Mobility, Space and Sound Activate Expressive Musical Experience in Augmented Reality

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ABSTRACT

We present a study of a freehand musical system to investigate musicians' experiences related to performance in augmented reality (AR). Head-mounted mixed reality computers present opportunities for natural gestural control in three dimensions, particularly when using hand-tracking in a creative interface. Existing musical interfaces with head-mounted displays use dedicated input devices that are not designed specifically for musical gestures and may not support appropriate interactions. We are yet to see widespread adoption of head-mounted AR musical instruments. We conducted an empirical study to evaluate musicians' ($N = 20$) experience of performing with a freehand musical interface. The results suggest that the design of freehand musical interaction in the AR space is highly learnable and explorable, and that such systems can leverage unique aspects of mobility, space and sound to deliver an engaging and playful musical experience. The mobile musical experience with a spatial interface design allowed performers to be more bodily engaged and facilitated gestural exploration for musical creativity. This work contributes to a more developed understanding of potentials and challenges in AR-based interface design for musical creativity.

CCS Concepts

•**Human-centered computing** → **Mixed / augmented reality;**
•**Applied computing** → **Sound and music computing;**

1. INTRODUCTION

Research into new musical interfaces has often been driven by new types of computers that enable novel musical gestures and experiences [16]. For instance, mobile computers with touchscreens have been widely explored [37, 20] with a proliferation of musical applications. In contrast, head-mounted computers such as Microsoft's HoloLens or Meta's Quest have yet to see a musical "killer app" and the dimensions of an authentic musical system for these types of computers are still relatively unknown. Existing mixed reality musical instruments use input devices that are not designed for musical gestures and may not support appropriate interactions [2]. However, current headset-based AR and VR computers support freehand interaction without controllers, which could support a more natural user experience [11] and expressive sonic practices [5]. Therefore, it is worth exploring whether a freehand 3D interaction design could provide more flexibility to musicians and enhance their musical expression in AR.

Figure 1: A musician applying freehand gestures to perform with an augmented reality musical instrument. Our study aims to understand musical experiences that are possible with this type of interface.

In this paper, we study musicians' experiences using an AR musical instrument with freehand interaction. We presented musicians with a simple musical interface representing a cylindrical keyboard on a Microsoft HoloLens 2. Sounds in this interface could be triggered by touching one or more cubic keys. Study participants evaluated the system through musical tasks and a short improvisation. The study was designed to consider both HCI-style evaluation [25, 8, 41] and artistic qualities [33].

Our findings show three key axes where freehand AR musical interaction supports a playful and engaging musical experience: mobility, space, and sound. A reflexive thematic analysis on the interview data revealed that musicians' obtained a mobile experience and the 3D arrangement of the interface allowed flexible and explorative musical gestures. The survey responses suggested that freehand interaction was learnable and explorable. These findings suggest that

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AR spatial design naturally activates musicians' bodies and hands, and the layering of digital and real spaces enables unique bodily interactions. When using such systems, performers may be inspired or limited by their previous musical experiences; however, musical expression can be frustrated by inaccurate hand-tracking. Our results contribute a more developed understanding of how musicians experience free-hand AR musical expression and provide insights into the design of expressive 3D musical interfaces.

2. RELATED WORK

2.1 Mixed Reality Musical Instrument

Mixed reality NIMEs have been developed for musical performance or sonic installations. These interfaces can be categorised as either AR or VR musical instruments [39] for difference musical experience.

Recent VR musical instruments (VRMIs) mostly were designed with hand-held controllers and headsets to enable a fully-immersed and embodied musical experience [1, 31, 12], such as *ChromaChord* [7] and *Carillon* [13]. These differ from earlier works that often used screen-based displays with a physical keyboard or track mouse discussed in the field overview [34]. The need for complexity, freedom and virtuosity to support expert gestures in VRMIs have often been discussed (e.g., [2, 13]), even though controllers can demonstrate a level of musical control including selection, manipulation and navigation.

