Collaborative Musical Expression Through Interactive VR Scores

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Abstract

While the technical affordances of virtual reality (VR) have provided new ways for artists to aestheticize immersion, spectator agency, embodiment and multi-sensory engagement, they have also opened new possibilities for composers interested in exploring how interactive musical scores might become a means through which collaboration itself becomes the locus of aesthetic expression. In this paper, the author will provide an overview of an ongoing project which explores new ways of thinking about musical collaboration in VR through the 3D visualization of interactive, graphic scores adapted from works by composers Earle Brown, Christian Wolff, and Toru Takemitsu. The research demonstrates how VR can transform traditional score interpretation by creating dynamic, interactive environments that enable collaborative musical expression, challenge conventional notation, and offer novel ways of negotiating musical performance through networked, multi-user interactions.

Keywords

Virtual Reality, Music Notation, Musical Collaboration, Networking, Multiplayer

1 Introduction - The Ontology of the Score

Musical scores are not ordinarily thought of as objects which can be interacted with in a material sense. Traditionally existing as static containers of information that unfolds over time, they are usually subsumed into the background during performance or altogether absent should performers have memorised the information bound within their pages. Given this legacy, it would seem counterintuitive for the visual aesthetics of scores to receive much attention. Nevertheless, the design and appearance of musical scores has received greater investigation in a growing variety of practice since the mid-twentieth century. The increasing adoption of digital displays [21], has facilitated the development of animated scores [9], networked scores [13], and even reactive scores responsive to performer and audience agency [12]. All of these developments have opened new creative affordances for musical expression and new pathways for critical discourse.

These rapid developments have presented particular challenges for how such digital, dynamic scores might be theoretically situated and in this respect object-oriented ontology offers a particularly helpful framework. Simondon's theory of individuation [19], suggests that the score can be understood as an individuated entity that embodies a set of pre-individual potentials, awaiting actualisation through the act of performance. It exists not merely as a passive set of instructions but as a dynamic reservoir of possibilities that shapes and is shaped by its interactions with musicians and listeners. Yuk Hui's extension of Simondon's ideas into the realm of digital objects extends and illuminates this perspective [10], suggesting that as digital objects such scores operate within a network of relations, continuously redefined by their context and interactions. Through such a theoretical framework, the score is thus an active participant in the digital ecosystem, possessing its own influence independent of human engagement.

The particular network of relations within which reactive scores operate - and how they can both facilitate collaboration and establish collaboration as a holder of aesthetic value - is the fundamental driving force of the project outlined in this paper. Leveraging the affordances of VR, the score no longer sits as a passive repository of information but rather, offers new modalities of performance and challenges our understanding of what a score can be. Some of these possibilities will emerge in the following sections of this paper which will focus on how the musical potentials of a score can be actualised through the collective agency of networked participants.

2 VR Adaptations

The mid-twentieth century witnessed an explosion of interest in non-linear musical forms which could not typically be easily represented by standard, common-practice notation. Coupled with a related consideration of how performance agency might be leveraged in novel ways, the score for works such as Earle Brown's iconic *December 1952* (1952) offered radical new ways of representing musical form, see Figure 1.

Despite their idiosyncratic approach to musical notation, such scores were nevertheless bound by the physical constraints of the medium upon which they were inscribed. While composers such as John Cage experimented with different printed medium such as transparencies in the 1950s, it was not until the adoption of digital displays that scores could transcend the inherent physical constraints of fixed mediums. The use of generative or procedural techniques of composition, for example, and the development of notation software such as MaxScore [5] and Bach [1] allowed scores to be instantiated in real-time during performance and displayed for performers on digital displays. These creative and aesthetic affordances have been considerably extended through the rapid evolution and growing accessibility of VR technologies. In adapting various historical works for a VR environment, the aesthetic affordances of multiplayer collaboration has emerged as a key focus.

