Designing a Malay Gamelan Digital Musical Instrument: The *Air Bonang*

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Abstract

Virtualising traditional musical instruments is gaining popularity as a means to preserve musical cultures. Various technologies are leveraged to support learning traditional musical instruments, which are neither popular nor easy to access. Despite this, many virtual instruments are often simplified in their designs and interactions to make them more attractive and accessible, disregarding the authenticity and naturalness of instrumental techniques and playability. This study presents a Digital Musical Instrument (DMI) design process based on the Malay gamelan instrument the *bonang*. Named the *Air Bonang*, the DMI is designed using our NEX2MI framework, which underlines three dimensions of designing traditional musical interfaces: they should be natural, expressive and explorative. The *Air Bonang* design process involved user requirements, development and validation. Using the User-Centred Design (UCD) method, quantitative and qualitative data were gathered through interactional video and a questionnaire. Results revealed that the *Air Bonang* can be used to learn *bonang* instrumental techniques while providing flexibility by introducing new gestural interactions unrestrained by the physicality of the instrument. The design process discussed in this article laid the foundations for design criteria for the *bonang* DMI.

Keywords: *Bonang*, Digital Musical Instruments, virtual reality musical instruments, musical interface, Malay gamelan

1 Introduction

Virtualising traditional or non-Western musical instruments has become a trend over the years due to the advancement of technology. It is seen as a sustainable platform for preserving these musical cultures by making them more accessible for people to learn about traditional musical instruments. Many virtual and digital applications of traditional musical instruments have been developed to cater to different needs and uses. These Digital Musical Instruments (DMIs) are often designed to compensate for the difficulty of learning musical instruments by simplifying the interaction, because gesture-sound mapping can be absent. While this steep learning curve appeals to novices, it diminishes the instruments' natural and expressive interaction, which hinders the development of virtuosity.

This study presents the design process of *Air Bonang*, a DMI based on the *bonang*, one of the instruments in the Malay gamelan ensemble. The gamelan is a type of orchestra commonly found in Southeast Asia, originating in Indonesia. The DMI is designed to simulate virtually the *bonang* playing gestures to preserve its significance in Malaysian musical culture. In addition, the *Air Bonang* leverages virtual reality technology to provide a novel way of playing the *bonang* that is unattainable with the real instruments due to the limitations of its physicality. The *Air Bonang* aims to provide accessibility and flexibility to users of diverse gamelan skills while maintaining the naturalness of the *bonang* gestures.

The design of *Air Bonang* is based on what we term the NEX2MI framework, which highlights three dimensions of its interaction: natural, expressive and explorative. This framework was formulated based on the lack of existing frameworks in the literature that emphasise the natural interaction of traditional musical instruments in virtual instruments as well as being informed by our previous studies (Saffian et al., 2022; Saffian & Norowi, 2021). Further explanation of the framework is given in Section 3.

This paper is organised as follows. In Section 2, the related works are discussed. Section 3 explains the conceptual framework of the Air Bonang. Section 4 explains the methodology, while Section 5 describes the data collection and analysis. In Section 6, the results of this study are presented and are then discussed in Section 7. Section 8 concludes the paper and, finally, the limitations and recommendations are presented in Section 9.

2 Related Works

Many extant methods, frameworks, taxonomies and guidelines for DMI development address different dimensions of the relevant instruments. These earlier guidelines focused on the human-computer relationship around the proprioceptive relationship of musicians and their musical tools due to the computer technology back in the 1980s. In one of the earliest guidelines, proposed by Miranda and Wanderley, gesture was highlighted as one of the essential factors to be considered when designing DMIs to be used as a control in a system, along with gesture capture strategies for the movements (Miranda & Wanderley, 2006). DMI designs should consider musical aesthetics and the relationship between the performer and the audience (Paine, 2013). Over the last two decades, and with more affordable technology, these guidelines and frameworks have branched out into more specific dimensions. For example, the design principles for Virtual Reality Musical Instruments (VRMI) highlight nine design principles incorporating musical and virtual reality principles (Serafin et al., 2016). Following the reality-virtuality continuum (Milgram et al., 1995), the Mixed Reality Musical Instrument (MRMI) framework offers three aspects that help with the creation and study of the instrument: embodiment, magicality and relationships (Zellerbach & Roberts, 2022). Although these frameworks provided the basis of this study, considering the platform that *Air Bonang* is built on, they apply to a more general context of music interaction. The framework proposed in this study is contextual to the DMI design based on traditional musical instruments, specifically the Malay gamelan, where its uniqueness and musical culture are preserved.

2.1 Accessing Musical Culture through Virtual Reality

Virtual reality (VR) has been widely leveraged to provide access to cultural heritage. It has been used to preserve a variety of tangible and intangible cultural heritages, including historical sites, arts, artefacts and music, among others (UNESCO, 1972). Such "virtual heritage" aims to represent cultural heritage in immersive and interactive virtual environments based on reality, involving computer graphics and multimedia content (Cecotti, 2022). Primarily used for tourism and educational purposes, virtual heritage for preserving musical culture is lacking. To promote the fun and enjoyment of playing several Chinese percussive instruments, *QiaoLe*, a VR virtual heritage system, was developed consisting of exhibition, open interaction and gameplay modes (J. Zhang & Bryan-Kinns, 2022).

In Southeast Asia, researchers have developed several VR gamelan instruments to preserve musical culture virtually. The *Go-Byar*, a VR system based on the Balinese *gong kebyar* gamelan, was developed for education (Dwipayana et al., 2019). The *Go-Byar* operates on the HTC VIVE VR device and is built with two gameplay modes where the user can choose to play freely or be accompanied by a gamelan song. The drawback of the system is that it requires the VR device to be tethered to a computer to run the application, limiting the user's movement when playing the DMI. Another media-based VR gamelan is the *VR Gamelan Gong Kebyar*, which also focuses on learning the ensemble using a Google Cardboard and Android-based device (Aryadana et al., 2019). Both systems rely heavily on external devices such as computers and mobile devices to run the VR system. This is probably due to the limitations of VR devices at the time of their inception. However, more recent works explore VR's immersive and interactional aspects. The *Warriors of the Gamelan Skeleton (WGS)* is a gamified VR gamelan that targets the gamelan's learning in an immersive and challenging environment (Syukur et al., 2023). Focusing on the metallophone gamelan instruments, the user can learn several gamelan compositions by striking the virtual instruments and following the musical cues given, much like the *Beat Saber* VR game. Another work compares VR hand-tracking technology with the VR controllers in playing VR gamelan, specifically in playing the keyed instrument called the *saron*, by focusing on four interactional aspects: collision, pressing, grabbing and release (Pangestu et al., 2022). Results showed that, despite a more realistic interaction using bare hands, the VR controllers provide more comfort to the user. All the systems described above are based on the Indonesian gamelan instruments. To the best of our knowledge, there has yet to be a VR-based DMI of the Malay gamelan in which its unique cultural heritages and musical practices can potentially be preserved through virtual reality.

In terms of virtualising musical instruments of the Malay culture, some efforts have been made. The *Virtual Kompang* (Leng, Norowi, & Jantan, 2018) explored the affordance and expressivity of playing the Malay hand percussion instrument on a mobile device, using the built-in tri-axial accelerometer in the mobile device to track the time accuracy and magnitude of the striking action in providing expressive control of the DMI. The study also explored the design of the user interface to provide the most natural interaction that would mimic the physical instrument. The *bonang* mobile application is another study focusing on mobile DMI (Hassan et al., 2020). The study was aimed at the teaching and learning context of the instrument; thus, it focuses on the application's development using the ADDIE (Analysis, Design, Development, Implementation and Evaluation) model (Peterson, 2003). Although the study claimed to meet its objectives, it was unclear whether the application was playable within a musical context. A recent study involves designing a VRMI based on *tumbuk kalang*, a mechanical device used to pound rice. As machines take over rice production processes, *tumbuk kalang* is now innovated into musical performances that include songs, dances and other musical instruments (Baharin et al., 2023). Because this study is still conceptual, tangible outputs, such as a prototype, have yet to be developed.

