# WithFeelVR: the Spatial and Textural Affordances of VR as a Mapping Strategy for an Accessible Digital Musical Instrument

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## ABSTRACT

*The spatial affordances of VR have been explored for musical purposes in recent years, but the tactile affordances that are becoming increasingly available with current hardware have been relatively underexplored for music. The prevalence of consumer VR systems has created a renewed interest in embodied theories in tangible computing. However, there is a moral obligation for designers of accessible systems to focus on people-centred design methodologies. This paper will explore how the affordances of Virtual Reality (VR), with respect to adaptable mapping strategies, have supported the design of an Accessible Virtual Reality Musical Instrument (AVRMI) whilst also supporting participatory design practices. To begin participatory design processes, it is essential to find common areas of understanding between designer and participants. Within this paper the authors describe design strategies that explore the spatial and tactile affordances of VR as an embodied method of establishing a framework for the participatory design of an accessible and immersive system for music making. We conclude by presenting further designs resulting from these initial stages.*

## INTRODUCTION

This work builds upon two particular points of reference: the work of Dourish [1], who sets out a guide for HCI practitioners, bringing together the worlds of tangible and social computing under the heading of Embodied Interaction Design, and Johnson who states that human understanding 'is a result of the massive complex of our culture, language, history, and bodily mechanisms that blend to make our world what it is' [2]. Most notable of Dourish's six principles, in this context, are:

- Embodied technologies participate in the world they represent
- Users, not designers, create and communicate meaning

Dourish discusses why tangible computing works and emphasises the importance of embodied theories. But as we can see from these two principles and Johnson's description of our understanding of the world around us, environment and context are highly influential on our understanding. Thus, Dourish embraces social computing, with people-centred design strategies such as User Centred Design (UCD) and participatory design being important examples. This combination of social and tangible computing makes it ideal for accessible design and immersive technologies.

In exploring the affordances of VR and AR, Steffen et al [3] argue that affordances 'facilitate examining VR and AR in comparison to physical reality'. In their list of features of each, the clear difference is that physical reality is bound by physical laws, but VR is not. Affordances, however, are goal driven and not immediately evident from features alone. As designers of musical interfaces our main goal is to produce music. The question, therefore, is what affordances can we extract from VR to support our music making goals? If we take, as an example, the virtual reality string instrument *Coretet* [4] or bottle blowing virtual reality instrument *Cirque des Bouteilles* [5] we might view the affordances not as the reproduction of physical world events but the exploration of music synthesis through real world interactions. The features of VR are immersive and embodied and with music creation as our goal we might explore spatial and tactile features with musical metaphors to extract new and unexploited affordances [6].

We investigate the potential affordances of VR and embodied musical metaphors as a musical language that may prove to be accessible across cultural and disciplinary differences, as a tool for participatory design and to improve the usability of a Virtual Reality Musical Interface (VRMI) through haptic feedback and mapping [7]. We do not present the full participatory practice involved in this work which occurred over many months. However, we do present some to demonstrate the use of social computing in the design and as a foundation for the mapping process.

# 1. EXISTING ADMI PRACTICES

Accessible Digital Musical Interfaces, are becoming more prevalent within Digital Musical Instrument (DMI) design, as reflected in growing submissions to ICMC, SMC and NIME. This is demonstrated in Frid's 2018 [8] survey of ADMIs presented at SMC, ICMC and NIME conferences. More recently the NIME 2020 conference's theme was 'Accessibility of Musical Expression' and included papers such as [9], [10], [11], [12], [13], [14] and the importance of participatory practices discussed in [15].

ADMIs are varied in context and execution and examples vary from adaptive routes using MIDI such as *Modular Accessible Musical Instrument* (MAMI) [16] and *The Music Cre8tor* [17], to movement based interfaces such as *Adaptive Music Technology Using the Kinect* [18], *Motion Composer* [19] and *Adaptive Use Musical Instruments* (AUMI) [20] and continued interest in brain-computer interfaces (BCMI) at ICMC conferences such as [21], [22] and [23].

As Frid's 2018 survey also notes, most ADMIs come in the form of tangible user interfaces (TUIs), with non-tangible interfaces following. Although many of the ADMIs in the literature refer to participatory methods within their design it is often difficult to ascertain the exact nature and structure of those participatory methods. This is perhaps due to the great variety in contexts and cases that ADMIs reside within, and participatory methods are seldom 'one size fits all'.

