Exploring the Impact of Spatial Awareness on Large-Scale AR DMIs

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Figure 1: Two sound components of drastically different scales are displayed in an AR environment.

Abstract

Large-scale Digital Musical Instruments (DMIs) offer immersive performance experiences and rich forms of expression, but often pose physical challenges and limit accessibility. The size of traditional large-scale DMIs limits the ability of performers to interact with the instrument, causing discomfort when engaging with distant components, highlighting the need for more flexible and user-friendly large-scale DMI designs. We present an Augmented Reality (AR) DMI that removes physical constraints by allowing performers to customise the size and layout of the instrument according to their performance environment. We aim to show how AR-based configuration supports immersive performance, promotes expressive gestures, and improves spatial awareness without sacrificing large-scale instrument capabilities. Our user study revealed increased physical engagement and spatial immersion, a strong sense of ownership, and a positive user experience. These findings indicate that our AR DMI is creatively empowering, reasonably addressing the constraints of large-scale instruments. Our research emphasises the potential of AR to enable flexible and customisable DMI design where interfaces can be adapted to suit the needs of individual performers.

Keywords

Human-centred computing, Mixed/augmented reality, Sound and music computing

1 Introduction

Digital Musical Instruments (DMIs) have revolutionised music technology, transitioning from traditional instruments to advanced digital systems for sound creation and performance. As a multidisciplinary field intersecting Human-Computer Interaction (HCI) and Sound and Music Computing, DMIs have grown significantly in variety and sophistication over the past four decades [11]. Meanwhile, Augmented Reality (AR) has emerged as a key technology within the Virtual-Reality Continuum [20], supported by the rapid evolution of AR hardware. The convergence of advancements in DMI and AR underscores the potential for developing innovative AR-based DMIs that transform musical interaction and performance.

The design of DMIs can be categorised into three scale-based levels: macro, meso, and micro [1], with size playing a crucial role in performers' expressiveness and the immersive experience during performance. Understanding the relationship between physical scale, gestural affordances, and expressiveness is fundamental to effective DMI design. However, implementing large-scale DMIs presents challenges: their size requires substantial physical effort, potentially causing discomfort; they impose spatial and performance limitations [17]; and their lack of portability restricts usage in diverse settings, limiting creative opportunities.

Our research focuses on three distinct yet interconnected aspects of performer-centred interaction with DMIs in AR environments. The performer, as the sole stakeholder in this study,

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engages with the DMI to create music. We explore how AR-specific interactions influence the perception of scale, spatial awareness, and overall performance experience.

First, we investigate how the scale of a DMI is defined and perceived within AR environments. Individual differences, such as height and arm span, can significantly affect how performers perceive the scale of a DMI, and these perceptual differences are even more noticeable in large-scale DMIs. Especially within AR DMIs, virtual components overlaying the real world alter performers' spatial perception, further amplifying these differences. Unlike physical instruments, the sense of scale in AR DMIs is less direct, as AR enables unique interaction methods—such as gaze control or air tap—that are otherwise impossible in the physical world. These innovative interactions offer new ways to bridge the physical and virtual worlds, offering more adaptable and immersive DMI experiences for performers with diverse physical characteristics. By designing an AR DMI that adapts to each performer's spatial perspective, our study aims to better understand and define the perceptual impact of scale on human-instrument interaction within AR environments.

Second, we explore the role of spatial awareness in DMI mobility and accessibility in AR environments. Spatial awareness is crucial for performers to navigate and interact effectively with DMIs. Enhanced spatial awareness improves mobility and facilitates access to different DMI components within AR. However, existing AR DMIs often lack intuitive interactions that account for spatial orientation, limiting usability. This study examines how performers' spatial awareness influences their movements and interactions with AR DMIs, ultimately enhancing both mobility and accessibility—which are essential for creating intuitive and effective AR musical interfaces.