2.2 The Malay Gamelan

The Malay gamelan is an ensemble distinct to the style of Malaysia, originating from Riau-Lingga, a Malay sultanate that existed from 1824 to 1911. It was brought to Pahang for a royal wedding in 1811. Like its Indonesian counterparts, the Malay gamelan consists of various knob-gong and keyed instruments made of bronze, wood, and iron. It has its own identity in terms of its tuning system, musical repertoire and playing techniques. The *bonang*, known also as *keromong*, is a five-tone knobbed-gong instrument in the ensemble. It has ten small gongs spanning a two-octave range (Hamdan et al., 2019). A player typically sits on the floor, using a pair of *bonang* mallets to strike the instrument (Fig. 1). The Malay gamelan has seen progressive musical and cultural changes over recent decades, which include musical styles, repertoire content and attitudes towards the gamelan caused by globalisation (Shah & Poheng, 2021). Newer compositions delve into a variety of gamelan instrument techniques to produce a wider range of timbral qualities, thereby influencing the instruments' affordances.

Figure 1: The Malay *bonang* or *keromong*.

3 Conceptual Framework of the *Air Bonang*

The *Air Bonang* is a VR application based on the Malay *bonang* (Fig. 2). Users can experience playing the *bonang* on an immersive virtual platform, which facilitates musical learning, performance and composition.

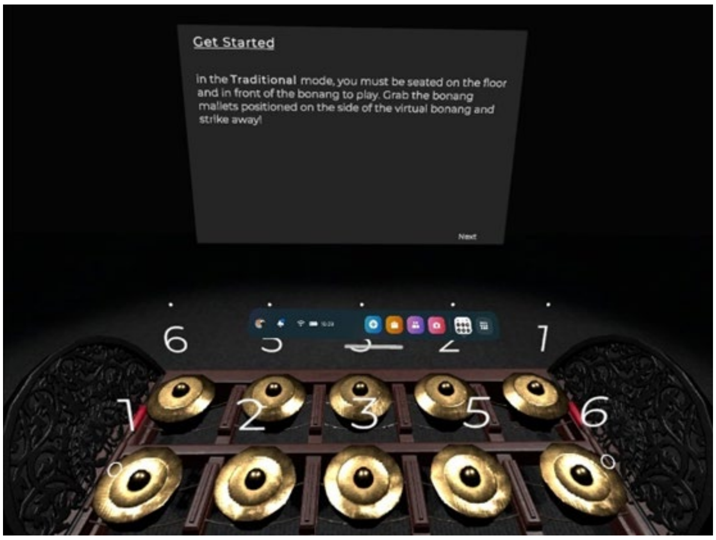

Figure 2: The *Air Bonang*.

Our conceptual framework named the Natural-Expressive-Explorative Musical Instrument (NEX2MI) emphasises three dimensions in designing DMIs inspired by traditional musical instruments (Fig. 3). It emphasises the importance of making the DMI natural, so it captures the natural and realistic gestural movement (Hemery et al., 2015) while preserving the authenticity of traditional musical instruments (Leng, Norowi, Atan, et al., 2018; M. Zhang & J. Zhang, 2020). The framework also highlights the expressivity of the DMI by integrating gesture-controllable parameters (Brown et al., 2018; Tanaka, 2019) to support its use in performance, composition and education. At the same time, it is essential to leverage current technologies to make them explorative in supporting musical creativity while not being constrained to traditional musical instruments' physical and cultural limitations (Altavilla et al., 2013; Tanaka et al., 2012). Because these three dimensions are linked, the DMI can be used to learn how to play the *bonang* instrument naturally and expressively, while also giving players freedom and flexibility to improve their gamelan performance.

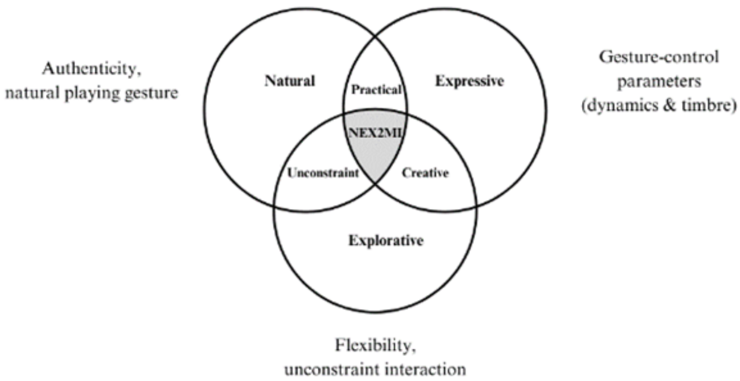

Figure 3: NEX2MI, the conceptual framework of the *Air Bonang*.

3.1 Natural

The user's bodily interaction with the computer system in an unrestricted and non-invasive way is considered natural. This concept, known as the Natural User Interface (NUI), was proposed to help learners learn musical gestures (Hemery et al., 2015). Naturalness is often associated with the realistic features of musical instruments, particularly in how they are played (Tzanetakis, 2016). In the *Air Bonang*, naturalness is exploited through the playing gestures of the instrument. The interaction retains its instrumental techniques, a feature absent in other gamelan-based DMIs. We propose that this aspect must be the primary consideration when designing any DMI based on traditional musical instruments, because learning and playing the correct techniques are important for users to grasp how the instrument is played authentically. Beyond gestures, authentic attributes like look-and-feel, design and sound quality can also integrate naturalness.

3.2 Expressive

Musical expression is intimately connected with human movement (Mulder, 2000). The term refers to the aspect of musical performance that transcends simply playing the notes. Generally, this results from the musician's familiarity with musical elements and performance traditions, such as music theory, history, instrument techniques, interpretation and emotion. Practically, this means bringing the music to life through the realistic application of dynamics, phrasing, timbre and articulation. Hunt et al. (2003) state that expressive mapping in DMIs is essential for virtuosic performance. In keeping with the natural aspect of the *bonang*, the *Air Bonang* focuses on giving users control over the dynamics and timbre of their interaction, just as they would with the real instrument. The acoustic properties of the *bonang* heavily influence its dynamic range, and the design of the DMI version must maintain these aspects. Similar to the timbral aspect, the Malay *bonang*'s timbre is distinct from its Indonesian counterparts. Traditional Malay gamelan music does not extensively manipulate the *bonang* timbre, but contemporary pieces frequently explore it through gestural manipulation and techniques borrowed from other gamelans, such as the Balinese and the Javanese (Shah & Poheng, 2021). Using digital technologies to provide greater timbral range can improve the expressive features of the DMI.

3.3 Explorative

While the first two dimensions deal with retaining the true identity of the *bonang*, the explorative dimension breaks the norms of Malay gamelan practice. This dimension provides interaction unrestrained by real-world restrictions, mainly bounded by the physicality of the *bonang* itself. Playing the *bonang* requires the player to be seated on the floor, typically in a cross-legged position. This unergonomic position poses some difficulties in reaching all of the pitch gongs due to the instrument's large size, which may cause "gorilla arm syndrome", fatigue, or heaviness of the arm caused by prolonged unsupported arm position (Hansberger et al., 2017). Malay gamelan performances have evolved from formal court music to expressive theatrical production. Thus, newer compositions have challenged the affordance of the instruments by integrating musical techniques from other musical cultures, challenging their integrity as heavy, bulky and isolated instruments. The *Air Bonang* exploits this through a flexible gesture and modular *bonang* gong arrangement in a virtual immersive environment. Explorative interaction enhances the natural *bonang* gestures while elevating their expressivity.