Participatory design can address imbalances in knowledge [24] and methods such as PICTIVE [25] through its use of low-tech objects and iconography can allow designers to find hybrid spaces in which designers and participants can metaphorically meet, negotiate and collaborate on the design of systems [26]. The authors believed it important to begin the participatory process by establishing a hybrid space for the conceptualisation and collaborative design of an AVRMI. This system exploits the affordances of VR and in turn, can be explored using a shared descriptive language that inhabits both tangible and social computing.

# 2. VR'S AFFORDANCES FOR INTERACTION AND SHARED MUSICAL LANGUAGES

The primary affordances of VR can be seen as related to its audio-visual and enactive spatiality. These spatial affordances are evident in the auditory and visual sensory outputs of head mounted displays and headphones. The spatial affordances of VR have been used to explore timbre [27], [12] and pitch organisation [28], [29]. Tactile affordances, through vibro-tactile feedback are mostly associated with gaming in interactions with GUIs and physics-based interactions such as hitting an object.

Integrating the audio-visual and spatial affordances of VR with texture data associated with 3D objects in game engines such as Unity, has the potential to be a source of control data for audio synthesis. It is the consideration of the tactile affordances from 3D objects along with their morphology as a spatial affordance that led to an idea that embodied models of timbre and pitch could form the basis of a shared musical language to address the imbalance of knowledge between designer and co-designers in the creation of an AVRMI. From an accessibility standpoint, a synergy of the audio, visual and haptic output modalities may be utilised to increase the 'bandwidth of information transfer' [30], to support the learnability of such a system while providing alternative channels of information should one of those modalities be missing or filtered due to physical impairment [31].

## 2.1 Establishing a Shared Descriptive Language

To establish a shared descriptive language for participatory design purposes, the authors considered what the imbalance of knowledge may be between designer and participants when designing an AVRMI. The participants (N = 4) within this project are musicians with intellectual or physical disabilities and no formal musical training. The researchers are trained musicians and as such the imbalance was identified as residing within musical language and that a shared language within the context of immersive music making may be found in the shared and embodied descriptions of musical qualities.

Descriptors of timbre are predominantly visual and tactile [32]. The texture features of 3D objects within game engines are controlled by texture maps. These maps affect lighting and are therefore predominantly visual. However, it is possible to access the data within these maps and therefore extract tactile features. By conceptually connecting the tactile descriptor of timbre and the VR feature of 3D texture, a VR system (with appropriate mapping and synthesis) can afford the performing of timbral modulations. And indeed, we can continue this process to find other affordances that may work well within the context of a shared musical language (Table 1).

This was explored through workshops using a granulator to change the timbre of audio samples and asking individual participants to describe the sounds they heard as rough or smooth. In another workshop the participants were shown two spheres with differing textures (one rough and one smooth) being 'performed' in a video of a prototype. They were asked to describe the sounds being performed as rough or smooth also. The participants were also asked, after individual sessions, to agree on descriptions as a group. There was consensus between participants and between participants and researcher on these descriptions. By connecting the tangible to a hybrid space for participatory design we began the design process firmly rooted in a framework based on Embodied Interaction Design, seeking metaphors and affordances which may have the potential to be accessible to participants without formal musical training.

| **VR Feature** | **Musical Descriptor-METAPHOR** | **Affordance** |
|---|---|---|
| 3D Texture in space | Rough or smooth sounds – TIMBRE IS TEXTURE | Performance of timbral modulations |
| Spatial morphology of 3D object | Pitch height - PITCH IS VERTICAL | Performance of pitch modulations |
| Spatial morphology of 3D object | Music moves - MOVING MUSIC | Scrubbing of audio samples |

**Table 1** Musical affordances of VR

## 3. AFFORDANCES AND METAPHORS: MAPPING FEATURES OF 3D MORPHOLOGY TO MUSICAL METAPHORS IN UNITY

Developed in Unity, WithFeelVR uses ray casting and collision detection to interact with objects in 3D space. Figure 1 shows the ray cast interaction using a line renderer to make the ray cast visible to the performer in an early iteration. As the performer approaches the object with their hand, a collider triggers the ray cast from one of various colliders attached to the hand. The ray cast detects a hit when it reaches the object. With a ray cast hit Unity gives us information from which we can extract morphological features at that point of interaction and begin the mapping process to musical metaphors. Figure 1 shows a texture map being written to, to create 'paint' on the easel, demonstrating the interaction with the model's texture at that interaction point. Other features such as whether the interaction occurs on a bump, or a depression, for example, can be calculated.

### 3.1 Normal Map as a Control Source

Normal maps are images in 3D graphics that are used to affect light by adding surface details that do not exist within the geometry of the model. As such they can visually portray the roughness of an object but importantly can be read to determine pixel values. The relative roughness of an object cannot be determined by a single value, however. WithFeelVR, therefore, samples a square of 5x5 pixels of the normal map around the hit point.

