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Networked Music Performance in Virtual Reality: Current Perspectives

Ben Loveridge
University of Melbourne, b.loveridge@unimelb.edu.au

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BEN LOVERIDGE[1]

Abstract

The ability for musicians to interact face-to-face has been highly impacted by the COVID-19 pandemic. Physical distancing and travel restrictions have forced teaching, rehearsals, and performances to be moved online. The use of videoconference platforms designed for conversation has also meant accepting their limitations when used in musical contexts. For example, in *networked music performance* (NMP), low-latency audio is usually transmitted alongside a separate video image. Since videoconference systems usually have a higher degree of in-built delay, the result is that performers often ignore the video image of each other in order to maintain a steady rhythm. If musicians usually avoid looking at each other during NMPs, could virtual reality provide a viable alternative to videoconferencing? In recent years, virtual reality has reemerged as an immersive medium with the ability to bring users together in an online space. However, there is a relatively small body of literature that is concerned with realistic acoustic interaction approaches in NMP when virtual reality is used as the visual medium. This paper explores research at the intersection of networked music performance, virtual reality, and virtual environments. It finds that virtual reality as a visual alternative to videoconferencing in NMP is worthy of further investigation and points to priorities for future research.

Introduction

The impact of the COVID-19 pandemic has affected the ability of musicians to interact face-to-face. As more musical activities have been forced to move online, it has become necessary for musicians to determine the most appropriate methods of online collaboration. In recent years, improvements to the quality of broadband connectivity has allowed musicians to collaborate remotely over the internet. One type of activity, known as *networked music performance* (NMP), has opened up opportunities in areas such as rehearsal, performance, and teaching. However, the

[1] University of Melbourne, Faculty of Fine Arts and Music, b.loveridge@unimelb.edu.au

overall nature of musical interaction is challenged by geographic distance, network performance, and available bandwidth.[2] Furthermore, the effects of out-of-sync visual cues in an NMP often results in performers ignoring the video image of each other in order to maintain a steady rhythm.[3] Attempting to achieve low-latency video requires significant bandwidth requirements and specialist networks, substantially increasing the setup and costs involved.

Determining the degree of necessary visual communication is a complex and underexplored area. When geographical separation restricts physical interaction, a key question to consider is this: What is the most appropriate way to capture, transmit and reconstruct musical interactions? Advances in video- and computer-game technology have encouraged the development of virtual instruments within virtual environments to create new styles of musical experience. However, there is only a relatively small body of literature that is concerned with realistic acoustic interaction approaches in NMP when virtual reality is used as the visual medium.

This paper examines published research in the areas of NMP, virtual reality, and the use of visuals in music performance. By examining these aspects collectively, the paper explores potential improvements to networked musical collaborations and suggests areas for further research.

Networked Music Performance (NMP)

Across the history of human civilization, music has played an important cohesive role in society as a form of communication, entertainment, dance, and ritual.[4] For thousands of years, musical activities occurred face-to-face, with aural and visual elements heard together at the same location. Recent advances in communication technology have enabled interaction over longer distances in shorter time frames, thereby increasing opportunities for remote music performance and collaboration.

The development of radio and telephony in the early twentieth century provided the capability for music to be broadcast to audiences over large distances. However, it was not until the introduction of computer networking in the 1970s that more widespread experimentation with interactive computer music would occur at a distance. Limited bandwidth at the time meant only data signals could be transmitted rather than full audio waveforms.[5] The sending of visuals over a

[2] Cristina Rottondi et al., "An Overview on Networked Music Performance Technologies," *IEEE Access* 4 (2016): 8823–43, https://doi.org/10.1109/ACCESS.2016.2628440.

[3] Juan-Pablo Cáceres et al., "To the Edge with China: Explorations in Network Performance," in *ARTECH 2008: Proceedings of the 4th International Conference on Digital Arts*, Porto, Portugal (2008): 61-66.