Finally, we analyse how spatial awareness influences performers' performance and learning curve when using large-scale DMIs in AR. As DMIs scale up, performers rely increasingly on spatial awareness to maintain efficiency and expressiveness. Large-scale DMIs, which require expansive gestures and spatial exploration, can lead to physical strain, gradually limiting engagement. This study leverages AR-specific interaction techniques to design a DMI that enhances spatial engagement and examines how these features impact the learning curve and performance. By fully utilising AR's spatial affordances, our design aims to minimise spatial constraints, reduce operational difficulty, and provide a seamless interactive experience.

The primary aim of our research is to develop a large-scale AR DMI that enhances usability and overcomes the physical constraints of traditional large-scale instruments. By focusing on performers' interactions within AR environments, our study seeks to provide a highly accessible, immersive, and adaptive musical experience tailored to individual physical characteristics.

Our research pursues three objectives:

- **Design an innovative AR DMI** that allows performers to customise and arrange virtual instrument components within their physical space, promoting deeper spatial engagement and a more intuitive understanding of the instrument's functionalities.
- **Introduce advanced interaction methods**, such as gaze-based control and dynamic virtual components, to overcome spatial limitations and offer new possibilities for interaction, enhancing the performer's creative expressiveness.
- **Examine the role of spatial awareness** in performers' mobility, accessibility, and performance, as well as its impact on the learning curve when engaging with large-scale AR DMIs.

Figure 2: A screenshot illustrating the usage scenario of the large-scale AR DMI designed and developed in this research.

The significance of our research lies in its potential to transform the way performers interact with large-scale DMIs by integrating the immersive qualities of AR with innovative interaction techniques. By addressing challenges such as physical discomfort, accessibility issues, and spatial limitations, the study offers a novel approach that combines the physical expressiveness of large-scale instruments with the flexibility of AR.

2 Background

The scale of DMIs plays a crucial role in shaping performer expressiveness and enhancing engagement during performance. Larger DMIs encourage expansive gestures [3, 17], which may contribute to a more immersive experience for the audience, potentially reducing their perception of performance errors and leading performers to a deeper understanding of their own instrumental gestures. For example, the MOAI [3] study compared two DMIs of different sizes and found that the physical design of the DMI (including its size) influenced the performer's gesture repertoire, which in turn affected audience perception. This led to higher ratings for the large-size version from the audience, although this could also be attributed to the perceived effects and novelty of the larger DMI.

Large-scale DMIs also provide performers with a strong sense of immersion, allowing them to feel as if they are one with the instrument during performance. For instance, in a study by Mice and McPherson [16, 17], the authors introduced a large-scale DMI that was 2 metres in height and width. They found that the size of the DMI significantly influenced both the performers' performances and their self-perceptions. This large-scale DMI allowed performers to employ expansive gestures, creating a deeper connection with the instrument and enhancing the overall performance experience. However, their study also revealed discomfort issues that arise from prolonged use of large-scale DMIs and that performers tended to play the tones that were closer to them. This finding highlights the spatial fragmentation problem that can arise with large-scale DMIs, requiring more physical effort and potentially limiting performers. Furthermore, large-scale DMIs also pose challenges in terms of construction and deployment costs, as well as portability.

A promising direction for rethinking larger DMIs involves leveraging virtual technologies to overcome spatial and ergonomic constraints. Several existing works have explored XR technologies in DMI design, as highlighted by broader surveys on musical XR systems [28]. Examples include VR-based systems such as Coretet [13], immersive virtual musical instruments (IVMIs) [2], and studies on control-display ratios in virtual DMIs [25], which demonstrate how virtual environments can reshape performer interaction and audience experience. Building on these ideas, AR DMIs leverage similar principles while offering the added benefit of blending virtual elements directly into real-world spaces. In this context, two core design elements—mobility and space—have been identified as central to AR DMI development, supporting flexible interaction and reducing physical strain [32]. Mobility refers to the way performers interact with the DMI allowing performers to express themselves easily with fewer constraints and less physical strain. Intuitive and comfortable body movements can enhance the performer's experience and improve their capabilities. By optimising mobility, AR DMIs can reduce discomfort caused by excessive physical movement, thus avoiding the fatigue issues often associated with large-scale DMIs.