To determine how rough the texture is at any given point we calculate the standard deviation of the pixel information. One flaw of using the standard deviation of the pixels occurs on boundaries where half of the pixels are entirely one colour and the other half another. This is evidently not rough, but the data is varied enough to produce a result suggesting that it is rough in our mapping strategy. However, in mapping to audio parameters and haptic feedback they produce an interesting 'quirk' that clearly signifies to the performer that they have crossed a brief boundary and thus works to notify the performer of this sudden change in texture both audibly and physically through vibro-tactile feedback. This is most obvious on tiled surfaces (e.g., floor or wall tiles) where the normal map is generally smooth, but boundaries are clearly visible.

**Figure 1.** Ray casting from finger to canvas '*instrument'* in an early exploration

**Figure 2.** An early iteration of a bespoke native Unity audio plugin for granulation loaded into an audio mixer (bottom) with parameters shown on right.

### 3.2 Mapping Material Texture to Granular Density

Having established the roughness of a particular point of interaction the standard deviation is normalised and used to change parameters in a bespoke Unity native audio plugin. The granulator (Figure 2) is loaded into an audio mixer within Unity. An audio clip can be loaded into a buffer within the granulator. This buffer is then used for granulation. The differences in texture interacted with determines the grain density by manipulating the grain duration, the delay between grains and the number of simultaneous grains (voices). The varying grain density in turn varies the timbral qualities of the sampled audio [33] and compositional structures may be formed via timbral variation through time [34] and interaction. The amplitude of vibro-tactile feedback is also mapped to the normalised standard deviation to create the synergy of audio, visual and haptic modalities.

### 3.3 Mapping Pitch Height to Object Morphology

The 3D objects such as that in Figure 2 are stochastic objects created using simplex noise deformation of a spherical mesh. They are stochastic and amorphous, but their general features can be altered in advance. These objects have no cultural or 'knowable' sounds, unlike a 3D model of a clock or trumpet, for example. This allowed us to test objects based purely on their shape and texture with participants and attach audio samples arbitrarily for compositions. Knowing the hit point coordinates from the ray cast it is a simple calculation to measure the hit point's distance from the object's centre and map this to the granulators pitch parameter, thus mapping bumps and depressions to pitch.

The 3D object in Figure 2 would seem to have waves across its surfaces and a relatively smooth surface otherwise. The waves are not part of the geometry but created by a normal map (thus creating interesting boundaries) but also with an added height map. Using the ray cast it is also possible to read data from the height map. No complex mathematical processes are needed. WithFeelVR simply measures the pixels of the grey-scale height map at the interaction point and adjusts the pitch ratio microtonally to add finer pitch control to the performance. The foundational pitch created by measuring the bumps and depressions of the mesh can be quantised to eight different scale structures. This allowed us to explore not only pitch height but pitch organisation with participants and discuss descriptors they might have for such organisation. Ultimately, though, the pitch organisation was not used.

### 3.4 Moving Music Metaphor and Objects as Paths

The present system design is also informed by Johnson's MOVING MUSIC metaphor; a complex mapping of spatial (motion) and temporal (MOVING TIME) metaphors [35]. For our purposes we consider our 3D object and its associated audio sample within Johnson's MUSICAL LANDSCAPE [36] metaphor. Just as our bodies can move across a physical landscape, we conceptualise musical events as existing upon a musical landscape. An example of the MUSICAL LANDSCAPE metaphor can be seen in the popular VR application *Beat Saber* (Beat Saber, 2021) where moving objects represent musical events to be struck by the game player in time. Within *Beat Saber* we might consider the user to be a passive observer on a MUSICAL LANDSCAPE, despite the obvious physical exertion. As they 'move' through the music they encounter and engage with musical events represented by 3D objects. Within WithFeelVR the user, however, takes the role of a participant controlling the motion through the MUSICAL LANDSCAPE.

Employing these metaphors in conception and through participatory design is quite simple. Many people, including our participants, are accustomed to scrubbing 'through' music from left to right on mobile devices and thus exploring a 3D object's sound by moving across it from left to right has been quite intuitive. There are no examples of exploring a 3D object's form to 'move' through audio that the authors are aware of. However, if we conceptualise a traditional UI slider used for music navigation within almost all commercial music playing software as an object containing or owning a sound, then moving a UI thumb allows the user to conceptually move through the music. This can be replicated by moving across a 3D object's form and scrubbing through an associated audio sample. The 3D object's form, thus, becomes a musical 'path' for the performer to move through.