[4] Jeremy Montagu, "How Music and Instruments Began: A Brief Overview of the Origin and Entire Development of Music, from Its Earliest Stages," *Frontiers in Sociology* 2, no. 8 (June 2017), https://doi.org/10.3389/fsoc.2017.00008.

[5] Leonardo Gabrielli and Stefano Squartini, *Wireless Networked Music Performance* (Singapore: Springer Singapore, 2016), https://doi.org/10.1007/978-981-10-0335-6_5.

network would only become possible in subsequent years through improved processing and reduced transmission costs.

The late 1990s saw improvement to internet bandwidth pave the way for the delivery of high-quality digital audio between connected locations over networks. Time delays involving video and audio synchronization were identified as major obstacles, while at the same time fields such as music education and performance were seen as key areas for further research.[6]

At the turn of the twenty-first century, researchers at the Center for Computer Research in Music and Acoustics (CCRMA) at Stanford University experimented with high-quality online audio streaming, recording, and two-way musical interactions over networks.[7] One of the major challenges found at the time was the ability to visually keep in sync, due to high video latency. These CCRMA experiments led to the development of an open-source application, JackTrip.[8] The software could deliver uncompressed digital audio between multiple sites over the internet, while allowing for redundancy of data loss. Furthermore, it could be run on a modest computer setup with minimal hardware, requiring only an audio interface, microphone, and an internet connection of at least 1 Mbps upload per connection. At the same time, acknowledging and embracing network delay in performances emerged as an area for future online musical exploration.

The use of the phrase "networked music performance" (NMP) is generally attributed to John Lazzaro and John Wawrzynek, who wrote that "a Network Musical Performance occurs when a group of musicians, located at different physical locations, interact over a network to perform as they would if located in the same room."[9] This paper will use the definition of NMP provided by Cristina Rottondi et al., who wrote, "Networked Music Performance (NMP) represents a mediated interaction modality characterized by extremely strict requirements on network latency."[10]

Consumer internet bandwidth has now improved to the degree wherein home-based collaborative experiences are now within reach for the everyday musician. This has opened up possibilities for the enhancement of training and education in many different fields, music being one of them.[11] Practical uses of NMP have been identified in course delivery, instrumental tuition, remote

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[6] Robin Bargar et al., "AES White Paper 1001: Networking Audio and Music Using Internet2 and Next-Generation Internet Capabilities," *Journal of the Audio Engineering Society* 47, no. 4 (April 1, 1999): 300–310. https://secure.aes.org/forum/pubs/journal/?elib=12107.

[7] Chris Chafe et al., "A Simplified Approach to High Quality Music and Sound over IP," in *Proceedings of the COST G-6 Conference on Digital Audio Effects (DAFX-00)*, Verona, Italy (December 2000).

[8] Juan-Pablo Cáceres and Chris Chafe, "JackTrip: Under the Hood of an Engine for Network Audio," *Journal of New Music Research* 39, no. 3 (November 2010): 183–187, https://doi.org/10.1080/09298215.2010.481361.

[9] John Lazzaro and John Wawrzynek, "A Case for Network Musical Performance," in *Proceedings of the 11th International Workshop on Network and Operating Systems Support for Digital Audio and Video*, NOSSDAV '01 (Port Jefferson, New York, USA: Association for Computing Machinery, 2001), 157, https://doi.org/10.1145/378344.378367.

[10] Cristina Rottondi et al., "An Overview on Networked Music Performance Technologies," 8823.

[11] Mel Slater and Maria V. Sanchez-Vives, "Enhancing Our Lives with Immersive Virtual Reality," *Frontiers in Robotics and AI* 3, no. 74 (2016), doi: 10.3389/frobt.2016.00074.

recording, rehearsals, improvisation, building community, and music therapy interventions.[12] These activities highlight how NMP can also help foster valuable social connections while preventing isolation among geographically dispersed musicians.