The selection of works by Brown, Wolff, and Takemitsu for VR adaptation was deliberate, based on several specific criteria that make these compositions particularly suitable for virtual reality implementation. First, each score already challenges conventional notational paradigms through its graphic approach,

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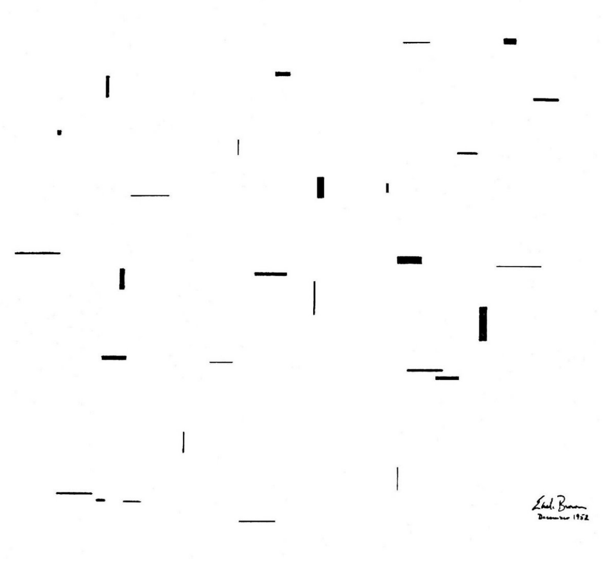

Figure 1: *December 1952* by Earle Brown. This seminal graphic score leaves much of the musical decision making to performers.

providing conceptual openness that aligns with VR's spatial affordances. Second, these works span different compositional approaches to indeterminacy — Brown's geometric abstraction, Wolff's network-like structures, and Takemitsu's circular organization—allowing exploration of diverse VR visualization strategies. The inherent non-linearity of these scores harmonizes with VR's capacity to break from the left-to-right reading tradition of Western notation, enabling truly spatial musical thinking. Additionally, these works were chosen for their explicit invitation of performer agency in the realization process, a characteristic that extends naturally to the collaborative manipulation possible in networked VR. The progression from *Four Systems* to *Jasper* to *Corona* also represents an increasing complexity in both notational approach and VR implementation, providing a path of logical development for the research.

2.1 Related Work in VR

While the work discussed in this paper extends existing research by the author on graphic scores in immersive environments [11], it is helpful to situate this within the broader landscape of symbolic music representations and instruments in VR. El Raheb et al. investigated transferring symbolic languages from paper to spatial cues in mixed reality [6], while Zellerbach and Roberts proposed a framework for a Mixed Reality Musical Instrument (MRMI) examining relationships between performers, virtual objects, and physical environments [24]. Their work emphasizes how symbolic representations in mixed reality can create intuitive relationships between gesture and sound, particularly relevant to an exploration of immersive graphic scores. This spatial representation of musical information presents unique opportunities for embodied cognition that traditional paper-based notation cannot provide, allowing performers to engage with musical structures through physical movement and spatial awareness.

The field of Virtual Reality Musical Instruments (VRMIs) has received considerably more attention, as evidenced by several systematic reviews and frameworks. Serafin et al. outlined nine design principles for VRMIs, emphasizing that they should not merely replicate existing instruments but offer new possibilities leveraging virtual environments [18]. Gómez-Sirvent et al. identified seventy-four studies of musical instruments in extended reality with applications ranging from education to rehabilitation [8], while Berthaut et al. proposed a scenography framework for immersive virtual musical instruments addressing dimensions such as musician visibility and gestural continuity [**?**]. Webster and Kourkoulakou examined the challenges of avatar representation and embodiment in immersive 3D audio composition environments [22]. Their research on the VRAS project highlights how questions of presence and virtual body representation significantly impact musical experience in VR, informing the approach to representing participants in shared score environments. The work explored in this paper bridges these approaches by exploring how immersive visualization of graphic scores can enhance collaborative performance through spatial understanding and multi-user interaction in ways traditional physical scores cannot achieve. Unlike many VRMIs that focus primarily on solo performance, these adaptations specifically investigate the affordances of networked multiplayer environments for collaborative music-making, addressing Serafin's principle of making VR experiences social while exploring how score interpretation can be collectively negotiated in real-time.

