclear how this ever-increasing fidelity might benefit musicians' practice.

#### 4.1.2 In the flow - Tapping into an abundant stream of inspirations.

Musicians not only reported feeling being 'there', but this 'there' remained interesting through the contribution of sound and the variety of virtual environments provided. Participants connected the immersive spaces they were exposed to with an enhanced ability to improvise and perform: *"I'm aware that the environment that has been created within VR is an illusion. But it's a very helpful illusion. [..] I'm responding to the background stimulus of what it's asking me to do. In other words, there are tone centres, which are giving me a guidance from where I can then move away from or back to (P1)"*. Another participant commented on how much it supported visualisation techniques often used by musicians to place themselves in a performance frame of mind: *"you [have to] envisage the space you're in. That's [..] what this is doing but this is just taking it to another level (P8)"*. The connection between feeling 'there' and the fact that this 'there' specifically facilitates the act of performing and improvisation correlates with several dimensions of flow described by Csikszentmihalyi [23] such as: merging of 'action-awareness'or being fully absorbed in the moment; direct and immediate feedback meaningful to the task; the ability to concentrate on the task; being an autotelic activity. Some participants made observations concerning warping or losing sense of time and space: *"I would say even then I felt slightly more focused when I was in the VR, because obviously, it kind of, you put on the headphones and kind of isolates the white noise, and you're just there and you just hear the instrument. And I felt like time definitely went more slowly (P16)"*; *"It just felt like I was in a different time dimension inside the VR (P17)"*. Remarks pointing to the positive emotions emerging from the evaluation sessions speak to the autotelic experience musicians felt while performing and improvising as well as the merging of action-awareness.

Although most participants reported a strong sense of presence that inspired them to be more experimental while in *VR Rehearse & Perform*, they also mentioned moments of distraction *"And I was distracted by the wow factor, that's for sure. But that would go obviously after you use it a bit. (P19)"*. However, we observed that the distractions described by participants did not seem to interrupt flow, but rather seemed to redirect it. P19 continues: *"But I was kind of... I was really trying to play and hear how the software... you know, how the software responded within the spaces. So it was partly about playing, it wasn't exactly about me playing, you know, it's like, how is it within this space? So I don't know if that's being distracted or not, or just having your focus in a slightly different space (P19)"*. 'Having your focus in a slightly different place' might also act as a brain boost, training important aspects of musicians' practice: *"I tried so many different things. Nature landscape distracted at first, very focused, after I started singing. Hall, again, distracted at first focused at points and then distracted at other points, because I wanted to look around, which is actually what would happen in a real performance, where there would be people in the seats and maybe somebody up in the balcony, and there would be musicians on the stage. So it's actually a really good exercise in a building focus and maintaining like integrity of your focus (P17)"*. However, we note that for this sensation of *constructive distraction* to work for musicians, the challenge and the skill level need to be balanced (one of the key dimensions of flow). If this condition is not met (i.e, for pianists who could not play without seeing the instrument), the distraction will result in frustration: *"The trickiest thing is not being able to see the keyboard. I don't play frequently on the piano and also, I don't read music, I tend to look at the keyboard all the time. So for me, I think particularly that was difficult (P13)"*. Whenever participants overcame this, they became fully self absorbed in the moment *"But after a little while, I think the reality of not seeing the guitar kind of set in, and then something clicked and I was just more on autopilot, and I was just able to hit the notes a little bit better (P16)"*.

## 4.2 The sound of being "here and there"

In general, participants perceived the acoustic experience as being realistic *"You play, you're in the room, you can hear the effect of the acoustics, which is mild, but it's noticeable (P13)"*. Moreover, P13, who was familiar with the Amaryllis Fleming Concert Hall, mentioned *"I think the quality of the reverb was high and it worked well. It was less artificial sounding, more natural sounding (P13)"*. The latency resulting from the real-time microphone input, impacted the experience of musicians in different ways. For example, P11 turned off the simulated sound *"I did not like hearing myself with a delay (P11)"*, while P17 and P2 removed their headphones and listened to the audio coming from the headset's speakers *"There was definitely a very noticeable latency when I had the headphones on [..]. But once the headphones were off, it was completely fine. I think if there was latency it was very minimal, to the point where I could just work with it. I could hear the reverb, which was really awesome (P17)"*. P9 noted that although they noticed some latency, it was something that they could get used to *"until I found the right balance of the feedback it was, it required a bit of playing around and getting used to, but then once I found it, it was quite impressive actually (P9)"*. P16 and P19 mentioned they did not experience any latency while playing. Overall, we observed that some of the participants utilised specific types of coping mechanisms to compensate for the audio perception of latency such as changing focus, tempo or dynamic, or shifting their gestures and strike ahead of the beat to align the delayed sound, which were observed also in a non-VR context by Greeff [36].