4 Methodology

4.1 *Air Bonang* Design Process

The *Air Bonang* is targeted at people who want to learn the instrument and skilled musicians who wish to use it in gamelan performances. The Meta Quest 2 hand controllers are optimised to serve as the *bonang* mallets used to strike the virtual instrument. The design process of the *Air Bonang* was based on the user-centred design (UCD) method, which incorporates users in an iterative processes. Fig. 4 illustrates the design process in three phases: 1) expert requirements in designing a Malay *bonang* DMI; 2) developing the *Air Bonang*; and 3) testing and validating the *Air Bonang*.

Figure 4: Design process of the *Air Bonang*.

4.2 Phase 1: Expert Requirement in Designing a Malay *Bonang* DMI

In phase 1 of the design process, a group of gamelan experts was engaged to ascertain their requirements in designing a DMI based on the Malay *bonang*. Six experts with diverse gamelan experience were interviewed on the origin of gamelan music, gamelan instrumental techniques, current practices of the Malay gamelan, and for their input in developing a virtual *bonang*. Using the purposeful sampling technique (Ahmad & Wilkins, 2025), the criteria for the selection of experts include having at least five years of experience playing the gamelan in both traditional and contemporary gamelan music. The experts comprised three males and three females and have had gamelan experiences for between 17 and 31 years. They have played various roles in the gamelan scene, namely as instructors, lecturers, reference experts, judges, musicians, composers, arrangers and directors, to name a few. The experts' feedback was compiled and relevant findings were considered in the early design of the *Air Bonang*. Further explanations of this phase are described in our previous study (Saffian et al., 2022).

4.3 Phase 2: Developing the *Air Bonang*

The experts' feedback helped us to frame the purpose of the *Air Bonang* properly. The *Air Bonang* is intended to preserve the *bonang* virtually; therefore, the primary goal was to retain the instrument's natural qualities. Additionally, VR technology enables enhanced interaction within the virtual environment. This led to exploring the gestural interaction of *bonang* playing in ways unconstrained by its physicality. The following describes the development of the *Air Bonang*.

4.3.1 3D Modelling and Mapping

The *Air Bonang* prototype was developed on Unity for the Meta Quest 2 device. The virtual *bonang* is modelled after the actual *bonang* in terms of its size and dimensions, as well as the instrument's wooden frame and individual *bonang* gongs. Only the exterior dimensions of the gongs were measured and replicated for the modelling. The hollow part beneath the gong was not modelled because it is not visible to the player. Fig. 5 shows the dimensions of the actual *bonang*.

Figure 5: Dimensions of the *bonang*: wooden frame (top) and individual *bonang* gongs (bottom).

Recorded sound samples of the instrument were assigned to the ten virtual *bonang* gongs. The *bonang* knob, known as *cembul*, produces a different timbral quality than the body due to the physicality of the instrument; thus, each *bonang* gong in the *Air Bonang* was accordingly assigned two different sound samples. The VR controllers were used to simulate this interaction, because playing the *bonang* involves striking it with a pair of mallets. The hand gestures were spatially mapped into three dimensions. The x-axis is mapped to the width of the instrument and the movements between the *bonang* gongs for different pitches; the y-axis maps the dynamics of the “striking force” to its loudness; and the z-axis is mapped to the different top and bottom registers, as shown in Fig. 6.

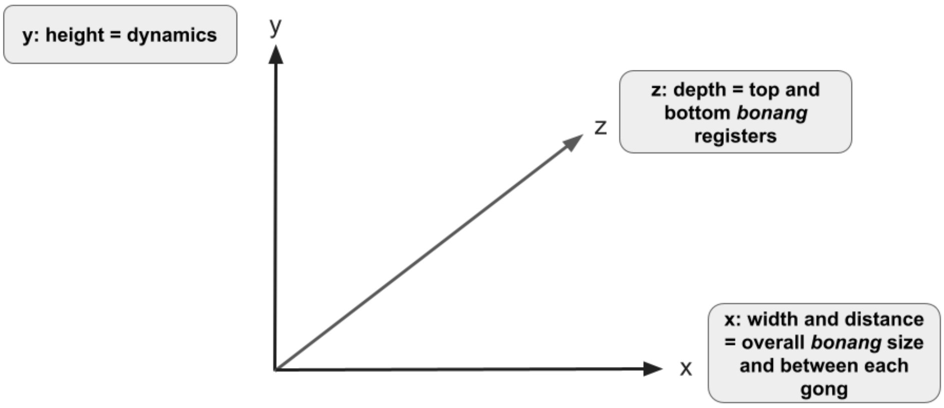

Figure 6: Mapping of gestures for the *bonang* DMI.

4.3.2 Gameplay

The *Air Bonang* has two gameplay modes: Traditional and Exploratory. The Traditional mode displays a 3D model of the Malay *bonang* where interaction is analogous to the actual instrument. This mode facilitates the natural execution of *bonang* instrumental techniques, enabling users to master the *bonang*'s hand gestures. A video demonstration of this mode can be viewed via this link: https://www.youtube.com/watch?v=4iglNzDKhHE. By contrast, the Exploratory mode provides an interaction in which the individual gongs representing different pitches can be moved around and rearranged within a 3D virtual space. Users can grab and attach these gongs to a virtual wall to play them depending on their musical intentions and desired output. The Exploratory mode offers the user greater flexibility and the possibility of enhancing musical interaction in ways not possible with the actual instrument (Fig. 7). A video demonstration of this mode can be viewed via this link: https://www.youtube.com/watch?v=LY8l2eHYUJY. The *Air Bonang* also provides customisation features in which users can change some playability aspects, including resizing the virtual *bonang*, adjusting the volume, and displaying the gamelan note numbers of the *bonang*'s pitches. To play the *Air Bonang*, the user strikes the virtual *bonang* gongs in the immersive environment using the hand controllers, which mimic the natural method of playing the *bonang* with a pair of mallets.

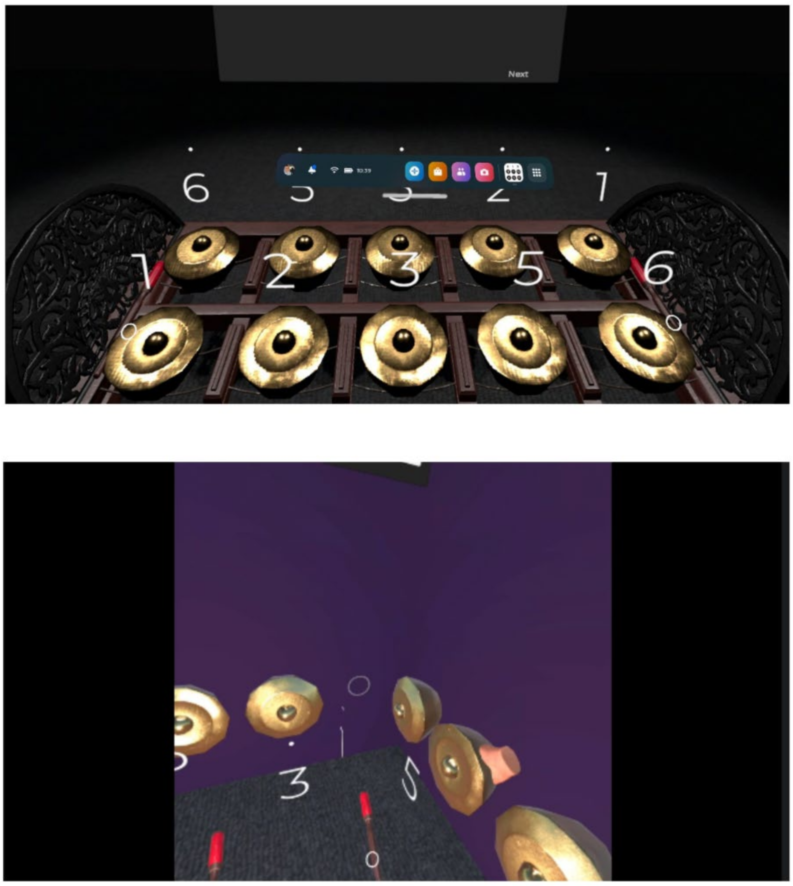

Figure 7: Traditional (top) and Exploratory (bottom) modes of the *Air Bonang*.