3 Implementations

3.1 *Four Systems* (1952-53) - Earle Brown

In terms of its visual design, the score for Earle Brown's *Four Systems*, for pianist, bears distinct similarities to December 1952 featuring four systems of rectangles of different sizes and spatial arrangements, see Figure 2a.

Figure 2: a) The first system from Earle Brown's *Four Systems* (1952-53) (upper), b) Part of the score presented in a VR adaptation as viewed by the pianist through an Oculus Quest 3 headset in pass-through mode

Brown's work is the first that the author has adapted for a networked, multiplayer VR environment where the score is presented as an interactive, three-dimensional visualization and viewed by a pianist through an Oculus Quest 3 head-mounted display (HMD) in pass-through mode, see Figure 2b. During performance, networked participants enter the space in which the score is situated and effect various transformations to its components which are visible to all connected clients. This transformations in turn affect the interpretive possibilities available to the pianist. There are two ways in which the score may be transformed. Firstly, the rectangular prisms which make up the score can be grabbed via hand-tracking and carefully repositioned, or even thrown, within the virtual room with their behaviour subject to room gravity and inertia. These relocations may result in collisions with other components of the score resulting in cascaded movements amongst other objects. Secondly, score objects can be resized by increasing or decreasing the distance between thumb and index finger which in addition to affecting the way the pianist might engage with the score, also affects some of the audio functionality of the score which will be discussed shortly.

Much as in the real world, virtual hands cannot interact with objects at a distance. For the *Four Systems* adaptation, two different solutions to this problem were implemented. In the first solution, raycasts were attached to the hands to target distant objects, see Figure 3, while in the second, the safety boundaries established when launching the application were changed to "Roomscale" so that users can physically wander over to distant objects and manipulate them directly. Such wandering is by default not available when an application is launched for obvious safety reasons.

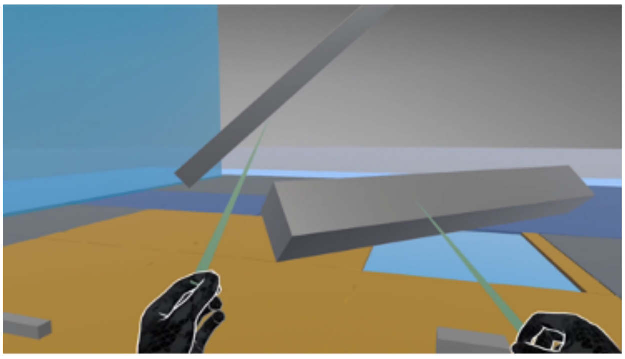

Figure 3: Raycasts attached to each hand allow the manipulation of score objects situated at a distance.

The VR adaptation also functions as a virtual instrument with each score object directly correlated to a prerecorded piano sample which is triggered back when objects collide or when a client "pinches" them within the VR space. The size of the objects is correlated to musical pitches - larger objects correspond to lower pitches while smaller objects correspond to higher pitches. The piano samples triggered by agents are broadcast to all connected clients and also to the live performance space in which the piano is located such that the pianist is performing amongst a tapestry of virtually activated piano sounds. In addition, the live interpretation of the pianist, is also streamed to each connected client for them to hear locally.

The VR adaptation of *Four Systems* thus presents a somewhat unusual performance model that is both localized within a live performance space and distributed to all connected clients. This performance modality is schematized in Figure 4.

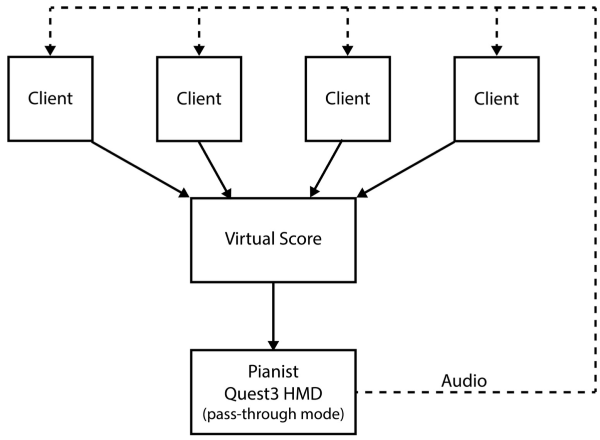

Figure 4: Performance framework for *Four Systems*.