Interestingly, using the Oculus Quest's native audio system created a unique sonic world, where the sound of the physical space musicians were located in, blended with the sound of the virtual space they were experiencing. P17 continued by explaining how they found value in this for their music-making *"The sound quality was pretty cool [...]I preferred not having the headphones because I could actually hear my own voice as well, whilst hearing audio from the headset output. And I think it helps to train, it adds an element of naturalness to it (P17)"*. In general, participants expressed different views about the optimal sound output device for their VR music jam and there was no general consensus if headphones or the Quest Audio system was better in terms of quality and experience. P8 commented that they preferred the Quest's audio system as *"... they just felt a bit more natural than the headphones. I mean, especially for an opera singer. I just feel that you know, having earphones really like is really [too much there] and it's... you know, it shuts down everything. I just feel more comfortable with the built-in speakers (P8)"*. On the contrary, P19 saw benefits in using the headphones because they *"[..] cut that out (i.e., the sound of the physical room), it did make a big difference, actually. So I could really hear the room* *(i.e., the virtual space). And I found that when I moved my head, I was hearing it sort of slightly differently in the room as well (P19)"*. For P2, removing the headphones had an impact on their immersion in spaces where the blended sonic world did not match their acoustic expectations of the space *"I felt more immersed in the flat, when it was a more closed acoustic, similar to the one in this room we are in. Whereas the hall didn't really do that for me. Maybe because it wasn't quite loud enough (P2)"*.

## 4.3 Relationship with the instrument

While wearing the headset, participants could see their hands but were unable to see their instruments (i.e., the instrument was not tracked and visible in VR - Figure 7). Accordingly, they relied on auditory and passive haptic cues to play music. Musicians often have strong bonds with their instruments and as Simoens and Tervaniemi [63] showed, feeling united with their instrument can lead to improved mental well-being, higher levels of confidence and reduced performance anxiety. It was therefore important to explore how the inability to see instruments in VR affected the musician-instrument relationship, how it influenced the perception of embodiment in VR and, consequently how it affected musicians' performance.

Music-playing is a multisensory experience involving perceptual, cognitive and motor components. One of the most prevalent forms of sensory information that accompanies audition when playing music is touch [82]. For musicians whose regular playing relies more on auditory and haptic feedback, not seeing their instrument had no impact on how they felt towards it. For example, P1 noted that once they found the flute's mouthpiece, everything was fine *"the VR didn't affect the level of what I do. It didn't detract from the quality and the style and the delivery..."*. Musicians who played string instruments took more time to adjust to not being able to see them *"...playing in VR, it was confusing at first, it took a little while for my brain to adjust to the situation (P16)"*. Nevertheless, after getting accustomed to the lack of visual feedback from the instrument, they perceived this as a positive aspect of VR, which enabled them to train new sensory skills and enhanced their connection to their instrument *"[I felt] probably more connected to it [the instrument] because I couldn't see it. And because it becomes a touch and feel and sound thing. I think it's preferable. Actually having the opportunity to almost play blindfolded is quite nice (P15)"*. Both P15 and P18 saw great potential in this aspect of *VR Rehearse & Perform* in terms of improving their practice *"I think I like not being able to see [the instrument], relying completely on muscle memory is definitely something that I should practice. [...] I feel [...] not being able to see the instrument is actually quite positive (P18)"*.

Even-though auditory feedback is crucial for all musicians, in the case of pianists, Banton [7] found that when deprived of visual feedback (i.e., not seeing the piano) they tend to make more mistakes than when deprived of auditory feedback (i.e., not hearing the piano). This was also evident in our study, as musicians who play key-based instruments were the group that struggled the most to play music and felt most disconnected from their instrument. P5, P12, P13 stated that they could not play continuously at all. P12 commented on his experience *"I didn't know which keys to press to really get out what I want… [...] but I felt very limited to how freely I can move around the keyboard (P12)"*. Surprisingly though, after getting used to not seeing their hands, P14 was able to perform an entire song in VR. They attributed this to having a 'perfect pitch' (i.e., absolute pitch [5]): *"I have what's called perfect pitch. So the reason probably, I could play things a little bit easier because when you play a note, I can hear the note. [...] I definitely was relying on that quite a lot when I couldn't see the keys (P14)"*.