In AR, most musical expressions are screen-based, using mobile phones and tablets [39], or experience-focused through users' engagement with virtual visuals without specific interfaces [38, 3, 32, 9]. Rather than using controllers to mediate interactions, these works explored designs for more direct control of musical elements such as freehand supported AR musical systems [39, 3] for natural gestural musical experiences. Additionally, a framework for mixed reality musical instrument design was recently proposed by Zellerbach et al. [42], who argued a focus on embodiment and the "magicality" of interactions design for a more expressive musical experience inspired by VR and AR NIMEs.

In terms of mixed reality musical instrument evaluation, existing studies tend to focus on technical aspects such as usability, immersion and audio in a specific VR context [43, 21]. There have not been propsoed methods for assessing the musical quality of mixed reality instruments specifically in active usage. In our work, we have adapted methods for measuring usability [25] and instrument quality [33] with the aim of understanding musicians' musical experiences of using a novel gestural musical interface.

2.2 Musical Gestures and HCI

Musical gestures are studied in different disciplines with different objectives, such as sound generation [10], music-making [19] and new musical interface and expression design [16]. HCI studies of musical gestures focus on musical interaction design [14, 16], which mediates between the user and the sound control in computer music systems. Wanderley [36] presented a model of digital musical instrument (DMI) for sound control design in interactive computer systems including three main components: the design of input gestures, sound production and feedback. This contrasts with acoustic instruments which are built upon materials, vibrations and physical environments. For example, touch-screen gestures, computer-based mouse navigation, VR mediated and embodied interaction designs presented new forms of musical interaction which not only provide musicians new options in music-making [15] but also enable bodily interaction for fluid and expressive musical experiences [17].

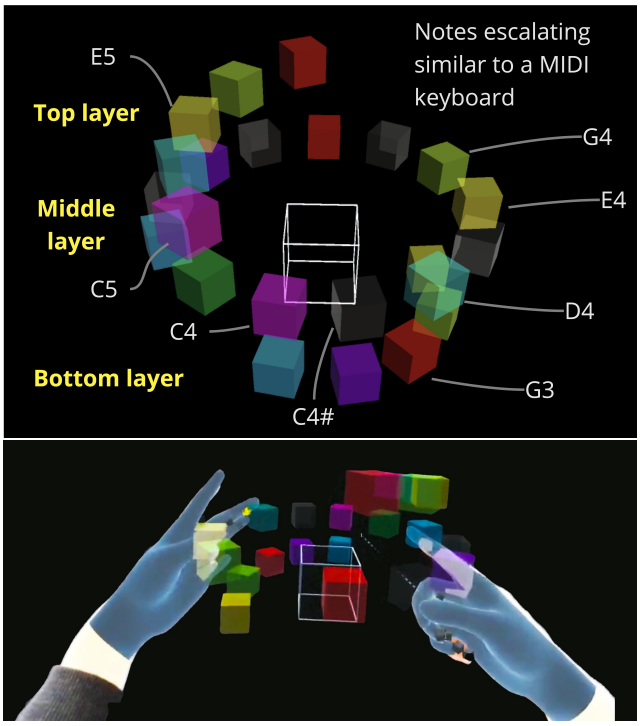

Figure 2: Top: the AR musical interface consists of three layers of coloured cubes and a cubic controller in the centre; touching each cube with a finger activates the corresponding tone. Bottom: an in-app view of the system in use.

In the context of our work, a review summarised various 3D musical interaction techniques used for musical expression in the mixed reality [2]. Although existing techniques (e.g., selection, manipulation and navigation) have shown to provide rewarding musical control experiences, there are still issues such as the lack of natural [11] and appropriate musical interactions [26]. Aspects of expressiveness and virtuosity [5], which encapsulate sophisticated sound control and supports performers' musical expression, have always been key considerations in designing new musical interfaces [23]. This suggests that more studies should be performed to explore design such as gesture-based [13, 11] designs that support flexible and expressive musical performances.