While mobility focuses on the performer's interaction with the instrument, space addresses the design of the virtual interface and its impact on engagement and immersion. Wang and Martin [31] explored three distinct AR DMI layouts and concluded that AR DMI design should not simply replicate traditional DMI layouts. Instead, it should fully leverage the flexibility and adaptability of virtual components in AR space. This allows for dynamic configurations and interactions tailored to the performer's preferences, unlocking the AR environment's unique potential for customisation and intuitive control.

However, AR DMIs also face challenges, particularly in controlling input precision and the lack of physical feedback. Unlike physical interfaces, AR components are intangible, making it harder for performers to achieve precise control [31]. To address this, Deacon and Barthet proposed using strong visual feedback, transforming abstract audio into visible trajectories [7]. This approach helps users intuitively track their progress and make finer adjustments, highlighting the importance of feedback mechanisms as a key research focus in this field. Building on these challenges, spatial awareness—an individual's ability to perceive and interact with their surroundings—is crucial in AR DMI design [14]. Enhancing spatial awareness reduces unintended interactions and improves usability. Similarly, Entanglement HCI emphasises the deep connection between performers and technology [12], framing AR DMIs as extensions of the performer's body. These perspectives highlight the transformative potential of AR DMIs while emphasising the importance of balancing technological innovation with human-centred design.

3 System Design

The testing environment for our research is the Microsoft HoloLens 2, an AR headset known for its advanced mixed-reality capabilities [18]. The AR DMI was developed using the Unity Game Engine [30], incorporating the third-generation Microsoft Mixed Reality Toolkit (MRTK3) [19] for spatial interaction and interface design. Sound generation was achieved through LibPd Unity Integration [6, 24], enabling real-time audio synthesis with Pure Data patches [21] within the Unity environment.

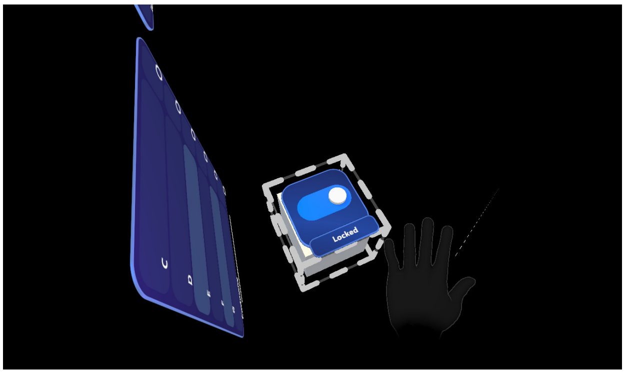

Figure 3: A screenshot of testing the AR DMI in the Emulation Environment.

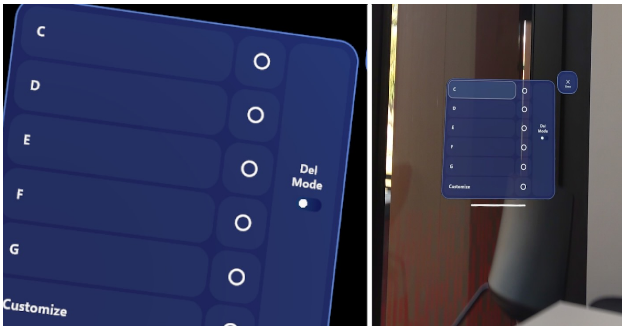

Figure 4: A screenshot of using AR DMI by streaming mode. Left: view on the computer screen. Right: view as seen by the performer through the HoloLens 2 AR headset

3.1 System Design Stages

In our research, the design and development of the large-scale AR DMI were divided into three stages. The first stage focused on designing and testing low-fidelity prototypes [27] of the DMI using Unity's XR Holographic Emulation environment, as shown in Figure 3. This setup enabled the rapid development and iteration of DMI prototypes. In this environment, we validated feasibility, and established features of the AR DMI such as the key concept of the 'setup phase'.