3.2 *Jasper* (1991) - Christian Wolff

Christian Wolff's creative output is extraordinarily vast and defies easy summarization. Nevertheless, perhaps his most recognized thematic pursuit has been a long-running engagement with how the collaborative, dynamic nature of performance can be aestheticized in distinctive musical forms and, following from this, how such collaborative processes might be denoted in performance scores. This foregrounding of collaborative relationships encourages an inclusive and participatory approach to composition and performance and is closely aligned with Wolff's political sensibilities [7].

While *Jasper* is a relatively late work in Wolff's oeuvre, it continues his exploration of many of the aesthetic possibilities of collaborative processes. Written for double-bass and violin, the third movement features a graphic score that closely resembles a node-graph, see Figure 5.

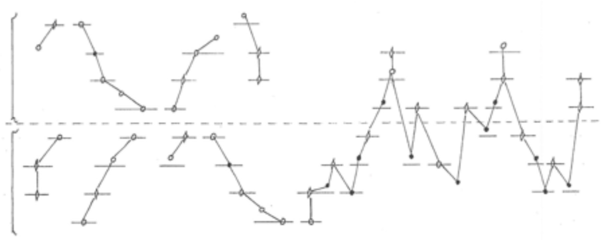

Figure 5: An excerpt from the score to the third movement of *Jasper* (1991) with the upper bracket denoting the violin part and the lower bracket the double-bass part. The short, horizontal lines denote the four strings of each instrument while the open and closed diamonds indicate notes.

The author's VR adaptation of the third movement of *Jasper* builds on many of the techniques developed in the earlier *Four Systems* adaptation including hand-tracking interaction and the same performance modality illustrated in Figure 4. Given there is no need for the two performers to be able to see their instruments in the same way as a pianist might, the presentation of the score does not require the AR-like presentation of pass-through mode. Rather, the score is presented to the two performers as an immersive visualization which can be fully read by turning through 360-degrees, see Figure 6.

In *Jasper* three classes of sonic events are denoted by different colored nodes - 1. Events of long duration (green nodes), 2. Events of short duration (red nodes), 3. Harmonics of either short or long duration (white nodes). In the VR adaptation, these nodes are wrapped around each of the performers preserving the original distribution along the x-axis in the original score. To

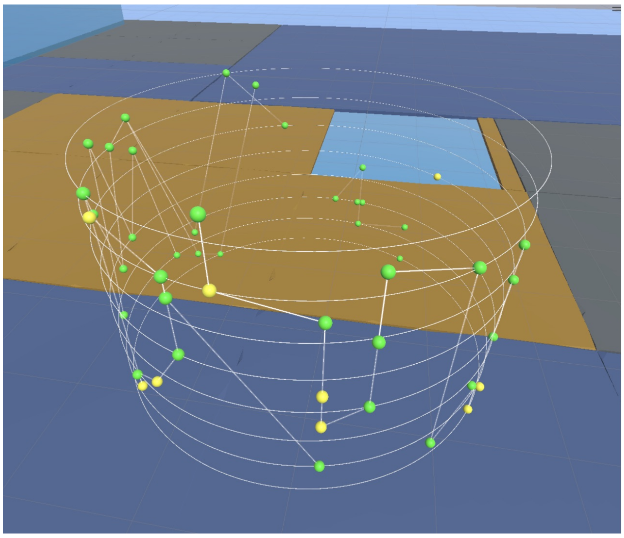

Figure 6: The immersive VR score for *Jasper* (1991) viewed from outside.

help distinguish the vertical position of each of the nodes, the strings - which in the original score are denoted by short horizontal lines - are drawn as rings surrounding the viewer within the VR scene, as shown in Figure 6. In Unity3D, the development platform used for all VR adaptations discussed in this paper, each of these rings are rendered as splines which helps facilitate the interactive capabilities of the score. Finally, nodes are connected by thin lines, corresponding to edges in a node graph, which in the VR adaptation are given a slightly different colour mapping to contrast them from the string lines.