### 3.5 Spatialisation – Timbre On Textures

By creating a native Unity audio plugin, we have allowed ourselves to take advantage of the spatialisation features that game engines do well. Unity spatialises audio before it is sent to a mixer. This means any synthesis created within a mixer (such as synthesis within a native audio plugin) is not spatialised. The solution came when exploring the possibilities of fine spatialisation. We wanted to spatialise the sound not only *from* the object but *upon* the object. We did this with a separate spatial audio source which is simply a game object with an audio source component and no rendering. The audio generated by the plugin is routed to the spatial audio source object which is moved during interaction to the hit point of the ray casting. The audio is thus synthesised according to the textural and morphological qualities of the interactive object but is spatialised by another object at that precise interaction location, so the sound appears to move around the object as the performer interacts with it. Thus rough/smooth sounds appear to be physically coming from rough/smooth areas of the object and enhance the sense of presence [37] through refined audio spatialisation. Spatiality, in this context, may be considered to contribute to the multimodal output through localisation of texturally altered audio (Figure 3).

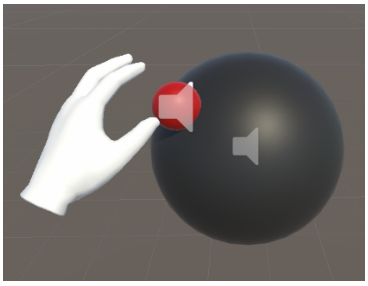

**Figure 3** Fine spatialisation: Granulation occurs on the black sphere but is routed to the audio source of the red sphere. In WithFeelVR the red sphere. would not be rendered, and sound would appear to come from that part of the black sphere.

## 4. ANALYSIS

### 4.1 Further Developments with Spatial and Textural Affordances

The mapping strategy presented here was the beginning stages of a large participatory design project for accessible ensemble/networked performance. It was the scaffold for that participatory project, and the establishment of an embodied language was essential to that project's progress and to ensure a large degree of participation. The initial design of WithFeelVR was modular with a singular source of musical interaction being touch via ray casting. The interaction between hand and 3D object provides many sources of data which are then separated into features for mapping based on musical descriptors and metaphors (Table 2) which in turn provides musical affordances.

| **Interaction Method** | **Feature extracted for input** | **Output** | **META-PHOR** |
|---|---|---|---|
| Ray cast from hand | Normal map - 3D texture | Timbral modulation of audio sample | TIMBRE IS TEXTURE |
| Ray cast from hand | Normal map - 3D texture | Vibrotactile feedback | TIMBRE IS TEXTURE |
| Ray cast from hand | Height map – 3D texture | Fine pitch modulation | PITCH IS VERTICAL |
| Ray cast from hand | Interaction position – Object shape | Pitch modulation | PITCH IS VERTICAL |
| Ray cast from hand | Interaction position | Audio scrubbing | MOVING MUSIC |
| Ray cast from hand | Interaction position | Fine audio spatialisation | MOVING MUSIC |

**Table 2** Feature extraction and mapped output

By beginning our process from an embodied interaction design perspective, we established an embodied framework for our iterative design process and opened that iterative design to participation from musicians with disabilities. After many months of iterative and participatory design the result of combining tangible and social computing was a networked VR music performance system where participants share compositions to be conducted and performed as an ensemble (Figure 4 & 5).

### 4.2 Interoperability

The first prototype of the performance system was created using Unity and a granulator in Max/MSP, with OSC providing communication between the two. However, a system for non-expert users and for usability purposes, this is less than ideal. A better approach for the user is to have a single application that requires no technical expertise to use (assigning ports, IP addresses, etc) which can be updated according to the needs of the project. A typical solution to this is to use libPd.

Creating a bespoke C++ plugin was part of our modular approach. Pure data in the embedded form of libPd has proven to be a useful development tool for audio synthesis in VRMIs such as Coretet [4] and Pathosonic [12]. By creating our own Unity native audio plugin using JUCE C++ we could maintain and update as our development demanded which gave us the added ability to use this plugin in VST format in another supporting application that creates compositional content for WithFeelVR. The result has been a user-friendly system that embraces interoperability.

**Figure 4**. Networked conducting using drawn gestures

**Figure 5**. Participants perform their compositions together in a network after numerous design iterations

### 4.3 Accessible Composition Interface (ACI)

The various embodied components of our shared descriptive language and the mapping strategies presented may be combined for musical story telling. Instrument may be conceived as 3D object and timbral modulation as material with varying combinations of these unfolding to produce a composed and structured performance using chosen audio samples.