The second stage focused on developing a high-fidelity prototype by streaming the system to an AR headset for intermediate-level testing, as shown in Figure 4. This phase primarily aimed to test the unique features of the AR DMI in AR environments, such as Air Tap and Gaze Control. The Double Diamond framework [8] was employed during this stage, with two iterations conducted, each guided by user stories [10] (shown in Figure 10) to clarify design goals and optimise user interaction experiences. During testing, we evaluated the system's usability, gesture accuracy, and the integration of advanced interaction modes, such as Follow Mode and Gaze Mode. Feedback played a crucial role in optimising the design (e.g., the layout of the menu interface) and interactions (e.g., drag-and-activate gestures).

The final stage involved deploying the system as a fully functional AR application and testing it on AR headsets. This stage focused on ensuring the AR DMI operated reliably on AR headsets. The design process was autobiographical [9], where the designer actively engages with the system as the primary user to gain firsthand insights into its functionality and user experience [23].

Figure 5: A screenshot of the menu interface of the DMI. The red and green boxes were added in post-processing.

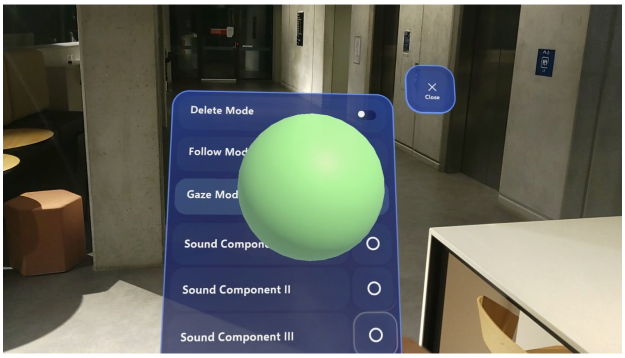

Figure 6: A screenshot of creating a Sound Component by clicking the button on the menu interface.

The first author served both as the designer and performer, facilitating immediate identification of design flaws, such as issues with the lock switch mechanism and gesture recognition, while also uncovering new requirements through reflective use.

3.2 Large-scale AR DMI

The design vision for this large-scale AR DMI is to allow performers to first customise the DMI interface according to their preferences and surroundings. Then, as they move freely within the space, they can interact with the DMI to create music. This approach aimed to enhance the performer's spatial awareness and interactive experience and create an immersive musical environment. To achieve these goals, we implemented the following design features:

3.2.1 Setup Phase and Performance Phase. This DMI is designed to go through two phases during use: the setup phase and the performance phase, emphasising how it differs from traditional AR DMIs by introducing a customisable interface. Unlike AR DMIs with pre-designed interfaces, this DMI allows performers to freely create and position interface components, enabling the instrument to be tailored to the environment in which it is used.

The menu interface serves as the primary tool for creating Sound Components (SCs). SCs are similar to synthesiser keys, producing sound upon activation, but uniquely, their sound can be controlled not only by hand but also through gaze. As shown in Figure 5, the menu interface consists of two sections: the upper red section is used to adjust the SC, while the lower green section is used to create the SC. In the lower section, clicking on an SC name allows performers to preview its sound. If satisfied, they can create an SC by clicking the corresponding button on the right, as demonstrated in Figure 6.

In the setup phase performers use the menu interface to place SCs in the performance space, designing a layout that suits their playing needs. A performer might choose to cluster the SCs around themselves or spread them throughout the room or the performance venue, making the entire space a part of their instrument. Once the layout is finalised, performers can transition to the performance phase, where they interact with the placed SCs to create music.