Interaction Styles in NMP

Early work into the effect of delays on ensemble performance found that an effective real-time musical collaboration should be delayed by no more than 20 to 30 milliseconds.[13] These tests were performed by musicians playing acoustic instruments. This was a critical research outcome since it helped to define the upper boundaries for steady-beat rhythmic music performances. Various styles of musical interplay in an NMP were further categorized by Carôt and Werner, the Realistic Interaction Approach (RIA) being described as most closely simulating a realistic interaction of two musicians in the same room.[14]

The RIA style is based on an example of two rhythm-based instruments being performed online with a stable one-way latency of less than 25 ms. To avoid any confusion with other uses of the term "real time," the term RIA will be used to describe the type of interaction described above. The longest practical distance between two sites using RIA is estimated to be approximately 1,000 kilometers; this limitation is due to network and soundcard delays.[15]

Studies related to the effects of tempo and latency in RIA-style performances have indicated that as network latency increases, performance tempo decreases correspondingly.[16] Although

[12] For more on course delivery, instrumental tuition, and remote recording, see Miriam Iorwerth, David Moore, and Don Knox, "Challenges of Using Networked Music Performance in Education," in *Proceedings of the 26th UK AES Conference on Audio Education* (2015), 62-66. For more on rehearsals, improvisation, and building community, see Miriam Iorwerth and Don Knox, "The Application of Networked Music Performance to Access Ensemble Activity for Socially Isolated Musicians," in *Proceedings of the Web Audio Conference 2019: Diversity in Web Audio* (2019), https://researchonline.gcu.ac.uk/en/publications/the-application-of-networked-music-performance-to-access-ensemble. For more on music therapy interventions, see Jeanette Tamplin et al., "Development and Feasibility Testing of an Online Virtual Reality Platform for Delivering Therapeutic Group Singing Interventions for People Living with Spinal Cord Injury," *Journal of Telemedicine and Telecare* 26, no. 6 (July 2020): 365-75, https://doi.org/10.1177/1357633X19828463.

[13] Nathan Schuett, "The Effects of Latency on Ensemble Performance" (MA thesis, Stanford University, 2002).

[14] Alexander Carôt and Christian Werner, "Network Music Performance: Problems, Approaches, and Perspectives" (paper presentation, "Music in the Global Village" conference, Budapest, Hungary, September 6-8, 2007), http://www.carot.de/Docs/MITGV_AC_CW.pdf.

[15] Carôt and Werner, "Network Music Performance: Problems, Approaches, and Perspectives."

[16] Chris Chafe, Juan-Pablo Cáceres, and Michael Gurevich, "Effect of Temporal Separation on Synchronization in Rhythmic Performance," *Perception* 39, no. 7 (July 1, 2010): 982–92, https://doi.org/10.1068/p6465.

audio delays may lead to alternative—and often interesting—types of interactions, video is generally seen as unimportant in the process.[17]

Visuals in Networked Music Performance

Visual information has been shown to be a key aspect in the perception of musical expression in musical performances.[18] Furthermore, expressive nuances from a musician's body language are able to be perceived, even when given a minimal amount of information.[19] Together, this suggests there is a foundational importance for the inclusion of visual exchange during a music performance. This raises the question: How do technological limitations affect the use of visuals in the context of an NMP?

An event held in 1991 by composer Pauline Oliveros explored the use of videophone technology to transmit frame grabs over a telephone line.[20] Images beamed to remote locations were displayed every six seconds due to encoding and transmission delays. Although participants acknowledged that the limitations shaped the nature of the interaction, the experience was still found to convey a sense of shared social connection.