Percussion instruments are another type of instrument that one would expect visual feedback is important when played. Before their session, P3 raised a concern about the fact that they would be unable to see their drum *"I think it's good to see the drums. [...] Because we do play the sides, the edge of the the actual drum skin right into the centre, it makes completely different sounds (P3)"*. However, they changed their mind after using *VR Rehearse & Perform* and identified a technique to overcome this. They found that if they touch the periphery of their drum when in VR, they could adjust well to not being able to see the instrument *"it wasn't a problem once I got used to the idea that I couldn't see out of my peripheral vision (P3)"*. P19 embraced the idea as they already had experience with playing in a blindfolded band. Due to the pandemic they had not performed blindfolded for about a year *"I kind of lost where the instrument was, and where the notes were [...] If I was going to use this [VR] seriously, I put more time into re-learning my tactile relationship with my instrument. (P19)"* . Nevertheless, when asked about their relationship with the instrument while in VR they described it as *"definitely experimental, it felt really playful. [...] I felt really connected because it's like, I know this instrument, and I know this thing so well. But spatially, I was having problems. (P19)"* They suggested that a simple solution for this would be *" a point of reference for where the vibraphone is, actually that's all it needs. It doesn't need to be a visual vibraphone it could just be where the edges are, or something like that. That would just make a massive difference"*.

Several participants sang in VR - some in combination with their other instruments. P17, one of the singers in our study, described their body as their instrument and explained how the strong feelings of immersion they experienced affected their relationship with it. *"I was so immersed in what my eyes were seeing that, I as a trained vocalist, forgot about my body and every now and then I remembered: wait no I have to like control my core to like, play my instrument"*. This suggests that although their feeling of being present in the environment (often referred to as Place Illusion [65]) was high, their feelings of body-ownership were reduced; hence they momentarily lost agency of the rest of their body. For vocalists, being aware of their body and breathing patterns is crucial not only in terms of the singing output, but also in terms of protecting their voice [48]. This lack of embodiment in the virtual environment *"... could contribute to bad habits about not being aware of your core support, and your feet (P17)"*. The same participant also commented that this aspect *"could be improved with familiarity so that you don't lose yourself completely."* or by *" having [ ...] a visual cue that says, hey, you have a body [...] you've got an entire, instrument below your neck that you need to be aware of. So even if it's like an avatar in a mirror [..] that could be very beneficial"*. Additionally, the headset presented another barrier to singing in some cases, due to its position on the face, which prevented the expression of some specific notes. P17 elaborated on this *"if you do something brighter, or clankier or something that requires your mouth to be like a bit wider [...] that*

**Figure 7: Musicians playing their instruments in *VR Rehearse & Perform***

*would be hard because the headset rests right on top of here. I noticed that as long as you're taking the jargon away, as long as you're doing, like rounded, warm sounds, it's completely fine."* In addition, P6, P8, and P9 who are opera singers, all commented on the weight of the headset and how it affected their singing *"the weight of the headset pulls down on the neck. And you really notice that as a singer because alignment is very important to get right. You find yourself constantly having to [move] against it (P6)"*. The weight and fit of the headset were a problem only for participants who sing.

## 4.4 Facilitating creative musical practice

*4.4.1 Access to restricted spaces.* The immersive visual environments as well as the dynamic acoustical properties of each corresponding space were frequently associated with an enhanced ability to prepare material for public performance. Participants described how *VR Rehearse & Perform* provided a meaningful sense of access to otherwise restricted performance venues, allowing musicians a novel sense of freedom to sonically explore a venue before performance, and contributed to an easing of anxiety associated with anticipation of performing in those spaces. As one participant described, *"preparing for a concert, one of the things you have to deal with is, is the psychology of performing"* elaborating that concert halls can be overwhelming but to prepare, *"practising as much as you can in the space is what you need to do (P19)"* . Musicians, however, rarely get many opportunities to rehearse in the spaces they are expected to perform in, and subsequently can struggle to feel adequately prepared for a performance. Four participants described how the quality of the visual environments was enough with *VR Rehearse & Perform* to evoke a feeling of really rehearsing in a concert hall, *"It feels like what it used to be, you know, a year and a half ago [before the national lockdown] (P15)"*. Another similarly described how *"the concert hall environment was stimulating a similar feeling to... performing in public (P1)"*. These feelings were in turn associated with an enhanced ability to be creative in venues that otherwise could feel intimidating and instead *"use it like a playground (P17)"*. P13 described how the VR rehearsal experience was superior to playing in dedicated rehearsal spaces that *"are tiny, they're padded, they are acoustically dead (P13)"*. In addition to evoking qualities of a familiar performance venue or experience through VR, participants described how *VR Rehearse & Perform* could allow access to *"sacred spaces within the world of music"* that are *"very hard to get access to (P19)"*. This idea was validated by another participant who remarked after their experience that it was *"probably the only way for me to play in that concert hall (P13)"*. Such *sacred* or rather iconic venues are not simply remarkable for their social or cultural prestige, but often have been uniquely designed to resonate in a particularly unique and pleasing way. Participants observed that the particular acoustics of each virtual environment as well as the ability to manipulate the level of reverberation and addition of ambient sound enhanced their experience.