3.2.2 Sound Component Manipulation and Mode. During the setup phase, performers can use hand gestures to adjust the size, rotation, and position of SCs, enabling them to design a layout as shown in Figure 7. For example, frequently used SCs can be enlarged for easier access, or an SC can be placed on a table within

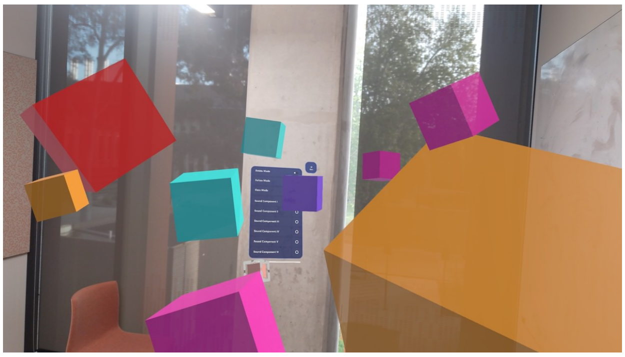

Figure 7: A screenshot of Sound Components of varying sizes created by the DMI.

the environment to enhance intuitive operation. Performers can enter a delete mode to remove any SCs they no longer need.

In the default SC mode, SCs are represented as cubes, and they produce sound when activated by touch. Activated SCs continuously loop a single note, reducing the need for frequent interactions during extended performances and minimising physical fatigue. The system offers two additional SC modes: Follow Mode and Gaze Mode. In Follow Mode, SCs are shaped like discs and are triggered by touch, similar to the default mode. However, SCs in this mode follow the performer's movements, always remaining directly in front of their field of view. In Gaze Mode, SCs take the form of spheres and are activated by the performer's gaze. This feature enables control of any SC in the space, regardless of its distance. By eliminating biases toward conveniently placed SCs, Gaze Mode promotes balanced interaction across all components.

3.2.3 Sound Aspect. The DMI offers six predefined sound frequency levels for performers to choose from when creating a SC. Each SC automatically generates a note within the selected frequency range, with its length and loop duration randomised. This design ensures sound diversity while reducing the performer's focus on sound customisation, allowing greater attention to the spatial arrangement of the DMI. Additionally, vibrato and echo effects adds depth and spatial presence. The volume of each SC dynamically adjusts based on its size and distance from the performer, as described in Equation (1).

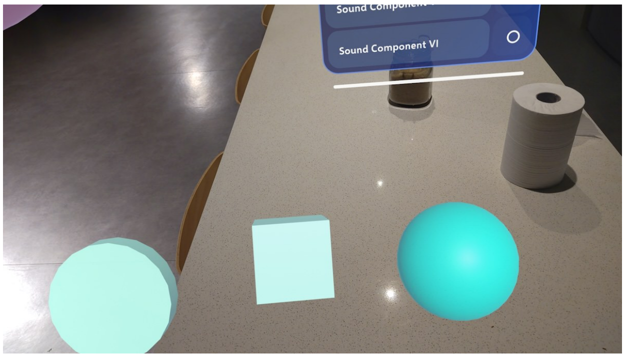

Figure 8: A screenshot shows the shapes of the Sound Component in three different modes. From left to right: Follow mode, Default mode, and Gaze mode.

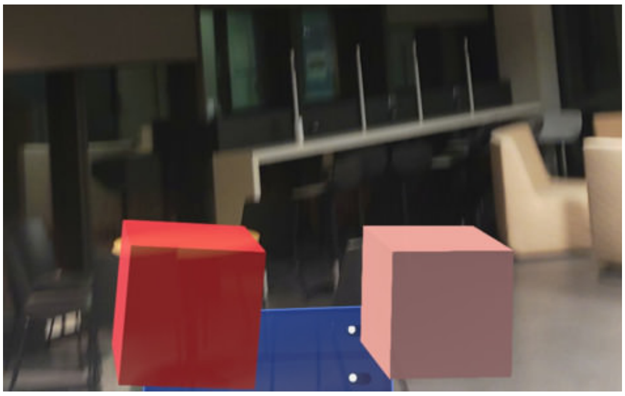

Figure 9: A screenshot of two Sound Components of the same size. The left one is activated, while the right one is not.