4.3.3 Gestural Interaction

Despite our intention to simulate the *bonang*'s natural gestures in the *Air Bonang*, several interactional aspects were compromised. The force directed to striking the physical *bonang* gong returns tactile feedback, which affects the velocity and effective mass at impact, corresponding to the loudness produced (Dahl, 2011). This sensation is nearly absent in the mid-air interaction of the VR system. However, many attempts have been made to deliver realistic haptic feedback to VR users, including handhelds, wearables, encountered types, physical props, and mid-air ultrasonic vibrations (Wee et al., 2021). The *Air Bonang* uses the vibration of the hand controllers as feedback to simulate a striking sensation when the user strikes the correct gong. Although not identical to playing the real instrument, this compensates for the loss of physical feedback and provides more control to the user. The hand controllers are leveraged for purposes other than *bonang* striking. The physical buttons of the hand controllers are used for two other interactions. The index trigger buttons are assigned to navigational gestures, which include pointing and selecting. The primary hand trigger buttons are assigned to operational gestures such as grabbing and releasing, primarily used in the Exploratory mode. Other top-mounted buttons and joysticks are assigned to operational functions (Fig. 8).

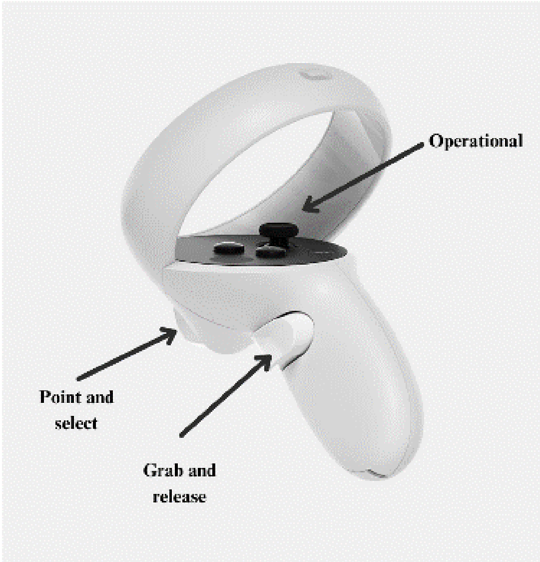

Figure 8: Mapping of Quest 2 hand controller for the *Air Bonang*.

The *Air Bonang* requires users to wear a non-tethered Meta Quest 2 head-mounted display (HMD). The HMD provides visual and audio feedback so the user is fully immersed in the virtual environment. The Traditional gameplay mode displays a replica of the actual *bonang*. The Traditional mode requires the user to be seated on the floor facing the virtual *bonang*. The user can hold the *bonang* mallets presented and strike the virtual *bonang* freely. Should the user wish to learn the basic *bonang* techniques, they can watch a video demonstration of the *serentak* and *berselang* techniques in the system. This demonstration can be viewed via this link: https://www.youtube.com/watch?v=UsLmi1mD_q0. Three numbered music notations of the Malay gamelan songs are also included as references: “Timang Burung”, “Togok” and “Perang Besar”, displayed by pressing the Y button on the left-hand controller.

By contrast, the Exploratory mode displays a 3D room where the virtual *bonang* gongs are placed on a table facing the user by default. The individual gongs are movable and the user can employ the controller to hold and release them or attach them to the walls and ceiling within the virtual space. There are ten rings on the walls indicating the locations where they can be placed. This gestural interaction breaks the norm of the horizontal and front-facing playing of the *bonang*; instead, it offers a 360-degree gestural movement. The user is no longer required to be seated uncomfortably on the floor, because this mode can be played in a standing position.

4.4 Phase 3: Testing the *Air Bonang*

To test the *Air Bonang*, we conducted an experiment involving 22 participants (Tab. 1). The participants recruited came from various backgrounds and were grouped into novices and experts. The novice participants were recruited voluntarily based on an open call. The expert participants were invited to participate based on their experiences and involvement in various gamelan activities, such as musicians, instructors, researchers, composers, arrangers, producers, and judges. The experiment was conducted in a lab-controlled environment setting with three objectives:

- To establish natural and effective interaction of the *bonang* gestures in the *Air Bonang*;
- To determine expressive musical controls for the *Air Bonang* based on responsive dynamics and timbre; and
- To investigate the affordances of the *Air Bonang*, where the interaction is unconstrained by the physicality of the instrument.

Table 1: Participants' demographic details.

	Sex	Age	Category (N = novice/ E = Expert)	Profession	Music Experience	Gamelan Experience
P1	F	22	N1	Student	No	No
P2	M	22	N2	Student	No	No
P3	F	24	N3	Student	No	Yes
P4	M	35	N4	Student	No	No
P5	F	25	N5	Student	No	No
P6	M	23	N6	Student	Yes	No
P7	M	27	N7	Student	Yes	Yes
P8	F	57	E1	Professional	Yes	Yes
P9	M	22	N8	Student	Yes	Yes
P10	M	50	E2	Professional	No	Yes
P11	F	23	N9	Student	Yes	Yes
P12	F	22	N10	Student	Yes	No
P13	F	40	N11	Professional	No	Yes
P14	F	47	E3	Professional	Yes	Yes
P15	F	43	E4	Professional	Yes	Yes
P16	F	40	N12	Professional	Yes	Yes
P17	M	39	E5	Professional	Yes	Yes
P18	M	32	E6	Professional	Yes	Yes
P19	M	33	E7	Professional	Yes	Yes
P20	F	26	E8	Professional	Yes	Yes
P21	M	30	E9	Professional	Yes	Yes
P22	F	33	E10	Professional	No	Yes
MEAN	10M /12F	32.5	12N/ 10E	10S/ 12P	14Y/ 8N	16Y/ 6N

4.4.1 Experiment Procedure

Upon arrival, the participants were briefed about the experiment and obtained their consent for participation. They were then assisted to wear the VR device, where basic use was explained. They then received step-by-step guidance through the experiment task, which was based on the evaluated dimensions described in Tab. 2.

Table 2: Evaluated dimensions and task procedure of the experiment.

Dimension	Task	Participant
Bonang techniques	Play the "Timang Burung" melody using the *bonang* instrumental techniques (*serentak* and *berselang*); or	Novice
	Play the "Timang Burung" melody using the *bonang* instrumental techniques (*serentak, berselang, meningkah*, and *bunga*).	Expert
Dynamic control	Play the "Timang Burung" melody using the *bonang* instrumental techniques at different loudness (soft and loud).	All
Responsiveness	Play the "Timang Burung" melody using the *bonang* instrumental techniques at different tempi or speeds (fast and slow).	All
Timbral control	Play the "Timang Burung" melody at the side of the virtual *bonang.*	All
General interaction	Explore the settings of the *Air Bonang* by changing these parameters: volume, numbered notation, and scale.	All
Musical affordance	Explore the Exploratory mode of *Air Bonang* freely.	All

The melody played was a four-bar "Timang Burung" melody, a traditional gamelan piece. This melody was chosen for the experiment because it has almost all the *bonang* pitches (except for pitch 1, played much later in the piece and therefore not played in the experiment) and uses simple rhythms. Because the melody corresponds to the different positions of the gong layout, it was essential to see how playing the melody affected the user's gestural interaction with the prototype. A numbered notation was displayed in the virtual environment as a reference for the participants (Fig. 9). Before executing the tasks, participants were encouraged to practise the melody several times and to inform the investigator once they were ready to proceed.

Figure 9: Number notation and music notation of the first four bars of the "Timang Burung" melody.