In 2008, a multi-ensemble concert titled "Pacific Rim of Fire" was held between Peking University in Beijing and Stanford University in Palo Alto, California.[21] Due to the 6,000 mile distance between sites, Terry Riley's "In C" was chosen as a suitable piece due to the known limitations this would enforce on the communication delay. High-quality uncompressed audio was sent over the network via JackTrip and measured with a one-way delay of 110 ms. Although falling outside of the bounds of an RIA-style performance, the two sites were able to play in a tight rhythmic alignment based on a feedback-locking technique.[22] Video latency, measured at approximately one second each way, provided a visual experience for the audience as well as for shared discussion among the musicians. In assessing the concert, achieving synchronized audio and video would have required not only higher frame-rate cameras, but also increased bandwidth, resulting in further

[17] Chris Chafe, "Living with Net Lag" In *Proceedings of the AES 43rd International Conference: Audio for Wirelessly Networked Personal Devices* (2011). http://www.aes.org/e-lib/browse.cfm?elib=16129.

[18] Jane W. Davidson, "Visual Perception of Performance Manner in the Movements of Solo Musicians," *Psychology of Music* 21, no. 2 (April 1, 1993): 103–13, https://doi.org/10.1177/030573569302100201.

[19] Sofia Dahl and Anders Friberg, "Visual Perception of Expressiveness in Musicians' Body Movements," *Music Perception: An Interdisciplinary Journal* 24, no. 5 (June 2007): 433–54, https://doi.org/10.1525/mp.2007.24.5.433.

[20] Joe Catalano, "Electronic Midwifery: A Videophone Celebration of Pauline Oliveros's 'Four Decades of Composing and Community,'" *Leonardo Music Journal* 3 (1993): 29–34, https://doi.org/10.2307/1513266.

[21] Cáceres et al., "To the Edge with China."

[22] Juan-Pablo Cáceres and Alain B. Renaud, "Playing the Network: The Use of Time Delays as Musical Devices," in *Proceedings of the International Computer Music Conference* (2010), 244–50.

delays of the audio signal. Since musicians would not be looking at each other constantly during the performance, it was felt this trade-off was not necessary.

Researchers have sought to address the challenge of latency over video with varying degrees of success. Conceived in 2005 and first publicly demonstrated in 2010, LoLa [LOw LAtency audio visual streaming system], was devised to tackle the issues of connecting remote musicians.[23] LoLa allows for both audio and video exchanges, but also a substantial audio-visual setup including both a high-powered computer and a large network bandwidth of up to 1 Gbps to handle the video connection. LoLa has been found to be an effective tool for networked music activities, however technical issues such as latency and access to high-speed networks are noted as major challenges.[24]

What musical moments are deemed to be useful for being seen on video in an NMP? There is some evidence to suggest that visual communication may be important when performers need to synchronize tempo changes or begin sections at the same time.[25] Videoconferencing applications have been found to be useful for between-song discussion in cases where visual latency has been too high to allow for synchronous performance.[26]

Overall, it has been recognized that there is a lack of research into both the importance of video as well as the effectiveness of video in an NMP.[27] Writing on LoLa, Gill Davies has summarized this sentiment as follows:

> A comprehensive assessment of the importance of video signals and the effects of audio-video misalignment remains to be investigated. It is still unclear under what conditions combining audio and video data will improve or negatively affect networked music interactions.[28]

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[23] Carlo Drioli, Claudio Allocchio, and Nicola Buso, "Networked Performances and Natural Interaction via LOLA: Low Latency High Quality A/V Streaming System," in *Information Technologies for Performing Arts, Media Access, and Entertainment*: *Second International Conference, ECLAP 2013, Porto, Portugal, April 8-10, 2013, Revised Selected Papers*, ed. Paolo Nesi and Raffaella Santucci (Berlin/Heidelberg: Springer, 2013), 240–50, https://doi.org/10.1007/978-3-642-40050-6_21.

[24] Gill Davies, "The Effectiveness of LOLA (LOw LAtency) Audiovisual Streaming Technology for Distributed Music Practice" (MA thesis, Edinburgh Napier University, 2015).