$$V(d,s) = V_{\min} + (V_{\max} - V_{\min}) \cdot \Bigg[\tag{1}$$

$$0.6 \cdot \left(\frac{d_{\max} - d}{d_{\max} - d_{\min}} \right)^2 + \tag{2}$$

$$0.4 \cdot \frac{s - s_{\min}}{s_{\max} - s_{\min}} \Bigg] \tag{3}$$

3.2.4 Sound Component Visual Feedback. Each frequency level of the SC is assigned a distinct colour to help identify SCs during interaction. Additionally, as shown in Figure 9, activated SCs feature deeper textures and exhibit a pulse-like scaling effect, with their size periodically expanding and contracting. The effect is particularly pronounced in larger SCs, where scaling creates a vivid contrast.

4 Evaluation

We performed a user test to assess the AR DMI's usability, engagement, and spatial interaction. Eight participants were recruited based on their interest in AR or DMIs, a number that, while small, aligns with norms in HCI [5]. All participants were over 18 but further demographic information was not collected. Participants first received an introduction to the AR DMI and HoloLens 2. Next, they customised the DMI interface by arranging SCs. They

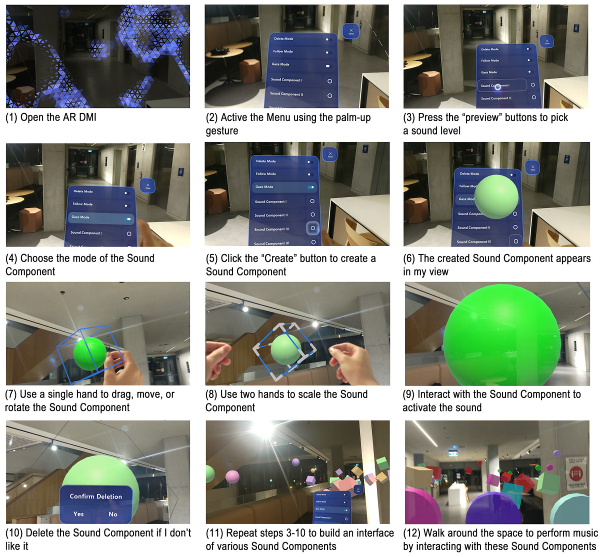

Figure 10: A visual user story illustrating the basic workflow of the AR DMI developed in our research.

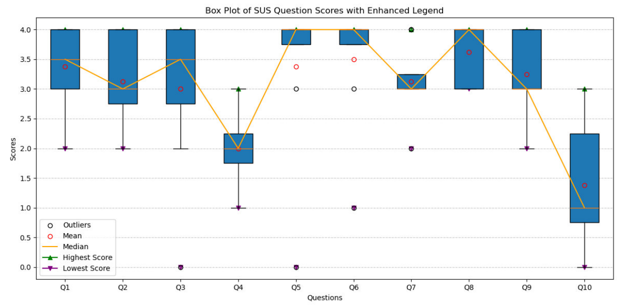

Figure 11: Distribution of individual SUS responses. The standard SUS questionnaire was used [4]

then explored the system's functionalities while using it to create music. Qualitative feedback was then collected through a semi-structured interview [29]. Finally, participants completed the standard version of the System Usability Scale (SUS) questionnaire [4] to evaluate the system's usability.

4.1 Quantitative Evaluation

Quantitative analysis was performed on the 8 SUS questionnaires collected during the experiments[1]. The SUS scores were calculated using the standard scoring method [4] to obtain a score out of 100. The average SUS score for the 8 participants was 74.7. According to the SUS benchmarks for SUS scores [26], this score falls within the "good" range. This suggests that the DMI's usability was generally well-received by the participants.