The novices were only required to play two basic *bonang* techniques: *serentak* and *berselang*. These techniques were selected because they were deemed feasible to execute even if the participants had no gamelan experience, as was also the case in the pilot study (Saffian et al., 2023). Meanwhile, the expert participants were required to play all four techniques, including the remaining *meningkah* and *bunga*. These two techniques are more advanced and require some knowledge of Malay gamelan music in terms of skills and musicality. Prior to employing the techniques, the participants were encouraged to practise beforehand to become familiar with the VR device and its interaction. Fig. 10 shows the participants playing with the *Air Bonang* in both Traditional and Exploratory modes. A post-task questionnaire was administered to the participants after completing the tasks.

Figure 10: Participants playing the *Air Bonang* in sitting position in Traditional mode (top) and standing position in Exploratory mode (bottom).

4.4.2 Experiment Setup

The study was conducted at the Centre of ICT Innovation, Faculty of Computer Science and Information Technology, Universiti Putra Malaysia. The participants' interaction with the prototype was video recorded to understand how they interacted with the prototype. The interaction analysis method (McMillan et al., 2015) analyses specific activities of smaller incidents of participants' interactions with the *Air Bonang*, which includes their interaction within the virtual environment of the prototype as well as their physical movements and reactions when using the VR device. The study used two video recording methods to capture participants' executing the experimental tasks. The first method captured their interaction from an external viewpoint, whereby two video cameras were positioned at the front and side of the experimental setup. Each camera was placed on tripods at an appropriate height and distance to capture a whole-body view of the participants, as illustrated in Fig. 11.

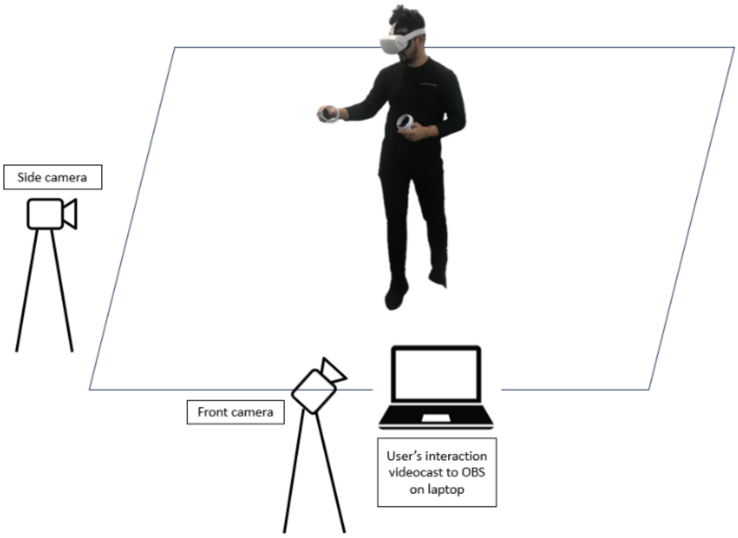

Figure 11: Camera setup of the experiment.

The second method of capture was through video casting of the interaction within the VR device. The prototype was developed on the Meta Quest 2 device, which has the feature to record the screen internally. However, because there is a limit on the device's internal storage space, the screen recording was cast to third-party software on a laptop using the *OBS Studio* software. In this manner, the software recorded the videocasts and captured the participants' external interaction with the webcam view (Fig. 12).

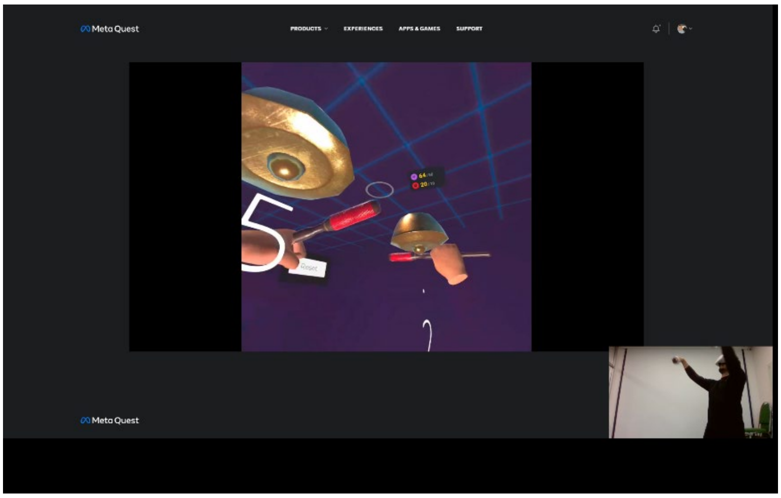

Figure 12: Video cast of the participant's interaction recorded via the *OBS Studio* software.

5 Data Collection and Analysis

The study used convergent design procedures for data collection and analysis (Creswell & Piano Clark, 2018), where qualitative and quantitative data are collected concurrently; however, they are analysed independently and only brought together during the interpretation. This study collected data from the interactional videos involving video and audio recordings, which were analysed separately. The interactional analysis method (McMillan et al., 2015) was used for video recordings to understand specific activities and smaller incidents of interacting with the DMI, especially in investigating the participants' interactional patterns, behaviours and reactions. The audio collected was analysed to understand the differences in dynamics upon striking the virtual *bonang*, where the amplitude values (in dB) were extracted and analysed using a spectrum analyser plugin in *Ableton Live 11 Suite*. Meanwhile, the questionnaire results were analysed using the *IBM SPSS* statistics software to produce descriptive and inferential results.

6 Results

The interaction videos showed that all participants could execute the two basic *bonang* techniques, *serentak* and *berselang*, albeit with different levels of skill and fluency. Although some novice participants had not played the *bonang* before, they could execute both techniques after some guidance from the investigator and with sufficient practise. The expert participants were asked to play two advanced techniques, *meningkah* and *berselang*, in addition to the basic ones. Seven of the expert participants were able to play using both techniques.

6.1 Natural Interaction

The natural interaction variables in the questionnaire were analysed from three perspectives: latency and speed, naturalness, and ease of use of the *Air Bonang* as compared with the actual instrument. Tab. 3 shows the ratings of these perspectives with minimum, maximum, mean and standard deviation values, these also illustrated in a stack graph (Fig. 13).

Table 3: Ratings for latency and speed, naturalness, and ease of use.

	Minimum	Maximum	Mean	Std. Deviation
Latency and speed	1	3	2.41	.666
Naturalness	1	3	2.40	.598
Ease of use	2	3	2.64	.492

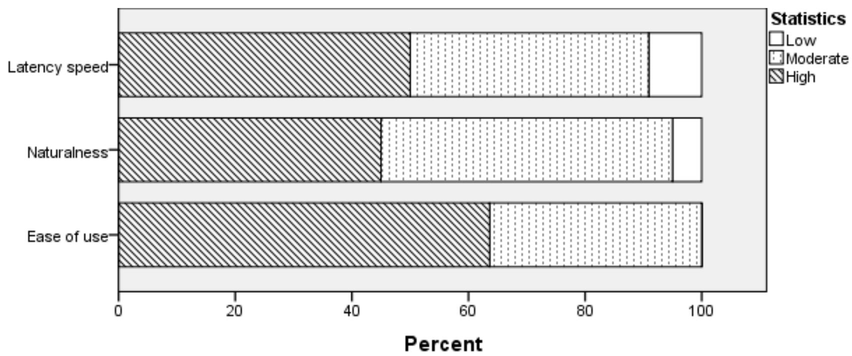

Figure 13: Stack graph of latency and speed, naturalness, and ease of use.

The naturalness perspective was rated moderate to high. Playing the *bonang* techniques on the *Air Bonang* was generally deemed executable and easy. Because the gamelan repertoire varies in terms of tempi, the positive ratings for latency and speed indicate that it adequately responds to playing the repertoire. The *Air Bonang* is also felt to be natural and quite similar to playing the actual instrument in terms of striking experience, gestural movement and quality of sound output.