As in *Jasper*, players within the VR scene can interact with the components of the score which directly affects the interpretive possibilities available to the two live musicians. There are two possibilities for score interaction both of which are facilitated via hand tracking - 1) By pushing nodes along the string lines, 2) By "plucking" the edges that connect nodes. Similarly to an abacus, nodes can be pushed either left or right along the string upon which they sit. Each of the nodes is subject to Newtonian physics behaviours upon collision with other nodes with the force of hand movement directly correlated to the velocity of movement along each string. This behaviour is implemented within Unity by aligning the movement of each node to the closest position along the spline upon which it sits. The second type of score interaction implemented is the plucking of edges that connect nodes which is implemented by a simple collision detection with the hands and which results in the playback of an audio sample of a prerecorded plucked string. The force of the collision is correlated to the volume of the playback sample and the length of the string is correlated to pitch with long strings sounding as low frequencies and short strings sounding as higher pitches. These audio samples are played to all connected clients.

3.3 *Corona* (1962) - Toru Takemitsu

In the late 1950s and early 1960s, composer John Cage began exploring how musical scores constructed from materials other than paper might offer new musical possibilities and creative affordances. Profoundly coupled with his well-documented concerns with the aesthetics of intention and listening, these experiments resulted in a series of works such as *Fontana Mix* (1958), *Variations I* (1958), *Cartridge Music* (1960), and *Variations II* (1961), amongst others, which radically repositioned relationships between performers, audiences, and scores. The works to emerge from this period found a particularly receptive audience in Japan, this no doubt also from the strong influence of Zen Buddhist traditions on Cage's creative practice, amongst its own experimental music practice represented by artist collectives such as Group Ongaku [14] and composers like Toshi Ichiyanagi whose *Music for Piano No. 7* (1961) features a score constructed from superimposed transparent sheets. Ichiyanagi's student Toru Takemitsu, continued to explore the musical possibilities of graphic notation in a series of works produced in the early 1960s the most striking of which perhaps is *Corona* (1962) which was premiered by Ichiyanagi and pianist Yuji Takahashi in February 1962.

Takemitsu created the score for *Corona* in collaboration with graphic designer Kôhei Sugiura [3]. The piece exists in two versions - one for solo piano, and the other for string orchestra. The piano version comprises five studies - 1. Study for Vibration, 2. Study for Intonation, 3. Study for Articulation, 4. Study for Expression, and 5. Study for Conversation. Each study features a single-page score printed in blue, red, yellow, grey, and white ink, respectively, on individual transparencies. While Takemitsu's performance notes are somewhat ambiguous, he suggests that each of these transparencies may be cut and intersected with others to form different arrangements [20]. The score for each study is characterized by its circular, non-linear structure with various musical events graphically presented along its perimeter. The pianist commences performance of a particular study by selecting a point along the perimeter and transversing their way around the circle in either a clockwise or anticlockwise direction at a speed loosely indicated as 1. possibly slow, 2. 2 min or 4 min, 3. possibly fast, 4. 1 min or 3 min or 5 min, and 5. tempo free [20].

The circular structure of *Corona*, where no one spatial location is more privileged than any other and where this in turn helps support a non-linear temporal ontology, lends itself particularly well to an arrangement and presentation in an immersive, virtual reality space. The author has chosen "Study for Intonation" for such an adaptation, see Figure 7.

In the VR adaptation of "Study for Intonation" developed by the author, the notational descriptors which denote the properties of various sonic events are stochastically distributed along the perimeter of the circle. The score is uniquely generated upon each instantiation within constraints defined in a set of predetermined rules - for example no more than three nodes may be drawn along any radial and no more than eight radials may be generated in any instantiation. Two such instantiations are presented in Figure 8.