3. MUSICIAN-CENTRED STUDY DESIGN

Our study aim was to explore the potential of freehand musical control in head-mounted AR. We were interested in musicians' performance experiences and the novel aspects that an AR system provides for NIME design. Our study used an AR musical interface developed by Wang and Martin [39], available on GitHub[1]. This system was chosen due to its focus on free-hand gestures with a head-mounted AR system. Users can perform natural hand gestures to play notes and manipulate options in 3D space (see Figure 2). In our study, this interface was deployed on Microsoft's HoloLens 2 (HL2) [22] headset.

3.1 Participants

[1]https://github.com/YichenWangs/cubing-sound-release

Participants with musical instrument experience were recruited from a university music and computing community. 20 participants, 10 female and 10 male were selected. 18 participants were 18–24 years and 2 participants were 25–34 years. Two participants were AR/VR researchers, one had participated in a VR user study. No participants had significant musical experiences using HL2.

3.2 Procedure

The study involved individual 60-minute sessions at a media lab appropriate for AR experiments. Participants' in-app views and audio were recorded. In each session, the participant first completed a 10-minute induction and then performed a series of musical tasks with the AR instrument following instruction.There were four musical tasks with escalating difficulty to assess the overall usability and playability of the interace. Following the tasks, participants filled out a questionnaire of twenty 9-point Likert-scale questions to evaluate their musical experience using the AR instrument. The questions[2] were grouped into four sections adapted from previous studies [33]: feature controllability and usability, learnability, explorability and enjoyment. After the survey, participants completed a semi-structured interview regarding their overall experience.

4. RESULTS

4.1 Survey

The survey data were coded to numeric values between 1 (strongly disagree) and 9 (strongly agree) following a non-parametric approach for data analysis [18]. Given the within-group study nature, a statistical analysis was performed using Pandas and NumPy libraries. Descriptive statistics were calculated on participants' responses to each question and their aggregated responses to each group of questions.

The aggregated responses to the learnability and explorability questions had the same median value 8. Responses to the enjoyment questions had a median of 6.5, and the median for feature controllability and usability questions was 6. For the *feature controllability and usability* group, questions related to the precision and control of the hand interaction (Q2 & Q4) perhaps pulled the aggregated score down, indicating limitations in the current AR system. In *enjoyment*, questions related to sound satisfaction and quality (Q17 & Q18) showed high variation with the lowest response of 1 and highest of 9 (median: 6 & 5; std 2.211 & 2.188). For *explorability*, Q13 also had high variation with a median value 6 and std of 2.012. This shows that participants had different perceptions on the variety of playing offered by the AR system. Notably, Q9 had the smallest interquartile range (1), showing that participants tended agree that this AR musical interface allowed them to learn new things (median 7).

4.2 Thematic Analysis

Approximately four hours of post-questionnaire interview recordings were made, each interview was 6–25 minutes in length. These recordings were transcribed and corrected using NVivo Transcription [29], and coded using a reflexive thematic analysis (TA) method [35] in NVivo [28]. This reflexive approach prompted a prototyping and promotion step in which initial codes were clarified and organised to central themes to form our findings.

[2]https://yichenwangs.github.io/cube-sound-user-study

Overall, the interviews revealed that this freehand AR music system presented a playful musical experience that can activate a deep bodily engagement. Specifically, we identified three key themes which contributed to this playful experience (see Figure 3) discussed as follow.

4.2.1 *Novel Mobile Musical Experience*

Participants reported that they had a new musical experience with this AR musical instrument which they enjoyed a lot. *P10* pointed out how professional this musical instrument was in the AR environment which made their experience fun and interesting. For *P1*, the mixed sense of digital and acoustic aspects delivered a unique instrument playing experience which prompted different gestures they had never used before. *P16* and *P4* shared similar insights saying that this experience brought them *"a new view of how music can work in a different way"* and to *"discover new possibilities and new combos within the same zone and the same instrument"*.

It appears that the mobility of the interface contributed this to this enjoyment. Six participants highlighted the impact of mobility in their comments. *P3* and *P19* noted the engagement with their bodies while performing musical tasks on the musical interface, which presented a closed and immersive feeling. While *P5, 7, 11, 13* specifically pointed out the interface design and the three-layer arrangement of sound cubes facilitated their "less restricted" playing experience *(P13)*. *P5* and *P7*'s comments focused on the interactive experience, where they appreciated the flexibility of changing the size, rotating and moving the interface around.