6.2 Expressive Musical Controls

In the study, expressive musical controls of the DMI centre around timbre and dynamic control. The questionnaire results indicate both variables' positive ratings, as shown in Tab. 4 and Fig. 14.

Table 4: Ratings for timbral and dynamic control.

	Minimum	Maximum	Mean	Std. Deviation
Timbral control	1	3	2.64	.581
Dynamic control	1	3	2.36	.658

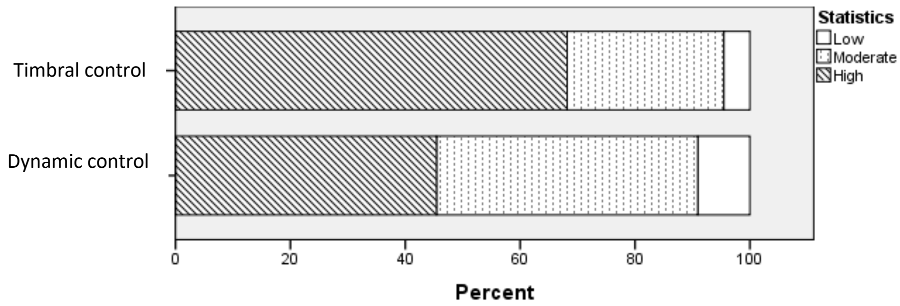

Figure 14: Stack graph of timbral and dynamic control.

The interaction videos show two types of movement when striking with different dynamics, particularly loud and soft. The participants can be seen raising their arms high before striking, making big and open arm movements, and making sharp flicks of the wrist to play loudly. In contrast, their arm movements were much smaller and gentler, with their bodies more relaxed, when executing the soft dynamic (Fig. 15).

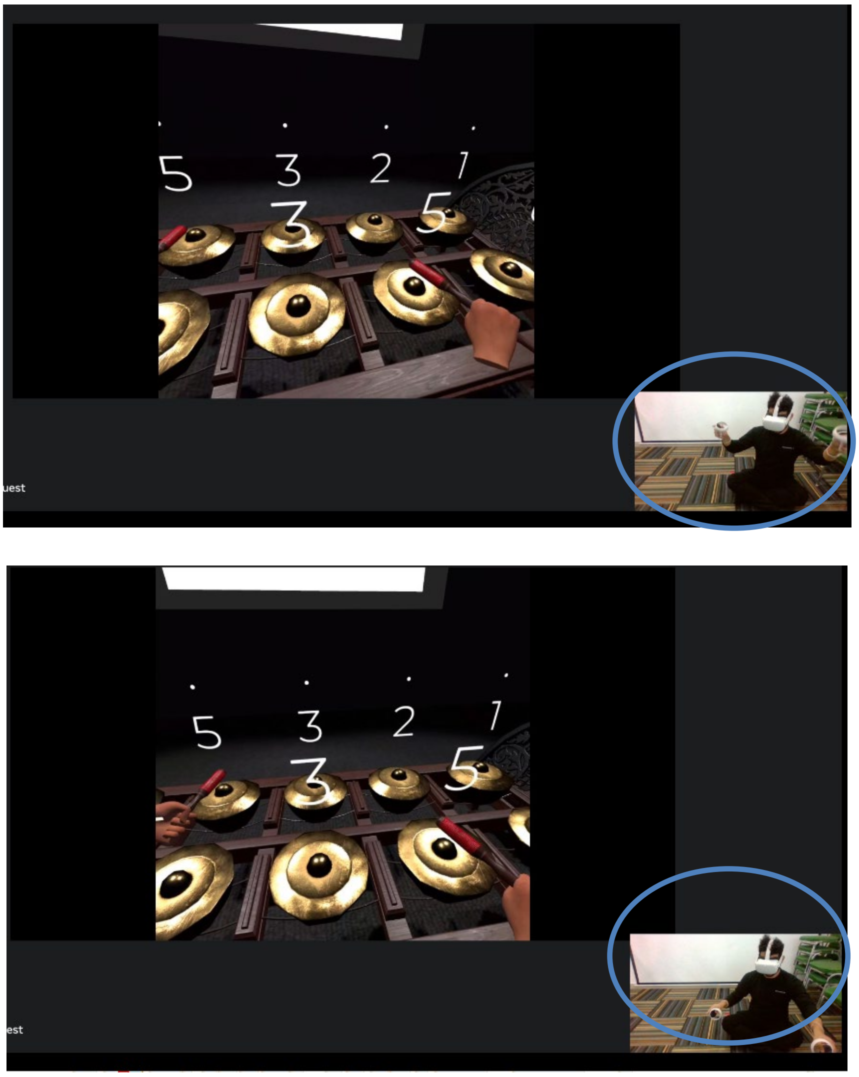

Figure 15: Different hand movements when striking loud (top) compared to soft (bottom) dynamics.

To support the observation made on the interactional videos, the audio of the striking movements was also gathered and analysed as logged data. The results in Tab. 5 show the mean amplitude of the first two bars of the "Timang Burung" melody plotted as a line chart (Fig. 16). The plotted lines indicate a difference when striking at different loudness. Although no consistent pattern can be seen emerging for both dynamics, there is a generally noticeable difference between the overall amplitude for loud and soft, represented by the blue and orange lines in the chart. Thus, it can be presumed that, although striking at different loudness is perceived differently from one person to the other, one can clearly execute the two different dynamics.

Table 5: Mean amplitude values (in decibels) of the first two bars of the "Timang Burung" melody.

Gong Pitch	**5**	**5**	**2**	**3**	**2**	**3**	**5**
Pitch	So	So	Re	Mi	Re	Mi	So
Loud (dB)	-11.34	-10.65	-12.69	-10.63	-12.32	-11.38	-12.32
Soft (dB)	-14.41	-15.42	-15.26	-13.66	-14.35	-14.13	-14.57

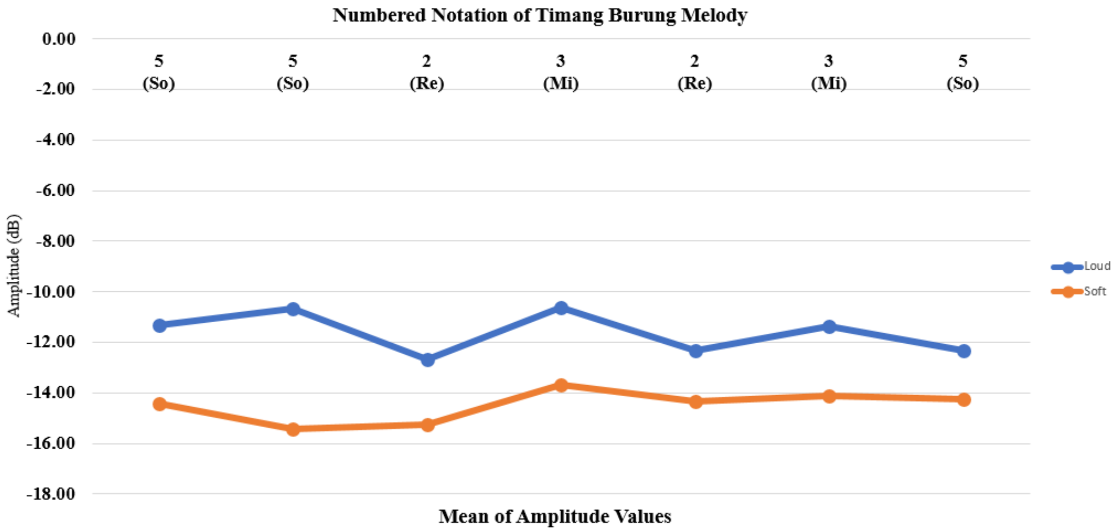

Figure 16: Line chart of the amplitudes over the first two bars of the "Timang Burung" melody.

The positive ratings for dynamic control in the questionnaire indicate that the participants generally agreed that the dynamics of the *Air Bonang* could be controlled in terms of its responsiveness to different loudness.