*4.4.2 Playing the Room.* The dynamic range of acoustic experience afforded by *VR Rehearse & Perform* was a frequently cited positive characteristic of the experience, as one participant explained: *"from a practising point of view, it has massive benefits, because you are interacting even more with your ears than you are by actually just looking at where the things are (P15)"*. The sound produced by a musician's instrument is a product not only of the particular resonating qualities of the instrument, but also of those sounds mixing with the environment. Accordingly, the acoustic properties of a given space become a literal extension of the instrument that the musician must take into account. As one of the vocalists in our study explained,*"the acoustics of the room can really change... how you project, how you shape your vowels, how you phrase, what colour you use for your tone, and texture (P17)"*. Participants responded differently to the various options for shaping the acoustics of the room and the ability to add and remove additional sounds. For one vocalist, *"I could hear the reverb, which was really awesome. I could play around with it and go to like the max setting (P17)"*, while the vocalist playing with a ukulele preferred and *"felt more immersed in the flat (P2)"*. Some enjoyed *"..that you can have an audience and turn them on or off (P14)"*, while another felt *"I don't actually care about the people that are in the audience (P15)"*. Not all of the participants explored the full range of additional sound options, but one that did expressed *"I really liked the kind of variety in the accompaniment I could have. There was like the nature sounds, and there was the musicians that I improvised over the guitarist, and then I improvised over a person dancing (P17)"*. The visual environment played a role in particular for improvising musicians who described that the presence of virtual environments directly affected what they paid attention to, *"When I was playing on my own, I was responding to the the sound in the room. When I'm playing with the background, I'm responding to the background stimulus of what it's asking you to do (P1)"*. Such observations support the potential of VR to not only address challenges musicians experience when travel is restricted, but to enhance traditional training and introduce new techniques for training the mind of the performer. In particular, our results indicate that the majority of participants experienced a direct impact from the VR world on not only what they played, but how they played, and how it felt to play. Overall, while participants varied in opinion on which particular room acoustics they preferred and how useful a given accompaniment might be, there was general agreement that *"if you're going to perform ...and then you have this like a week before or two weeks before, I think it could be quite useful, because then you already have an inkling of what like(sic) sound carries (P17)"*. In addition to helping performers shape their sounds for performance in a particular venue or setting some participants pointed out that *VR Rehearse & Perform* would be a useful tool for overcoming some of the psychological challenges related to performance.

*4.4.3 Mindset for performance.* Besides the challenge of adapting to the acoustics of a given venue in a relatively short period of time, we learned that even being in a music hall virtually can induce anxiety for many. Performance venues can be intimidating to musicians for a variety of reasons. Strikingly, in our study we found participants describing that in the concert hall, *"I really felt a bit more kind of inhibited (P2)"*, *"It was weird there...I think because I'm anticipated slightly apprehensive about going back to a big theatre (P19)"*. Another described how unlike the other VR locations, in the hall they felt, *" in the back of my head is, (sic) is pulling it, you know, like you would be if you're on stage (P16)"*. Similarly, the fourth participant described, *"When you're playing in the [virtual] flat, it could be compared to, similarly to, practising at home- in the hall, I'm focusing on an exterior and playing as though I'm playing to an audience (P1)"*. These feelings were noteworthy in how they affected performance: *"in the [hall], some of my bugbears with classical music started to come into play...should I really be playing like free improvisation?...I can't do wacky crazy stuff (P19)"*. Feeling 'weird' and 'inhibited' in the hall, rather than being perceived as an obstacle to rehearsing in VR, was described as a potential source of empowerment. *"So this is great, I can be here trying this out and (sic) getting confident again within a bigger space (P2)"*. P17 described, *" as a performer I struggle with opening my eyes and looking at the people in front of me, but I could do that in VR."* They explained further *"in terms of training, spontaneity, and nervousness and kind of shyness, to an extent, I preferred being in VR, because it just proved to me that technically, I'm competent, it's just interpersonally, I'm a little nervous or a little shy (P17)"*. P16 and P1 both described how in a performance anxiety context, VR *"could be a really useful experience, you know, in school (P16)"* or *"great aid for musicians, even actors, dancers, and anybody that's doing a mic, stand-up comedians, or even politicians or people having to deliver conferences or speeches (P1)"*.

*4.4.4 Stimulating creativity.* A key motivation for our study was to see how VR might address some of the challenges musicians have reported during prolonged periods of social isolation [20]. The need for this was reinforced by such observations from our own participants describing how they *"do lose inspiration just being in the same environment over and over and...you start to feel very sluggish (P17)"*. Therefore, we set out to investigate to what extent virtual worlds could inspire more enjoyment, and function as a 'trigger' to be creative, as a direct 'input and creative prompt,' and as a way to stimulate a 'psychological safe space.' Overall, musicians enjoyed the environmental variety provided, with one participant describing *"the variety between the landscapes was so striking, I really enjoyed just being able to travel from this grassy natural world, into a constructed Hall into a little flat (P17)"*. The ability to feel present in the environments was reported to have a direct affect on feelings of creativity: *"Aesthetically, it puts me in a more creative space (P19)"*. In general, participants shared similar observations that, *"in terms of how it makes you feel, it certainly puts you in the right kind of frame of mind (P13)"*.