[25] Laura Bishop and Werner Goebl, "When They Listen and When They Watch: Pianists' Use of Nonverbal Audio and Visual Cues During Duet Performance," *Musicae Scientiae* 19, no. 1 (March 1, 2015): 84–110, https://doi.org/10.1177/1029864915570355; Michael F. Schober and Michelle F. Levine, "Visual and Auditory Cues in Jazz Musicians' Ensemble Performance," in *Proceedings of the International Symposium on Performance Science* (2011), 553–554.

[26] Davies, "The Effectiveness of LOLA (LOw LAtency) Audiovisual Streaming Technology for Distributed Music Practice."

[27] See Gabrielli and Squartini, *Wireless Networked Music Performance*, and Miriam Iorwerth and Don Knox, "Playing Together, Apart: Musicians' Experiences of Physical Separation in a Classical Recording Session," *Music Perception: An Interdisciplinary Journal* 36, no. 3 (February 2019): 289–99, https://doi.org/10.1525/mp.2019.36.3.289.

[28] Rottondi et al., "An Overview on Networked Music Performance Technologies," 8.

Furthermore, geographic distance, network performance, and bandwidth are known to impact the nature of the musical interaction.[29] This suggests there are a number of overlapping considerations when planning for an NMP over the Internet. Although the most common methods to date of displaying visual cues in an NMP has been through the use of videoconferencing, the re-emergence of virtual reality as a viable consumer product is now worth considering in the context of networked musical collaboration.

Virtual Reality

Ivan Sutherland first outlined his vision for "The Ultimate Display" as the ideal way to visualize mathematical concepts through a computer.[30] This vision was realized three years later with an apparatus described as "a head-mounted three dimensional display."[31] Sutherland's display apparatus—which would be akin to an augmented reality headset from the twenty-first century—marked a starting point for research over the next few decades.

The popularization of virtual reality (VR) in the 1980s is commonly traced back to technology pioneer and musician Jaron Lanier, who described the term as "a technology that uses computerized clothing to synthesize shared reality."[32] One of Lanier's early visions for VR was to be able to improvise the creation of reality in the same way that a musical instrument could create sounds. Lanier would later express his frustration that this area was still yet to be fully realized.[33]

Multiple explanations of the term VR have been given over the years. This paper will use the following definition:

> A medium composed of interactive computer simulations that sense the participant's position and actions and replace or augment the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation (a virtual world).[34]

[29] Rottondi et al., "An Overview on Networked Music Performance Technologies."

[30] Ivan E. Sutherland, "The Ultimate Display," in *Proceedings of the IFIP Congress* (1965), 506–508.

[31] Ivan E. Sutherland, "A Head-Mounted Three Dimensional Display, " in *AFIPS Proceedings of the Fall Joint Computer Conference, Part I* (1968), 757, https://doi.org/10.1145/1476589.1476686.

[32] Kevin Kelly, Adam Heilbrun, and Barbara Stacks, "Virtual Reality: An Interview with Jaron Lanier," *Whole Earth Review*, no. 64 (Fall 1989): 110.

[33] Peter Rubin, "A Conversation with Jaron Lanier, VR Juggernaut," *Wired*, November 21 2017, https://www.wired.com/story/jaron-lanier-vr-interview/.

[34] William R. Sherman and Alan B. Craig, *Understanding Virtual Reality*, 13.

In 1988, Jaron Lanier's company VPL produced the EyePhone, one of the first commercially available products to use a head-mounted display (HMD) (fig. 1).[35] However, technological limitations meant it could not live up to its early promise, and by the mid-1990s, mainstream enthusiasm for virtual reality had waned. The use of HMD-based VR would remain confined mostly to educational and research labs for the next 15 years.

Figure 1: The VPL DataGlove, headmount, and EyePhone Model 2 System on display at the Silicon Valley Virtual Reality studio, Mountain View, California, October 13, 2017. Photo by author.