The timbral control of the *Air Bonang* was rated positively in the questionnaire, as shown in Fig. 14 above. The participants agreed that they have control over the timbre of the *Air Bonang* due to its timbral mapping, where one has to strike it in different positions, namely, the body and the knob of the *Air Bonang* gong. Additionally, the Pearson correlation coefficient was also conducted to understand the relationships between the variables, and results showed that the strongest correlation is between musical expression and timbral control ($r = 0.789$, $p = 0.000$), indicating a significant positive high relationship, shown in a scatterplot in Fig. 17. These results support the study's objective of providing expressive musical interaction through timbral control.

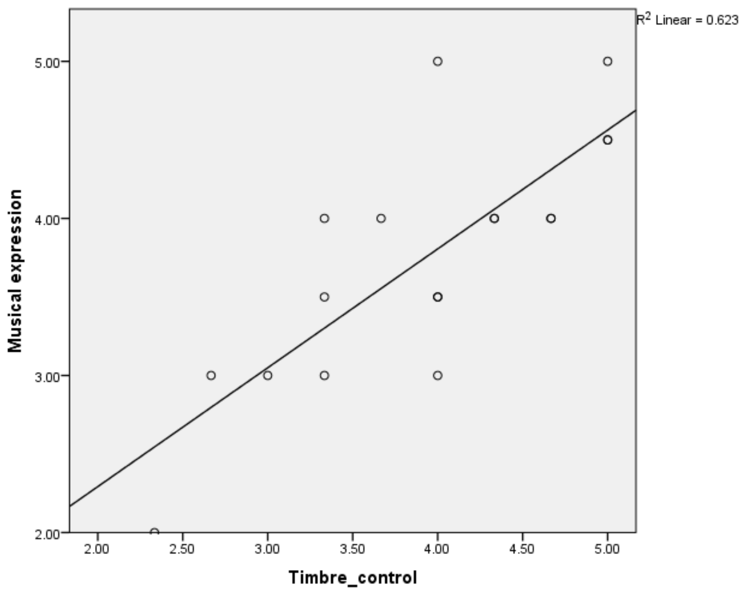

Figure 17: Scatter plot of the strongest correlation between musical expression and timbral control.

6.3 Affordance

This dimension aimed to see any interactional patterns that emerge, particularly how they relate to the affordances of the Exploratory mode of the *Air Bonang*. We observed two types of affordances: musical affordance and general interactions.

6.3.1 Musical Affordance

Musical affordance was mainly observed from how the participants rearranged the virtual *bonang* gongs within the Exploratory mode. Because no limitation was imposed, this could afford musical playing in varied ways. Some participants were more intentional than others with their gong placement, arranging them in specific patterns such as according to the numbered notation or being inspired by other musical instruments' layouts and techniques, such as the drum set and gong *kempul* (a set of small gongs used in Malay gamelan), while others were placed randomly. Other than gong arrangements, musical affordance could also be seen in how the virtual walls were used. From the interactional videos, it was found that most of the participants utilised the left and right walls to place the virtual gongs. Only a handful placed the gongs on the front and back walls, with the top or ceiling the least often used (Fig. 18).

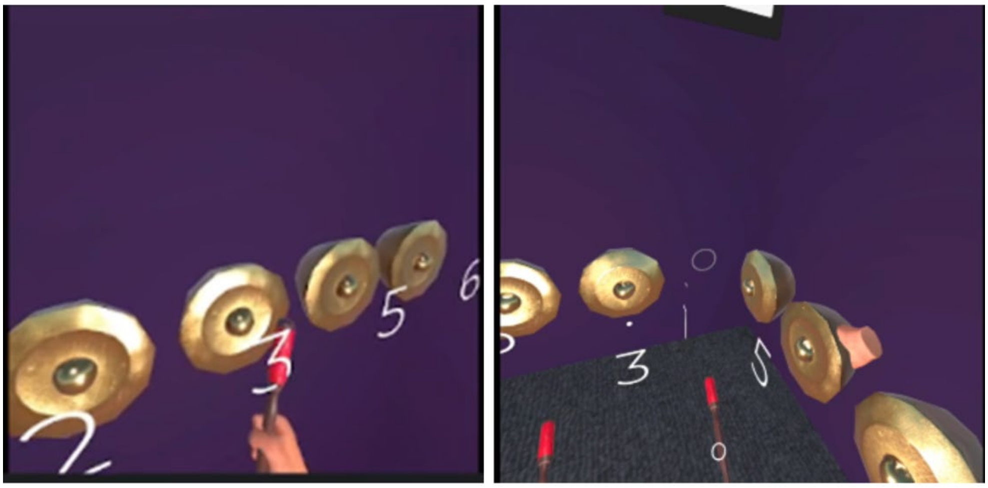

Figure 18: Gong placement on a single wall (left) and multiple walls (right).

6.3.2 General Interaction

This type of interaction refers to how the participants generally use the *Air Bonang*, including non-task gestures, behaviours and errors. Out of the 22 participants, 16 (72.7%) had never used any VR device before, thus facing some initial difficulties with the prototype. They were observed to have difficulties using the hand controller to point, select and hold despite knowing which button to press on the hand controller. Those with VR experience ($n = 6$) could easily use the VR device and navigate the virtual environment smoothly. There were instances when the virtual *bonang* was located some distance from the user in the environment, creating difficulty in reaching out to play it. Some participants who faced this issue would either bring themselves physically closer to the instrument or use the joystick on the hand controller to bring the *Air Bonang* closer to them, indicating literacy in using the joystick.

Non-task gestures also include sitting and standing positions when playing the *Air Bonang*. The Traditional mode requires the participants to be seated on the floor to play; the participants were either kneeling or cross-legged. In the Exploratory mode, the participants had to stand to play because the virtual *bonang* was placed on a table. Transitioning between these two modes required the participants to change their positions accordingly. Apart from intentional gesture affordance, users made mistakes or had accidents while interacting with the DMI, which were identified as errors. These include accidentally flipping the virtual gongs over the table, dropping gongs on the floor, and walking behind the virtual environment. We also observed the participants attempting to correct these errors by retrieving the fallen gongs (Fig. 19).

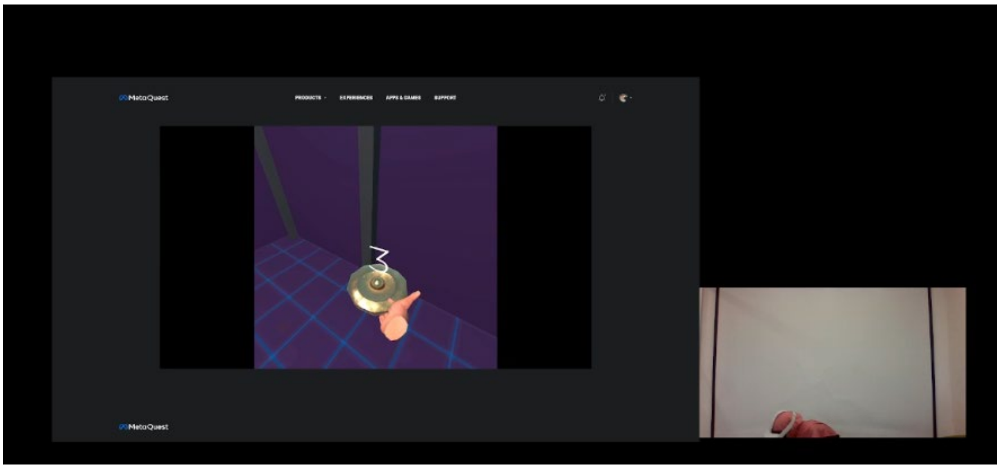

Figure 19: Participant bending down to pick up a gong that had fallen to the floor.