Notably, participants had a wide range of different interpretations of how the different VR environments stimulated them creatively: *"you'd find yourself playing different in different situations (P15)"* and they expressed desire to explore how different environments can inspire different types of music playing *"what would interest me in the different environments is that it could push you creatively, you know put me in an Astrobot world, I'm going to play something different than what I would in an auditorium, or what I would in a little sort of smoky bar setting. And it's got loads of great potential for experimentation (P15)"*. For others, the ability of VR to isolate the user from the outside world and completely immerse them in new environments provided a safe space for experimentation *"there was like a minute where I was like I cycled through a bunch of different styles where I went from like Eastern style singing into like scalped jazz, singing and then read mixing and then I just cycled through a bunch of styles and that is something normally I would do inside my own bedroom or like in the bathroom or a very isolated [space] (P17)"*.

Moreover, for P18, being in the virtual orchard inspired feeling linked to the music they were playing, describing how they felt *"enlightened...because it kind of goes into the piece of music"(P18)*, reflecting a sense of cohesion between the musician's internalised 'sonic world' and the external one. Similar feelings were observed from P19 while playing music in the flat *"I was trying some other things out with my voice so there was something that was happening that made me more creative. It made me want to create more with the song because I was in a place where which I felt was imaginatively and creatively in line with the song itself (P2)"*. This connection between the music as a kind of existing sonic world that became 'enlightened' by the orchard environment or 'creatively in line' with the flat, supports Reybrouck's explanation that creativity in the musician manifests as a *"continuous interaction with their environment in an attempt to keep any disturbances within critical limits"*. Traditionally, the environment of rehearsal rarely matches the internalised sonic world of the piece, suggesting there is a cognitive load for the musician to ignore the 'tiny, padded, acoustically dead' practice environment they usually find themselves in: *"... we usually stay away from the practice booths [..] 'cause it's so difficult to know what you're doing when when it's so completely dense, and you get nothing back (P9)"*. Our results suggest that VR technologies have the potential to expose musicians to environments that match the emotions their music induces, providing a meaningful way to reduce the cognitive load, and in turn allow for more creative attention to be placed on musical expression itself, therefore inspiring different kinds of creative practices.

**Table 2: Summary of findings**

| Main theme | Sub-theme | Key findings |
|---|---|---|
| Presence as an antecedent of flow | Presence and mes-mersion | Virtual iconic venues enabled music-makers to experience stronger feelings of magnetic pull than casual settings (i.e., the orchard, the flat). This induced the right creative mindset and unleashed musical performances that go beyond the everyday. |
| | In the flow | The connection between feeling 'there' and the fact that this 'there' specifically facilitated the act of performing and improvisation correlates with several dimensions of flow [23]. |
| The sound of being "here and there" | n.a. | Music-makers found the acoustic experience realistic. The latency impacted the experience of musicians in different ways and some participants utilised various coping mechanisms to adjust to it. The unique sonic world created by Oculus Quest's native audio system was perceived valuable by some of the musicians, while others preferred the more targeted sound the headphones provided. |
| Relationship with the instrument | n.a. | The absence of instruments from the VR simulation impacted musicians differently depending on the instrument they were playing: 1) key-based instruments: significant challenges; 2) string instruments: more time needed to adjust, but once this is achieved, the practice is seen beneficial; 3) percussion instruments: experimental relationship; 4) singers: lack of body awareness and problems with the fit of the headset. |
| Facilitating creative musical practice | Access to restricted spaces | *VR Rehearse & Perform* provided a meaningful sense of access to otherwise restricted performance venues, allowing musicians a novel sense of freedom to sonically explore a venue before performance. |
| | Playing the Room | Exposure to a variety of sonic worlds in VR helps performers shape their sounds for performance in a particular venue or setting. |
| | Mindset for performance | *VR Rehearse & Perform* enabled musicians to enter the mindset for performance and this was perceived as a potential source of empowerment. |
| | Stimulating creativity | The environmental variety was positively associated by musicians with feelings of creativity. VR provided a meaningful way to reduce the cognitive load, and in turn allow for more creative attention to be placed on musical expression itself. |

# 5 DISCUSSION

The applications of VR are extensive and range across numerous domains of knowledge, however research has not looked until now at how VR might benefit music-makers and their creative practice. Specifically, while some research efforts have focused on VR musical instruments for extending musical experiences (see [59] for a survey on this), the complex relationship musicians have with rehearsal and performance spaces has been neglected. Music-makers are always playing a duet with the space. Authentic sound reconstructions in VR could thus open up the possibility for musicians to incorporate, in their creative practice, a variety of virtual rehearsal and concert spaces to enhance their practice. To enable this and to find meaningful ways to support musicians, we took a user-centred approach, where we involved music-makers in the process of formulating a set of design requirements for immersive experiences dedicated to musical practice. Based on these requirements, we built *VR Rehearse & Perform*, a system that allows music-makers to engage in their musical practice in three customisable – both visually and acoustically – environments.