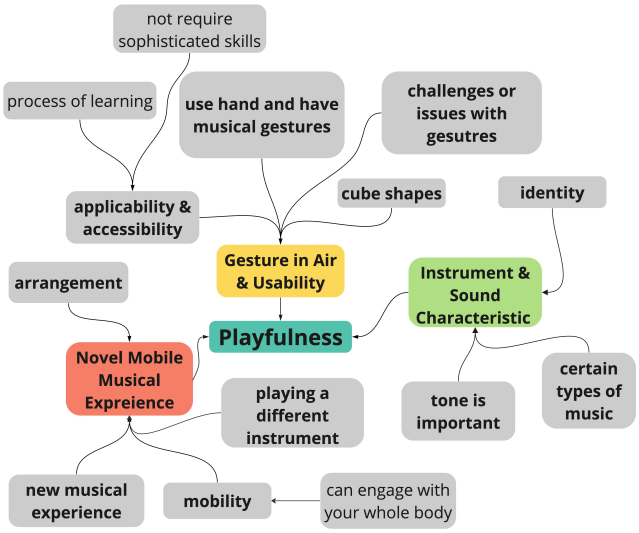

Figure 3: Three key themes promoted from the reflexive TA process, characterising a playful freehand AR musical expression done in Miro software [30].

4.2.2 *Musical Gesture in Air and Usability*

A rich vocabulary related to musical gesture was identified when participants discussed their experience on the AR interface. *P3* and *P11* were impressed that they could arrange (multiple) fingers in space to make sound. *P2* and *P13* 's comments further elaborated that they were not limited to a certain position or posture to play notes. *P7* reported a "tactile" feeling, even though *"putting your fingers into the sound it's like a digital thing"* and there was no actual physical feedback.

Participants connected their gestural experience with the concepts of *applicability and accessibility*. Eleven participants suggested that the control-to-sound mechanism on this interface made playing sounds very easy. They also mentioned this design would suit a variety of people (*P10*), particularly beginners who did not have prior musical experience or may have a physical disability. As pointed out by *P14*, it was how the cube shapes were designed for musical interaction, which allowed to *"touch it and makes sound [in] very simple ways."*

The participants also discovered difficulties about freehand gestures' usability. There were lots of comments related to the headset's hand tracking in the study including hard to play some chords, false gesture recognition and confusion about the instrument location, which affected the user experience.

4.2.3 Instrument and Sound Characteristic

Our participants mostly agreed that the sound characteristic of this AR system was drone-like, having a long sustain, and soft and relaxing tones. Some further commented that the electronic sound seemed to suit the context of an AR NIME. *P9* pointed out that musical preference for this instrument could be quite personal and we heard a range of views. *P10* reported that they liked the sound produced in the system due to their personal preference. Some were neutral about the sound (*"I don't particularly find this sound amusing or not." -P6*) and others didn't like it (*"I guess I don't love the sound." - P9*). *P3* clarified that the AR instrument used in this study might suit a specific musical style: *"it doesn't lend itself to like a super crazy, fast-paced jazz performances. But you can walk around the room and just create this awesome ambient pace by like moving around from place to place."*

Some participants reflected on their experience with existing musical instruments. *P1, 8, 19* noted that tone was important and that was what makes an instrument unique while *(P3, 5, 10)* suggested that each instrument serves a specific sound. For example, *P1* said *"Electronic music is everything overlap together, and you can't tell the tones for like a proper acoustic instrument they have their specific [sound] for different instruments. It's prefixed [and] defined because that's how the instrument [is]."* In contrast to the above suggestion of a consistent material-sound-instrument relationship, *P10* and *P20* reported a feeling of creating new interactions with an old instrument. Relatedly, *P16* stated that they imposed their piano-playing pattern when trying to play with the AR musical system, an example of using old interactions on a new instrument.