[1]The standard SUS questionnaire [4] uses 5-point agreement scales on the following statements: 1) I think that I would like to use this system frequently, 2) I found the system unnecessarily complex, 3) I thought the system was easy to use, 4) I think that I would need the support of a technical person to be able to use this system, 5) I found the various functions in this system were well integrated, 6) I thought there was too much inconsistency in this system, 7) I would imagine that most people would learn to use this system very quickly, 8) I found the system very cumbersome to use, 9) I felt very confident using the system, 10) I needed to learn a lot of things before I could get going with this system.

Figure 11 shows the distribution for each SUS question. The median scores show some well-received aspects of our system: Q4 (users would not need technical support) and Q5 (the system was well integrated). Less positive aspects were: Q6 (too much inconsistency), and Q8 (cumbersome to use). While the median of Q10 (I needed to learn a lot of things) was low, it had a wide interquartile range and whiskers, signifying diverse perceptions of how much learning was required for our system. Some participants gave a score of "strongly disagree" for Q3 (easy to use) and Q5 (well integrated) highlighting individual issues some users encountered.

4.2 Qualitative Evaluation

Each semi-structured interview conducted during the experiments was audio-recorded with participants' informed consent and subject to a process of Thematic Analysis [15].

To identify and refine themes, we used Miro Board [22] to facilitate data visualisation and adopted the Affinity Diagramming method [27]. Affinity Diagramming is a simple yet effective technique for processing qualitative data, breaking it into smaller parts and organising it into coherent themes. Through this process, we generated 292 initial codes, refined them into 76 distinct codes, grouped them into 23 sub-themes, and ultimately identified 4 final themes which we discuss below.

4.2.1 Final Theme 1: Physical Engagement and Spatial Immersion in AR DMI. The AR DMI enhances spatial immersion by encouraging performers' physical engagement and movements, fostering a deep connection with the instrument. Freely navigating and manipulating components improved spatial awareness and created an engaging experience. Strategic placement and organisation of virtual instrument components are crucial for facilitating intuitive interaction and control. As *P1* expressed, "…when I move the layout, it depends all on my fingers, and I can use fingers to move it smoothly…" Proper spatial arrangement enables performers to access and manipulate elements effortlessly, making the performance more seamless and natural. As *P7* stated, "…everything is under control, like I've got it all managed with my gaze, not even needing to use my hands."

Dynamic sound feedback and engaging visual animations further enhance this immersion, as they respond to the performers' movements and gestures, reinforcing the connection between physical actions and virtual responses. As *P4* commented, "…the whole experience feels more dynamic… almost like I'm shaping a living, breathing space."

4.2.2 Final Theme 2: Empowerment through Flexibility, Personalization, and Creative Exploration. The AR DMI empowers performers with flexibility and opportunities for personalisation, fostering an environment conducive to creative exploration. Performers can customise the layout and arrangement of virtual instrument components within their physical space, designing interfaces tailored to their preferences and artistic visions. This freedom cultivates a strong sense of ownership, enabling performers to shape instruments to meet their creative needs.

By breaking away from traditional norms, the AR DMI encourages exploration of new musical possibilities and innovative interaction methods. The ability to manipulate and experiment with SCs in a virtual environment inspires performers to push the boundaries of conventional music-making, leading to unique and personalised artistic expressions.

This combination of flexibility and creative freedom transforms the performer's experience, making it more engaging and fulfilling. More than an instrument, the AR DMI acts as a collaborative partner in the creative process, adapting to evolving ideas and inspirations. By empowering performers to explore their creativity, it enhances the musical experience and enables the production of highly expressive and individualised performances.