The visuals and the dynamic range of the acoustic experiences afforded by our system had a direct impact not only on what musicians played, but also on how they played and how it felt to play (see Table 2 for a summary of our findings). Many participants appreciated that the environmental variety functioned as an inspiring creative prompt that triggered a creative mindset and contributed to an easing of anxiety associated with the anticipation of performing in those spaces. From our participants' observations, it appears that VR has the potential to become a solution to some of the challenges they face beyond the pandemic. They described that *VR Rehearse & Perform* allowed them to place their creative attention on musical expression itself, supporting existing and inspiring new forms of music-making. Most musicians observed potential for a more effective training from home or from spaces that do not meet their acoustic needs. Inspired by their experience with *VR Rehearse & Perform*, two participants have since bought a VR headset and integrated it in their musical practice. In the following sections we discuss some insights we gathered from our observations which can inspire future research and design of musician-centred VR experiences.

## 5.1 Creative distractions

The variety of virtual environments and the contribution of sound allowed our participants not only to feel 'there', but also to transform this 'there' into something interesting, that enhanced their musical practice. Most of our participants' behaviour and observations suggest that they achieved a state of flow while performing in *VR Rehearse & Perform.* Some reported experiencing distractions during the interaction with the system, but these distractions seemed to have fueled their subsequent experimentation. It is important to emphasise here that distractions should not necessarily be seen as a barrier to facilitating flow, as long as they open up a new creative output rather than halting performance. "Having your focus in a slightly different space" may stimulate broader associative thinking and creativity in music as shown in research on the benefits of multitasking. This suggests that focused attention may in fact be detrimental for a creative performance and phenomena that involves concurrent thoughts or emotions, such as mind wandering and interruptions might improve the performance on creative tasks [40, 41, 46]. Dreyfus and Dreyfus [31] actually emphasise the role that intuition plays in facilitating skilled performance. However, one must also keep in mind that mindless inattention to detail can suppress full control – one of the core characteristics of flow.

It is important to also note here that despite the clear rationale for assuming a clear correlation between flow and performance, results yielded by empirical research defy easy interpretation [51]. While a number a studies have found a positive relationship [22, 71] in the context of games, academic performance or sports, other suggest that the relationship performance-flow is weak or even nonexistent [29, 32]. Notably, Harris et al. [38] found in their systematic review that "current evidence is unable to determine the exact nature of the flow-performance relationship" despite identifying a "consistent medium-sized relationship between flow experience and task performance" across 22 studies. These variation in results might be supported by the work of [78] who showed that different types of tasks can elicit different types of flow. Further investigation is necessary to explore how flow relates to performance in the musical practice. Our observations present an opportunity for further study into how to engineer creative distractions in the context of audio-first immersive experiences, so that the resulted energy and increased cognitive flexibility 'spill over' into musical practice.

## 5.2 Music anywhere and everywhere

Musicians rarely get opportunities to rehearse in the spaces they later perform in and subsequently frequently struggle to feel adequately prepared for a performance. Additionally, every style and type of music often evolves in a particular acoustic ambience; therefore, each composition sounds best in the space with its intended acoustics [12]. With VR, any room can serve all the purposes and become a space that not only triggers a creative mindset but enriches the musical practice in ways that until now have not been possible.

Virtual and acoustic reconstructions of historical venues [39, 42] have been done in the past, but not in the context of musical practice. The results of our study indicate that such reconstructions could be utilised for designing musician-centred VR experiences aimed at supporting musical training and rehearsal. By providing access (both visually and acoustically) to simulated performing venues, VR opens up the possibility for musicians to incorporate performance halls' acoustics into their regular practice. Theoretically, this has always been possible by travelling to venues and playing music in spaces with different acoustic characteristics. Practically, however, this is impossible as performance venues are often inaccessible. Moreover, these spaces can be recreations of "sacred" venues, enabling musicians to experiment with the "finest halls in existence" [12]. During our study, we observed that the immersive concert hall environment – perceived as one of the "sacred" places to perform in – had a magical, transformational power on musicians, *mes-mersed them* and empowered them to explore new ideas.