In 2012, the Oculus Rift was released as a low-cost HMD, reawakening a new wave of development for the medium of VR. The company Oculus was purchased by Facebook in 2014 for approximately $2 billion; further advancements in technology saw the introduction of the untethered, free-roaming Oculus Quest in 2019.[36] This level of investment highlighted the level to which VR was seen as an important medium in the future of online social interaction (fig. 2). However, most development centered around entertainment and gaming applications with relatively few related to music-making or performance (fig. 3).

[35] Tomasz Mazuryk and Michael Gervautz, "Virtual Reality: History, Applications, Technology and Future" (1996), http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.42.7849.

[36] "Facebook to Acquire Oculus," Newsroom, Facebook, March 25, 2014, https://about.fb.com/news/2014/03/facebook-to-acquire-oculus/.

Figure 2: Facebook CEO Mark Zuckerberg outlines his goal to connect one billion people to virtual reality during his keynote address at Oculus Connect 4, San Jose, California, October 11, 2017. Photo by author.

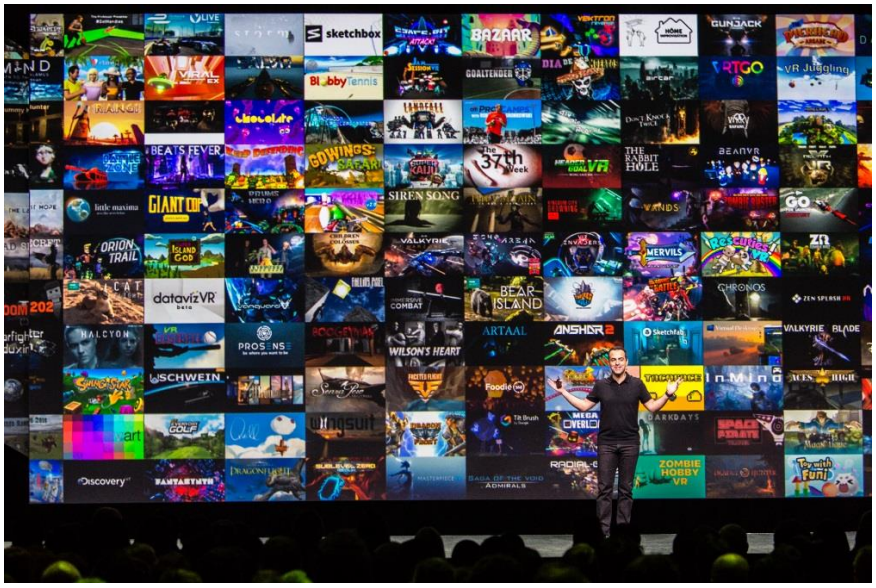

Figure 3: Vice President of VR at Facebook Hugo Barra takes to the stage to highlight the 2,000 titles available on the Oculus platform at Oculus Connect 4, San Jose, California, October 11, 2017. Photo by author.

Sense of Presence

One of the major affordances that VR can provide is known as "presence," the feeling of being in the same location as someone else, even though physically separated. The term presence as it relates to VR first emerged from the concept of "telepresence," commonly used in the field of telerobotics. This type of technology allowed a user to operate a remotely controlled device from the first-person perspective at a distance.[37] Telepresence has been used to describe the perceived feeling of actually being "there" at the remote site of operation. Mel Slater and Sylvia Wilbur describe presence as "a state of consciousness, the (psychological) sense of being in the virtual environment."[38] James Cummings and Jeremy Bailenson found that increased field of view, stereoscopy, and tracking can all assist with a greater sense of presence.[39] Other researchers have suggested that VR can provide a sense of presence or physical immersion, as opposed to other forms of media such as radio and television, that can only provide mental immersion.[40]

VR is also described as an "immersive experience"—but what does it mean to be immersed? It is necessary to clarify what is meant by the term since use of the definition varies among researchers and is often used interchangeably with that of presence. Slater and Wilbur describe immersion as a technology trait, "the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality, to the senses of a human participant."[41] Although several definitions of the term have been proposed, this paper will use William Sherman and Alan Craig's definition of immersion as the "sensation of being in an environment."[42] This description, related to a state of either physical or mental immersion is closely related to that of presence. Although presence has been a recurring consideration in the literature, few studies exist measuring presence in an NMP while using VR. That being said, over recent years we have seen increasing use of virtual environments for musical collaboration.