Just like the VR scores developed for *Four Systems* and *Jasper*, the VR score for *Corona* is expressly intended for a performance model wherein the performer is presented with a score that is manipulated and also performed or sounded by networked clients in what amounts to both a local and distributed mode of performance. In *Corona*, clients enter the VR space in which the score is situated and interact with its various components by either 1) repositioning them, or 2) playing or sounding them as if they are a musical instrument. Both modes of networked interaction are broadcast to all other connected clients including the live pianist who views the score as it is being transformed through an Oculus Quest 3 HMD in pass-through mode. The repositioning of score components includes the stretching of the radials which extend outwards from the score's central circle

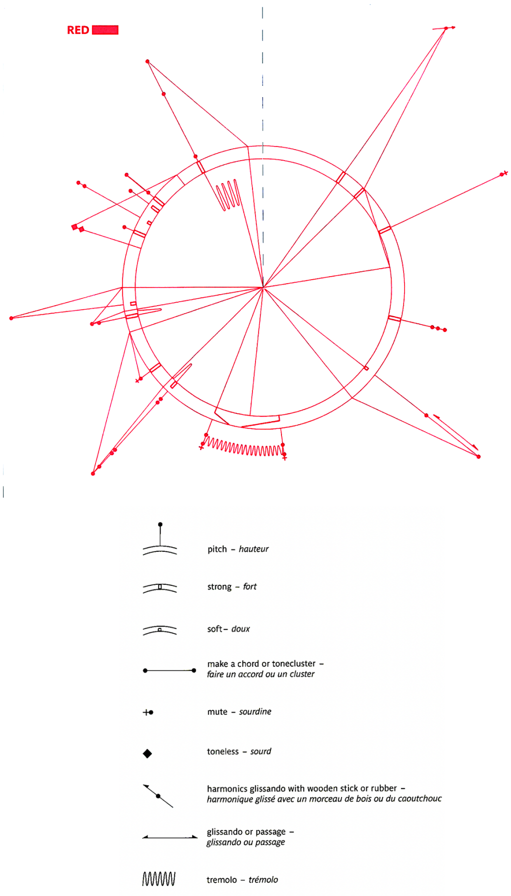

Figure 7: a) The score for "Study for Intonation" from Toru Takemitsu's *Corona* (1962) (upper), b) A key to some of the notational descriptors (lower)

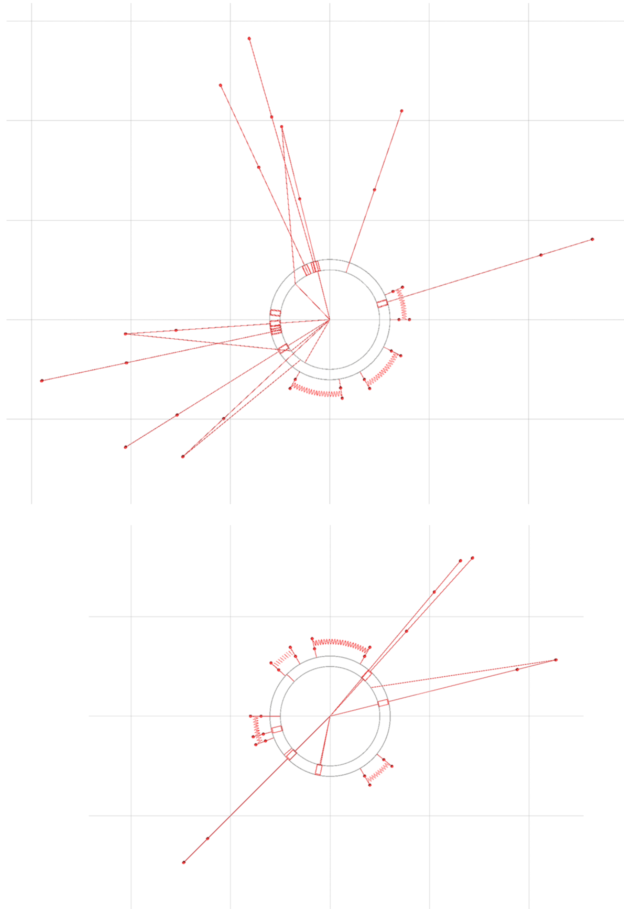

Figure 8: Two uniquely generated instantiations of "Study for Intonation" from *Corona* (1962).

via repositioning of the "nodes" which are positioned at its end terminals, and the spatial repositioning of these nodes along invisible circular splines. These interactions are effected and facilitated through hand-tracking in a similar method to that outlined in earlier discussion of *Four Systems* and *Jasper*.