Musician-centred VR experiences have the potential to benefit those who want to play in a virtual venue before taking the stage for the first time; those who want to know how their voices would sound in a particular space; and those who wish a virtual space to sing in or be inspired by. Furthermore, VR has the potential to benefit new musicians who are unfamiliar with stage dynamics or those unable to obtain enough practice time in a certain space. By having access to virtual replicas of locations, musicians could rehearse there and get a sense of the room's acoustics without being physically present. This can impact their familiarity with the venues by providing them with a psychologically safe space to practice in, which could help lessen emotions of musical performance anxiety when on stage. The VR environment can therefore assist by preparing the musicians for the stage, with the visual familiarity and sense of space imparted by the spatial audio reducing the sensations of strangeness, trepidation, or unfamiliarity associated with walking out onto a new stage for the first time, or after a long break (for example, due to the impact of COVID-19 on access to indoor spaces).

## 5.3 The quest for balancing accurate acoustics and lower latency

The average audio latency of *VR Rehearse & Perform* differed depending on the acoustic setting: 1) 20 ms for the the approximate, plausible acoustics emulating the sound of auditoriums of different sizes; 2) 40 ms for the accurate acoustics based on the RIR of the Amaryllis Fleming Concert Hall. This audio delay is similar to the early reflections [73] that can be experienced by musicians in large acoustic spaces such as churches, with the added long reverberation times [10]. Participants in our study found the latency of the plausible acoustics mostly unnoticeable and manageable. Opinions varied when it came to the perceived latency of the accurate acoustics settings: key-based instruments players were most affected by it, experiencing significant challenges while performing due to the tactile feedback their instrument require; string, percussion and voice instruments music-makers noticed the latency and used various coping mechanisms to deal with it – for example they: i) took off the noise-cancelling headphones and listened to the blended acoustics of the physical and virtual world which provided an illusion of reduced latency; ii) decreased the tempo of their performance; iii) started to sing louder to drown out the delayed sound. We note that the audio delay was unnoticeable for two participants who are used to playing music on online platforms and the afferent latency of this. These mixed perceptions are in line with findings reported in [8, 36, 74], where the amount of tolerable latency was shown to vary significantly for musicians, with values between 40 ms - 80 ms. The results of Greeff [36] indicate that the capacity to tolerate performance hindrances such as unwanted amounts of latency is not influenced by the formal training, but by the previous studio experience, the approach to performance, and the ability to put emotion into the musical act.

There are various possible solutions to address these variations in the perceived latency threshold for an optimal performance. One could consider replacing the accurate sound reproduction with its plausible version for example using the method suggested in [64]. This alternative is supported by VR studies that analysed the effect of visual cues on the plausibility of audio rendering and showed a dominance of vision over acoustic cues [6]. However, Remaggi et al. [55] signal a gap in the literature related to the thresholds for the evaluation of acoustics' plausibility in VR reproductions. It is therefore not clear how different sound reproductions are perceived in a multimodal medium like VR where the presence of visual stimuli might mask the perceptual differences between real and synthetic acoustic environments. Given the limitations introduced by the audio latency, it would be important to explore how musicians perceive this latency under sound reproductions of different levels of accuracy and the impact of each sound reproduction on their experience in VR. Another possibility is to allow musicians to spend more time in *VR Rehearse & Perform*, therefore enabling them to adjust to its latency. Detaching the aural part from Unity and implementing it in more advanced audio programming environments (e.g., PD/ Max/MSP, etc), can also reduce the latency problem but in the same time, affect the portability of the solution. Finally, as technology continues to advance, and more powerful processors are introduced in standalone headsets, the real-time processing of *authentic* audio will come with less and less latency.

## 5.4 Virtual environments as creative triggers

VR can not only teleport users to familiar spaces but also to inaccessible physical spaces, as well as new "magical" visual and sonic environments. In our study we observed that the three different spaces musicians were able to teleport in, induced different types of emotional responses. In the concert hall participants reported feelings similar to those they have when performing. In the orchard, participants felt 'enlightened and relaxed'. In the flat, they felt more at home, more comfortable therefore more experimental. These feelings influenced the types of music they chose to play, or the way they performed. This unique aspect afforded by VR enabled music-makers to access a variety of creative triggers, which enhanced their ability to infuse various emotions in their performance, to compose and improvise.

Each of these spaces became a different instrument musicians enthusiastically started to experiment with. Whether for performing known pieces or for prototyping new music inspired by the sounds of the places they were immersed in, all musicians appreciated positively the immediate access to the various sonic virtual worlds. Although, audio was initially deemed as more important than the visuals, once musicians started experimenting with the virtual environments in *VR Rehearse & Perform*, they remarked that the visual cues allowed them to experience and enter different mindsets. Music is multisensorial, therefore being 'there' had a significant appeal for music-makers because it stimulated various sensory areas. In choosing the audio elements to accompany the various environments, we observed that our participants chose congruent effects, that semantically matched the settings (i.e., the sound of the birds in the orchard; the noise of the crowd in the venue). An interesting direction for future research would be to explore if there are occasions where a break in semantically matching sounds and environments (for instance by providing visuals that adapt to sound based on crossmodal correspondences [79]) can provide new types of creative pathways for musical practice.