According to Figure 11, the data further supports this perspective. Questions Q3 and Q5 received higher median scores, with medians of 4 and 3.5, respectively. These results suggest that participants found the system's flexibility and customisation features to be well-implemented, reinforcing the transformative impact of AR DMI on the creative process.

4.2.3 Final Theme 3: Innovative Interactions Enhancing Usability and Emotional Connection. The AR DMI introduces innovative interaction methods, such as gaze control, component auto-follow, and hand-based gestures, which enhance usability and foster a deeper emotional connection between the performer and the instrument, as *P7* stated, "…it makes me feel like I'm communicating with the instrument rather than just playing it." By simplifying virtual component control and providing multiple interaction options, the AR DMI caters to diverse user preferences, enhancing both accessibility and flexibility. Gaze interaction, in particular, creates a sense of immersive communication, allowing performers to naturally control the instrument. The engaging visual feedback and component identification further strengthen this connection, as *P5* remarked, "…they sort of jump around… they will come to life and something… full of energy.

4.2.4 Final Theme 4: Positive User Experience through Engaging Design and Ease of Use. The AR DMI delivers a positive user experience with engaging visuals and intuitive design, enhancing satisfaction and usability. Its straightforward interface minimises the learning curve, allowing performers to focus on creativity. Features like customisable interfaces, Follow Mode, and Gaze Mode simplify interactions and accommodate diverse user preferences, as *P3* noted: "…it's like the distance between me and the components doesn't really matter anymore. I can easily control any component, no matter where it is." Dynamic visual feedback and animations strengthen the connection between performers' actions and system responses, fostering immersion. This combination of aesthetic and functional design ensures an enjoyable experience, as reflected in the high median score of 3.5 for Q3 in Figure 11.

4.3 Connecting to the Research Questions

Final Theme 1 and 2 demonstrate that performers define and perceive the scale of the AR DMI through physical engagement, such as walking and interacting with SCs, and spatial immersion, like entering SCs larger than themselves. The freedom to arrange and navigate components further personalises the experience, highlighting the flexible perception of scale in AR environments. Final Theme 2 and 3 demonstrate that performers' control over the scale and position of SCs enhances mobility, allowing free exploration or confined operation based on layout preferences. Innovative interactions, like gaze control and auto-follow mode, improve accessibility, enabling performers to navigate and control the AR DMI intuitively, regardless of spatial constraints. Final Themes 1, 2, and 4 illustrate that enhanced spatial awareness, coupled with intuitive design and customisation options, improves performance quality and reduces the learning curve.

By enabling performers to design their own layout and offering multiple interaction methods, the AR DMI fosters seamless learning and efficient interaction, supporting fluid and expressive AR performances.

5 Conclusion

The four final themes derived from the user testing of the AR DMI highlight how it redefines performers' interactions with large-scale DMIs by blending the physical expressiveness of traditional instruments with the adaptability and flexibility of AR technology. By addressing challenges such as physical discomfort, accessibility issues, and spatial constraints, the study demonstrates the potential of immersive AR features, innovative interaction techniques, and user-centred design to enhance the performer experience and expand possibilities for creative musical expression. This integration not only achieves the research objectives but also highlights the potential of AR DMI to contribute to the evolution of digital musical interfaces and inspire further exploration in music technology and human-computer interaction.

During the quantitative and qualitative analysis, we identified several limitations of the AR DMI and proposed future improvements. Control sensitivity issues, particularly in Gaze Mode, resulted in unintended activations that disrupted performance flow. Setup challenges, such as time-consuming customisation and difficulty with AR gestures, hindered creativity. Follow Mode occasionally obstructed performers' views, reducing usability, while insufficient identification of Sound Components caused confusion during performances. Additionally, physical discomfort from repetitive gestures and the weight of the AR headset impacted usability.

6 Ethical Standards

This study was approved by the Australian National University Human Research Ethics Committee (Protocol H/2024/0979). Participants provided informed consent, and their participation was voluntary. There are no observed conflicts of interest in this study.

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