Since pianists cannot physically rotate while performing to read an immersive score, the score presented to the pianist of *Corona* is simply presented along an imaginary y-plane located in a position closely aligned to the piano music rack. As the score is transformed and sounded by networked clients, the live pianist is presented with an ever-changing variety of interpretive possibilities. Similarly to *Four Systems*, this interpretation is broadcast to connected clients in what amounts to a closed feedback loop.

3.4 Multiplayer Connectivity

The multiplayer functionality of the three VR adaptations presented enables clients to manipulate the score from any location in the world. This connectivity is facilitated through the Photon Fusion 2 SDK, using a network topology classified as "Shared Mode." In this implementation, the virtual room in which the score is situated retains state authority over the score objects. Each object has a unique Network ID when instantiated. Each object has a unique Network ID when instantiated. When clients directly manipulate a score object, state authority is temporarily transferred to them, allowing all connected clients to see the spatial transformations of score objects in real time.

The room is hosted on a Photon server which requires a fixed region to enable multiplayer interaction. Remote procedure calls (RPCs) are sent to the server when an action by a client needs to be distributed to all connected clients. In *Four Systems*, *Jasper*, and *Corona*, RPCs are triggered when audio cues need to be played on all connected HMDs as a result of score interactions.

Network performance is affected by geographical distance from the server. During testing, the application was hosted in Singapore with multiple clients simultaneously connected in Australia and Europe. Network performance was measured using Photon network statistical tools. The consumer bandwidth per client averaged around 710 bytes per second, with approximately 30 packets in and 65 packets out. These values were low enough to minimize the impact of packet loss on performance and usability.

In all three adaptations, the performance of the live musicians is captured in real time and streamed to all connected clients via the Photon Voice SDK. The SDK was originally designed to facilitate live voice chat between players within a multiplayer gaming environment and can support chat at 48kHz with a bitrate up to 512kbps. Anecdotal evaluations of the audio performance, as heard through the internal loudspeakers of the Quest HMD reported satisfactory quality although this is somewhat mitigated by the frequency response of the internal Quest 2 loudspeakers with a significant roll off below 150Hz and above 5kHz [15].

4 Aestheticizing Collaboration in VR

The question of how collaboration between agents can be aestheticized to facilitate the development of novel musical forms and performance modalities is a key driver of this project. While this question is not new, having been a core focus of composers such as Wolff [16] and Cardew [4], it has received limited artistic investigation within the framework of VR. In the VR adaptations discussed above, collaboration leverages the multiplayer, networked framework offered by the Photon Fusion SDK. Given this SDK was primarily developed to facilitate multiplayer game development, game theory offers helpful insights into collaborative musical experiences.

Salen and Zimmerman analyse various modes of multiplayer interaction which are largely shaped by the types of goals and whether such play is cooperative or competitive. Their discussion of "collaborative play" and the value of alliances is particularly relevant to musical aesthetics [17].

4.1 Facilitating Collaboration

Alliances can be facilitated or hampered by game-play mechanics and the ways in which networking requirements are integrated within game design. The degree of network latency, for example, can help facilitate or disrupt collaborative experiences and has been a fundamental consideration in network-based musical performance [2]. For performances that depend on precise synchronization, even slight latency can disrupt the rhythmic integrity of a piece. In the VR projects discussed here, however, a more fluid and flexible approach to performance is presented where the timing of events is open to interpretation, thus mitigating latency's impact on musical collaboration.

4.2 Strategic Collaboration

Given the live performers of *Four Systems*, *Jasper*, and *Corona* are not able to manipulate the scores which they interpret, i.e. reactive agency is only afforded to the virtual participants, it is possible for agents within the virtual space in which the score is situated, to engage in strategic transformations of the score to shape the live interpretation in predetermined ways.

For example, in *Jasper* agents may choose to minimize the distance between nodes or alternatively keep them maximally separated both strategies of which will lead to perceivable changes in the live performance. In these strategic situations, the relationship between performers becomes more overtly goal-directed. Conversely, it is equally possible that relationships between agents not be directed towards common goals. In this situation, performance adopts a more exploratory focus with the performers navigating their way around the various musical possibilities presented by the score.