And indeed, this is what happened with further development and because of our embodied framework. Through further iterative design and with an established embodied language, a composition application called Compose WithFeel was created to support WithFeelVR using the VST version of the granulation plugin to provide auditioning. 3D objects and materials provide compositional methods of dictating timbral and pitch modulation when later performed in WithFeelVR. Figure 6 shows 3D objects used in a timeline editor with materials added to create a composition. Other iconography, developed through participatory means, represents audio samples, environments and avatars chosen by the composer and is beyond the scope of this paper.

**Figure 6.** Compose WithFeel: a DAW-like application. Choosing 3D objects and materials for composition.

### 4.4 Participatory Design: VR by Proxy, Online Workshops, and Iterative Design

The dominant activities for the participatory design were workshopping and iterative design. Covid-19 forced this work online for a significant time. Online workshops were facilitated using screensharing, open discussions, and proxy use of the software being developed. VR by proxy was extremely useful and as [38], [39] demonstrate, VR by proxy may have educational benefits. The learning benefits within this online design process were mutual but online design has some downfalls.

When in-person workshopping was finally available, certain issues became obvious that were not noticed in online sessions. However, these were mostly found to be issues in code and networking. During in-person sessions all participants composed, conducted, and performed using the system after a short period (4-6 sessions) of training. One participant was given a VR set-up to work with at home during online sessions. They only used this set-up when the group met online. When in-person sessions began they were much more adept at using the software than their counterparts who had previously only used the software by proxy. Thus online participation is useful but may not be optimal.

### 4.5 Further Analysis

Some of the VR features we have presented are not immediately obvious when working with a game engine such as Unity. Collision detection and object position/rotation are the most obvious features when exploring potential musical affordances in a game engine setting. Through the exploration of Unity's technical documentation, we have discovered other features that we have used to explore musical affordances.

Where controllers were impractical to use because of a participant's physical impairments, head-gaze and haptic wearables were introduced along with animated hand motion. The participant in question took to this method with great ease and although they were not physically using their hands the multimodal output was unbroken due to the use of haptic wearables attached to their wrists.

VR is not suitable for all. Certain medical conditions can make it potentially hazardous for individuals, while covering the face or head has the potential to trigger adverse emotional reactions in others. For this reason, WithFeelVR was also built to work without VR. The multimodal output was again recreated with the use of haptic wearables to maintain a synergy between the audio, visual and tactile modalities.

The participants were asked to assess the overall system of software, including the Accessible Composition Interface, using the System Usability Scale (SUS). SUS was chosen because it is short, and the statements are relatively easy to understand [40]. It was, however, adapted by using varying emojis to represent 'strongly disagree' to 'strongly agree' to help the participants understand their answers and some support was given in completing the assessment. Not all participants were able to participate in the assessment. Using this method, the system scored 81.7. The average usability score in SUS is 68, putting the WithFeel system well above average for usability with this very small sample of users ($N = 3$). Further analysis would be beneficial regarding usability with a greater sample of users who were not part of the participatory process. But as a participatory tool this allowed the participants to self-assess.

## 5. CONCLUSION

One approach to building a VRMI is to replicate the affordances of the physical world in their entirety. We have chosen to explore musical affordances that are only possible in synthetic worlds in combination with those found in the physical world. These new affordances might best be explored in a participatory manner to explore commonalities in our perception and learning of affordances within VR.

Embodied interaction design has allowed us to start from simple beginnings, looking at tangible methods of music making while establishing methods for social computing in the form of participatory design simultaneously. We explored the affordances of VR by examining the embodied musical descriptions of participants with intellectual or physical disabilities and combined those with features extracted from the Unity game engine. The tactile affordances of VR for music making are relatively unexplored within the literature and by exposing the capability to exploit 3D geometric and material properties for music performance, we were able to open doors to further iterative and participatory design that engendered new design artifacts for conducting and composition within an immersive environment.

An interoperable system combining a C++ composition application, audio plugin and Unity developed performance system was complex but embodied interaction design from the outset ensured the design was focussed on the embodied musical descriptions and feedback of the participants, aiding in a continuity of design.

Here, we presented our early development stage examining the musical affordances of VR; mapping multimodal output based on embodied musical descriptions from participants for performance. We then summarised further developments to demonstrate how maintaining this embodied approach can lead to more complex designs that results in composition for, and conducting within, VR.

People-centred design practices can bring about unique and unexpected outcomes [26], [41] and asks that we find commonalities of language for our design endeavours. Our context for social computing was accessibility but people-centred approaches can come in many contexts. The authors are unaware of 3D texture maps being used for interactive audio synthesis in VR for instance. We believe the combination of embodiment and people-centred approaches led to such innovative ideas in our design. We believe these strategies might also be exploited by the wider computer music community.

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