## 5.5 Designing with the instrument in mind

Existing studies in musical VR experiences are mostly focused on the virtual interactions which take place within the virtual world [2, 59], or passive experiences where the user sits backs and listens [62]. However, when designing VR for musicians, there is a need to consider how they interact both with the physical space their body is in and the virtual space their 'mind' is in. This interaction is evident in their relationship with the instrument, which is located in the physical space while they are in the virtual environment.

For musicians, their instrument is often an extension of their creativity and feeling connected to it might directly promote enjoyment, engagement and motivation when playing [63]. While conducting our study, we anticipated that one of the barriers musicians would face is the inability to see their instruments in VR. This was indeed the case for key-based musicians who were able to see their hands but not their instruments' keys, as well as some of the singers who felt a disconnection with the rest of their body and consequently a lack of embodiment within VR.

Surprisingly, for string-based and percussion musicians, although frustrating at first, this lack of visual cues appeared to also open up new ways of bonding with their instruments. However, the role visualisations play in relation to professional musicians remains unclear. Participants in our study reported that not seeing their instrument enabled them to explore using other senses, such as touch or hearing, enhancing their connection and instrument awareness – after all it is well known that professional musicians often do not look at their instrument while playing [1]. One could argue that this could also be achieved by playing blindfolded or by having the lights off. However, VR provides the unique possibility of still engaging with the visual senses, enabling the musician to focus more on the environment and the sound they are producing rather than the accuracy of their hand placement. Nevertheless, when designing musician-centred VR applications, developers should consider ways of including musicians' instruments as part of the experience. This would make such technologies accessible to a broader range of musicians.

Various methods could be used to achieve the incorporation of the instrument. For example, several 3D models could be produced representing the most common instruments and then mapped with the musician's real instrument using a tracking marker. A promising option would be to use the recently launched Oculus Passthrough API[8], which enables a blend of the virtual and physical world. Moreover, in the case of singers, looking at a mirror with a virtual avatar could potentially induce stronger feelings of body ownership and embodiment within the virtual environment, which has proven effective in other contexts such as virtual counselling [66].

[8]https://developer.oculus.com/blog/mixed-reality-with-passthrough/

### 5.6 Limitations

According to our findings, musician-centred VR experiences are a promising medium for supporting music-makers' practice, complementing traditional techniques. Yet, we also encountered seemingly-inevitable challenges of this technology.

*Latency.* Accurate complex acoustics, portability and low latency seemed incompatible in the current technological VR context. With *VR Rehearse & Perform* we aimed to empower all musicians – independent of their budget or tech savviness – therefore, we chose to design a portable, standalone solution requiring minimal setup that can be tested in a lab but also in-the-wild. While this affected the average latency perceived by musicians, we maintained its value below the threshold shown to disturb performances in real settings (40 ms) by tethering the headset in *Round 3*. Further investigation is needed to understand why this was perceived differently by musicians and to identify the optimal way to mitigate it.

*The absence of the instrument.* The inability to see their instruments while in VR proved to be a barrier for some musicians (especially key-based instruments players). This is a limitation we were aware of and will address in the future, however at this stage we wanted to explore what are the possibilities of VR without the complexity of object mapping and tracking.

*Music making as a social activity.* Although for many musicians, creativity practices have a strong social dimension, *VR Rehearse & Perform* is only addressed to solo music-makers. Indeed, one of the challenges mentioned by musicians in our study was related to maintaining social connections within their creative community. However, in this study we chose not to focus on this social aspect due to the complexity of prototyping and evaluating multiplayer VR experiences with real-time audio playback.

*Participation due to COVID-19.* Finally, several practical restrictions emerged as a result of the study taking place during the ongoing COVID-19 pandemic. A consequence was a lower and less diverse number of participants than we initially planned for.

## 6 CONCLUSION

This paper describes a musician-centred study investigating how VR can support musicians in their creative musical practice. To answer this, we followed an iterative design process and we developed *VR Rehearse & Perform*, an original VR system, based on design requirements gathered from musicians and performance experts. Our results indicate that VR –not without its limitations – can be leveraged to support musicians in their practice for rehearsing, performance preparation, improvisation, composition and indirectly managing performance anxiety. Our observations contribute to a broader, more generalised discussion of how to design technology for creative practices (e.g., performing arts, theatrical experience).

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