4.3 VR Specific Affordances

Correlations between music compositions and games, and between music performance and game play have been a source of creative inspiration for various composers such as Iannis Xenakis [23] and John Zorn. To what extent, however, might the specific affordances of multiplayer XR offer unique musical possibilities? The question is perhaps founded on the inherent physical distance and disembodiment through which networked agents interact. The subtle bodily cues and gestures which typify interaction amongst musical performers situated within the same room cannot be replicated in a multiplayer, networked space and the poor haptics of most VR technologies adversely impacts any simulation of real-world experiences.

Rather than attempting to replicate traditional performance interactions, the key to leveraging the aesthetic affordances of multiplayer VR is to design aesthetic experiences founded on the medium's inherent technical capacities. These might include:

• Creating unique physical forces that mediate interactions within virtual spaces • Tracking interactions and using this data to drive score transformations • Using 3D spatial audio as a means of mediating interaction between clients

4.4 Transformed Musical Experience

VR score adaptations fundamentally alter the performer's relationship with notation and collaborative music-making. For pianists engaging with *Four Systems*, the experience shifts from reading a fixed score to navigating a dynamic, evolving visual field manipulated by multiple agents. This creates a heightened awareness of the score as a living entity rather than a static prescription. Sonically, this transformation manifests in several ways: performers tend to respond more directly to spatial reconfigurations with corresponding changes in dynamics and articulation; the continuous feedback loop between virtual manipulations and acoustic performance creates emergent musical structures impossible in traditional scoring; and the blending of pre-recorded piano samples with live performance creates a rich sonic tapestry where the boundaries between different agents' contributions become veiled. In *Jasper* and *Corona*, the dimensional expansion of the score into fully immersive 3D environments encourages performers to approach pitch selection, timing, and timbre with greater freedom, as the traditional linear reading of notation gives way to a more exploratory engagement with musical parameters. Initial observations suggest that performers develop new frameworks for interpreting these scores, with a heightened sense of collaborative agency despite the physical separation between participants.

5 Summary and Future Work

While the development of VR technology and associated design software continues to be largely driven by the gaming industry, they nevertheless provide exciting new possibilities for creative expression and aesthetic investigation. For the author, these possibilities are manifested in the exploration of interactive multiplayer performance scores presented in 3D immersive visualizations.

The author is extending the work described in this paper in three areas - 1. The integration of player avatars to provide better awareness of the activity of other agents, 2. The integration of AI performers built through a model trained on the decisions made in previous performances by agents, and 3. A structured evaluation of how performers engage with these VR adaptations. For this evaluation, studies will be conducted with musicians from diverse musical backgrounds including those familiar with experimental notation and those from traditional performance practices. The evaluation will examine several key dimensions: the intuitiveness of score interaction, the impact of networked collaboration on performance decisions, how VR mediation affects musical interpretation compared to traditional score reading, and the overall experience of musical collaboration in virtual environments. This will involve both qualitative methods (semistructured interviews, think-aloud protocols during performance) and quantitative measures (such as analysis of interaction patterns and musical outcomes). It is hoped that such an evaluation will provide critical insights into how these systems function not just technically, but as tools for genuine artistic expression and collaboration, potentially revealing aspects of the design that could be refined to better support diverse performance practices.

As work on this project has progressed, the concept of the musical score as an instrument with its own potential and agency has become more significant. In this framework, the score is not merely a static set of instructions but an interactive tool that musicians engage with and which in turn can help shape that engagement through its design. This performance model also highlights the score's agency in the musical process as it actively influences the performer's decisions, providing a framework through which collaboration is mediated, and becoming an integral part of the creative act and collaborative experience.

6 Ethical Standards

This research involved the development of VR adaptations of musical scores for collaborative performance but did not involve direct human subject testing at this stage of development. The research received no specific grant from any funding agency, however the VR equipment used in this project was provided by The University of Sydney. Future evaluation with human performers will be conducted following appropriate institutional ethics approval and informed consent procedures.

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