The participants rated the explorative aspect of the *Air Bonang* from moderate to high, as shown in Tab. 6 and Fig. 20. The explorative aspects of the DMI include the virtual environment, interaction, flexibility, and enjoyment.

Table 6: Ratings for the explorative aspect.

	Minimum	**Maximum**	**Mean**	**Std. Deviation**
Explorative	2	3	2.82	.395

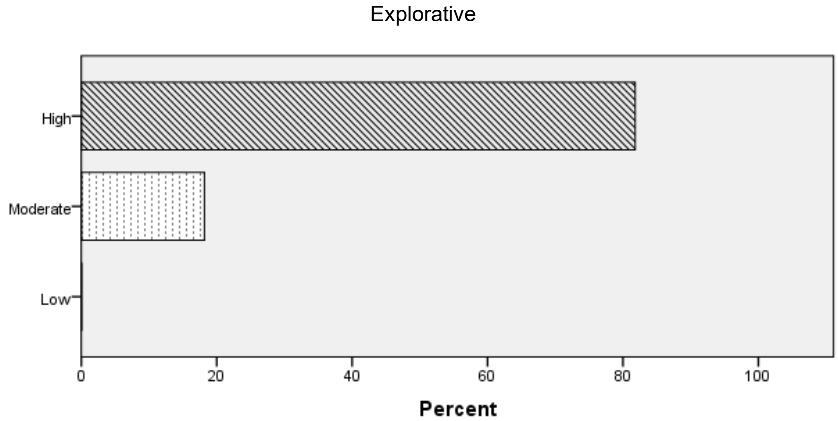

Figure 20: Stack graph of the explorative aspect.

7 Discussion

The NEX2MI framework was tested in the user study to validate the design of the *Air Bonang* as a natural, expressive and explorative *bonang* DMI.

7.1 Naturalness

From the study, the natural *bonang* gestures are mainly associated with the realistic aspects of *bonang* playing, including the execution of its instrumental techniques, striking gestures, striking accuracy, and feedback. All participants could employ the basic *bonang* techniques with different degrees of fluency. Mastering any musical instrument requires substantial practise (Ericsson & Harwell, 2019), which could also apply to playing the *Air Bonang*. The similarities in its design and interaction allow users to learn the proper gestures and techniques of the instrument, keeping the musical integrity of the original Malay gamelan instrument.

The study reveals that the naturalness of the *Air Bonang* is mainly associated with gestural interaction. Gestural interaction is a common theme in the music interaction field and HCI, emphasising the importance of natural gestures between humans and computers. Naturalness in music interaction is also related to playing musical instruments in their original ways. Musical interfaces based on non-Western instruments, such as the Chinese *guqin* (M. Zhang & J. Zhang, 2020) and the *Virtual Kompang* (Leng, Norowi, & Jantan, 2018), incorporate naturalness by keeping true to the actual instruments' gestural interaction, such as through plucking and striking. This aspect is seldom discussed in the designs of virtual musical instruments inspired by traditional musical instruments, yet they make interaction easier and more attractive when learning to play these instruments. Many systems tend to focus only on the aesthetics of the instrument, such as design, visuals and sound quality, but they often do not extend it to more meaningful interaction, such as playing real musical repertoires.

7.2 Expressiveness

Keeping true to the naturalness aspect of the *bonang* instrument, the musical expression aspect of the DMI centres around providing users with control of the dynamics and timbral quality of their interaction, much as they have with the actual instrument. The dynamic control of the *Air Bonang* is determined by the striking force of the hand movement to produce the desired loudness. The logged data from the study reveals clear differences in soft and loud dynamics produced upon striking. Striking the virtual *bonang* is, however, done in mid-air, which takes away the physical sensation of striking the physical instrument. Despite a slight challenge to simulate this sensation naturally into the DMI, the *Air Bonang* attempts to replicate this by incorporating the hand controller's haptic feedback through vibration upon striking accurately.

Another expressive feature incorporated into the *Air Bonang* is timbral control. The timbral mapping is based on the assignment of the *bonang* sound samples to specific areas of the gongs, namely, the knob and the body, according to the different timbral qualities produced. The user can control these timbres by striking these different areas of the virtual *bonang*. Using realistic sound samples is paramount to providing expressive timbral control in the *Air Bonang* and for preserving the cultural integrity of the Malay *bonang*. Although not explored in this study, virtual technologies can be leveraged to enhance expressive timbral control in the *Air Bonang*, such as changing the timbre through digital manipulation and simulation of other musical techniques common in Malay gamelan playing. One such technique is the *tekap*, where the timbre of the *bonang* is altered by dampening it with the padded part of the *bonang* mallet. This type of timbral control can be explored through gestural interaction to emulate how the technique is played on the real *bonang*. Manipulating timbral quality using bodily gestures to produce different tones is common in many musical instruments (Li & Timmers, 2020). For example, producing different tones on most hand percussion instruments, such as the conga, bongo and *kompang*, uses different strokes of the hands.

7.3 Explorative

While preserving the authenticity of traditional musical instruments in DMI design is essential, technology can also be leveraged to provide explorative interactions. The *Air Bonang* is designed to provide users with the best of both worlds: to learn the proper techniques of playing the *bonang* and to explore new gestures in playing gamelan music. The Exploratory mode of the *Air Bonang* crosses the musical and cultural boundaries of *bonang* playing by optimising the virtual environment to provide unconstrained gestural interaction. The Malay gamelan is attached to rituals and religious activities and thus has its etiquettes and taboos (Chan, 2013; Matusky & Beng, 2017). Its instrumental techniques are rooted in its roles as court ensembles that one must respect, hindering freedom in gestural and performative aspects. The flexibility and versatility afforded by the *Air Bonang* elevate the current musical practices of the Malay gamelan, affording a degree of "magical interaction", one of the design principles of virtual reality musical instruments (Serafin et al., 2016) describing interaction that is not limited by real-world constraints. By exploiting the immersive environment, this "magical" interaction transcends the limitations of traditional gamelan playing.

8 Conclusion

This study aimed to validate the design of a DMI based on the Malay *bonang*, named the *Air Bonang*. Based on a conceptual framework proposed as NEX2MI, it focuses on designing a *bonang* DMI that is natural, expressive and explorative in order to facilitate musical learning, performance, and composition. This research is based on the iterative concept of User-Centred Design (UCD), where users are engaged in the development and evaluation phases. The design process began with eliciting gamelan expert feedback on essential aspects of the Malay *bonang* to be integrated into the *Air Bonang* in order to ensure its musical cultures can be preserved while providing access via technology. The design of the *Air Bonang* offers two gameplay modes that preserve the authenticity of the actual instrument and leverage VR technology for more explorative interaction. The DMI was then tested in a user study involving gamelan and non-gamelan players. Results indicate that the *Air Bonang* is sufficiently natural and expressive to support learning *bonang* techniques, preserving its authenticity. The *Air Bonang* also provides explorative features to elevate further Malay gamelan performance as a whole.

9 Limitations and Recommendations

The study has certain limitations. First, it involved a one-off session where the participants were only engaged to undertake predetermined tasks. Hence, multiple evaluation sessions of the *Air Bonang* might yield more meaningful results if participants have familiarised themselves with the DMI. Second, the experiment was conducted in a controlled setting where the tasks were designed to answer specific research objectives. This approach restricted the opportunity for the participants to be more explorative and creative with their interactions. Playing various gamelan repertoire with the *Air Bonang* in a more realistic setting will further validate it as a playable and reliable DMI. Other than the experimental methods, improvements of the technical aspect of the DMI could also be considered, such as the implementation of dynamics and responsiveness.

This study's scope is limited to a single *bonang* instrument of the Malay gamelan. Malay gamelan instruments are typically played together as an ensemble rather than individually. Therefore, we recommend further investigation into the collective playing of the instruments in the immersive environment. Other than the musical aspect, playing the ensemble collectively would also affect social and behavioural aspects through multiplayer interaction. This aspect motivates our future work.

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