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[37] Thomas B. Sheridan, "Musings on Telepresence and Virtual Presence," *Presence: Teleoperators and Virtual Environments* 1, no. 1 (January 1992): 120–26, https://doi.org/10.1162/pres.1992.1.1.120.

[38] Mel Slater and Sylvia Wilbur, "A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments," *Presence: Teleoperators and Virtual Environments* 6, no. 6 (December 1997): 605, https://doi.org/10.1162/pres.1997.6.6.603.

[39] James Cummings and Jeremy Bailenson, "How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence," *Media Psychology* 19, no. 2 (April 2, 2016): 272–309, https://doi.org/10.1080/15213269.2015.1015740.

[40] William R. Sherman and Alan B. Craig, *Understanding Virtual Reality: Interface, Application, and Design* (San Francisco, CA: Morgan Kaufmann, 2002).

[41] Mel Slater and Sylvia Wilbur, "A Framework for Immersive Virtual Environments (FIVE)," 604.

[42] For more on different approaches to the concept of "immersion," see Mel Slater, *Measuring Presence: A Response to the Witmer and Singer Presence Questionnaire*, *Presence: Teleoperators and Virtual Environments* 8, no. 5 (October 1999): 560-565. https://doi.org/10.1162/105474699566477; William R. Sherman and Alan B. Craig, *Understanding Virtual Reality*, 10.

Networked Music in the Virtual World

The introduction of the World Wide Web and the development of computer-gaming platforms have provided musicians the opportunity to perform within multi-user environments.[43] Performances by the Avatar Orchestra Metaverse in the virtual-world platform Second Life made use of pre-scripted avatar movements to trigger sound samples within the virtual world.[44]

A study by Michael Schober suggested the use of virtual environments for musical collaboration could enhance the feeling of being together.[45] However, it was found that when both performers read from a musical score, neither performer tended to look at each other during the performance. In another study, abstract avatars have been used to represent performers on a two-dimensional screen to contextualize a performer's visual focus.[46] Observations in this study identified that performers looked at the avatars constantly to assist with visual interaction during an improvised work with no score. Therefore, this suggests that musical styles that do not require notation reading could allow for an improved sense of togetherness. Findings from this study indicate that further research is necessary to help clarify when and how the virtual environment may be appropriate in NMP.

In recent years, there has been an increasing amount of research on the development of virtual instruments in virtual environments. The work of Anıl Çamcı and Rob Hamilton combines the use of VR headsets with game engines to create new types of instruments and interactions.[47] Coretet, designed for a co-located live performance context, allows performers to play sounds from a virtual stringed instrument while in VR.[48] Players share a virtual space while seeing each other's instrument and avatar, networked together within the same physical performance space. An application that facilitates remotely located performers to share virtual instruments in VR is *EXA:*

[43] Roger Mills, "Liminal Worlds: Presence and Performer Agency in Tele-Collaborative Interaction," in *Tele-Improvisation: Intercultural Interaction in the Online Global Music Jam Session*, ed. Roger Mills (Cham, Switzerland: Springer, 2019), 145–66, https://doi.org/10.1007/978-3-319-71039-6_6.

[44] Gema F. B. Martín, "Social and Psychological Impact of Musical Collective Creative Processes in Virtual Environments; The Avatar Orchestra Metaverse in Second Life," *Musica/Tecnologia* 12, no. 1 (August 2018): 73–85.

[45] Michael Schober, "Virtual Environments for Creative Work in Collaborative Music-Making," *Virtual Reality* 10, no. 2 (October 2006): 85–94, https://doi.org/10.1007/s10055-006-0049-z.