5. DISCUSSION

Both surveys and interview studies revealed that participants had an overall playful and positive musical experience. While the surveys supported the learnability and explorability of the system, the interviews revealed a more personal kind of musical engagement that participants had with this instrument. Connections were drawn between the AR instrument interface and musical reflections from the participants' experiences as music makers. Considering our overall findings we suggest that expressive AR musical experiences can be framed in terms of three high-level concepts: mobility, space, and sound.

5.1 Mobility in Music-Making

As reported in Section 4.2.1, participants' pleasant experience with the freehand AR interface was not solely from the excitement of a new technology platform. Instead, the unique way of playing the instrument, including having musical gesture performed in the air and a mobile flexible interface, allowed participants to use their hands and bodies in a less restricted manner for music-making.

In the survey, higher ratings in the *learnability* and *explorability* groups suggested that the AR system was easy to use and provided a variety of musical options. Furthermore, the interviews revealed that the participants enjoyed being able to arrange fingers in space and in different angles and postures. This affordance allowed the participants to perform musical gestures without sophisticated skills and facilitated new musical creativity.

The discussion implies a connection with natural hand interaction even though it wasn't directly mentioned in interviews. This shows that natural hand interaction is important for AR musical interfaces. Reflecting on the magicality and naturality of interaction discussed in the existing literature [42], using freehand interaction in the AR environment can provide a unique and natural experience that is different from other types of musical interfaces.

5.2 Spatial Dimension of Musical Interface

While mobility emphasises the musical experience in playing the AR instrument, the spatial dimension reflects interface design and the relationship in the control-to-sound model. In interviews, we found that the "arrangement" and "cube shapes" of the AR musical interface allowed participants to "arrange (multiple) fingers in space" to play. Participants specifically noted that they found the musical control in the AR musical instrument simple and accessible. One may argue that this compromises musical virtuosity in favour of simpler sound control design; however, the balance between learning difficulty and virtuosity has long been discussed in NIME design [40, 5, 24], it may be possible to support both.

More importantly, the finding of designing for "musical gesture in space" does not imply an arbitrary 3D musical interface floating in space where musicians perform random gestures. Instead, it is worth considering that 3D interactions in an AR environment can overcome physical limitations in the real environment. This sits in contrast to the requirement for tight relationship between materials, tactile interaction and sound in digital musical instruments [44, 27] and towards more imaginative non-physical action-sound relationships that may be very expressive.

5.3 Sound and NIME design in AR

In both the survey and interviews, there were discussions about the musical qualities and aesthetics in this freehand AR musical instrument. Surveys showed participants were neutral about the sound quality and aesthetics in this system. In interviews, multiple participants disclosed their individual sound preferences and discussed how that affected their views on using this instrument. Some participants appreciated the drone-like sound and the three-layer arrangement, while others found the electronic sound not very pleasing. Some participants also suggested that the system might only be suitable for a certain type of music such as a soundscape. Moreover, the concept of new interaction with an old instrument may suggest a gap between the sound generated and imposed interaction pattern in current AR system and vice versa.

This AR musical system had been originally designed through an autobiographical approach [4], with one primary

performer and designer focussed on their own musical practice for head-mounted AR musical expression. This first-person research process may have led to design decisions that do not suit everyone. Other users may still require additional time to understand and use the system for better familiarity and intimacy [6], as making music through interface and expression goes beyond a simple one-time study session. The music synthesis aspects of the system can also be adjusted either by the design, or by the user through a graphical interface as in most commercial synthesisers. That said, a NIME's context and musical characteristics should not be neglected in its evaluation.

6. CONCLUSION

In this work, we formally studied musicians' experiences with a freehand AR NIME. Our findings identified three high-level concepts: mobility, space and sound, which contributed to an engaging and playful musical experience in the AR space. The mobile musical experience with the spatial 3D musical interface allowed performers to be more bodily engaged and facilitated gestural exploration for musical creativity. These findings provide new design inspirations to create more engaging, imaginative, and expressive AR musical expression.

7. ETHICAL STANDARDS

This study was approved by The Australian National University's research ethics office (Protocol 2022/413). All participants provided informed consent and their participation were voluntary as informed in the study protocol. There are no observed conflicts of interest in this study.

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