[46] Franziska Schroeder et al., "Addressing the Network: Performative Strategies for Playing Apart," in *In International Computer Music Conference* (2007), 113–140.

[47] Anıl Çamcı and Rob Hamilton, "Audio-First VR: New Perspectives on Musical Experiences in Virtual Environments," *Journal of New Music Research* 49, no. 1 (January 2020): 1–7, https://doi.org/10.1080/09298215.2019.1707234.

[48] Rob Hamilton, "Coretet: A Dynamic Virtual Musical Instrument for the Twenty-First Century," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (2019), 1391395, https://doi.org/10.1109/VR.2019.8797680.

The Infinite Instrument.[49] Player interaction is enabled through a combination of options such live sound triggers, looped recordings, and spoken communication through an in-built headset microphone. Issues of latency are still a factor when distances between performers exceed the acceptable threshold for live performance.[50]

Investigations in virtual choir performance have been explored using pre-recorded, 360-degree video. A study by Helena Daffern et al., found that users felt limited not being able to move about the space or possessing a rendered body.[51] A longer-term goal of the research was described as being able to explore interactive VR with avatars while investigating ways to address latency.

A preliminary experiment on the effect of latency on presence in a networked environment was conducted in relation to studying and practicing music.[52] This was achieved with musical duos facing each other directly via a video display and reading off a score. Results suggested that future studies should investigate more immersive audio-visual feedback solutions, such as binaural rendering and full-body projections, and that "properly designed spatial elements in remote interactive environments may facilitate the compensation of time-dependent misalignments in the performance and communication."[53]

A case study into the use of VR in a networked music therapy session was reported by Tamplin et al. (fig. 4).[54] This study evidenced the extent to which VR could provide a transformative experience to those with spinal cord injuries through participating in a therapeutic context of group singing. Their method combined VR with RIA and found that participants who sang in the VR scenario experienced a reduced amount of self-consciousness. Participants commented that not seeing the real world around them or the reactions of others in the room was a liberating experience. One of the suggestions coming out of this work was whether it would be possible to combine NMP and virtual reality into a single system.

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[49] Zach Kinstner, "'EXA Music: The Infinite Instrument,'" Medium, March 31, 2017, https://medium.com/@zachkinstner/exa-the-infinite-instrument-user-guide-9b8ff6ab6bf7.

[50] Ian Hamilton, "Start A VR Band With EXA's Multiplayer Music Update," UploadVR, January 31, 2019, https://uploadvr.com/exa-band-music-make-vr-multiplayer/.

[51] Helena Daffern et al., "Exploring the Potential of Virtual Reality Technology to Investigate the Health and Well Being Benefits of Group Singing," *International Journal of Performance Arts and Digital Media* 15, no. 1 (January 2019): 1–22, https://doi.org/10.1080/14794713.2018.1558807.

[52] Stefano Delle Monache et al., "A Presence- and Performance-Driven Framework to Investigate Interactive Networked Music Learning Scenarios," *Wireless Communications and Mobile Computing* (2019): 1–20, https://doi.org/10.1155/2019/4593853.

[53] Delle Monache et al., "A Presence- and Performance-Driven Framework to Investigate Interactive Networked Music Learning Scenarios," 17.

[54] Jeanette Tamplin et al., "Development and Feasibility Testing of an Online Virtual Reality Platform for Delivering Therapeutic Group Singing Interventions for People Living with Spinal Cord Injury," 365-75.

Figure 4: Music therapist Dr. Jeanette Tamplin performs during a trial of the "Music Therapy in Virtual Environments" study at the Royal Talbot Rehabilitation Centre, Melbourne, Australia, September 20, 2017. Photo by author.

Another area of recent research has been around the ideal experience of a musical performance or interaction in VR. As Jack Atherton and Ge Wang write, "Good design for VR uses the core properties of the medium—isolation, interaction (agency), immersion, presence, embodiment, perspective—in the pursuit of greater human goods."[55] Their work in allowing the user to create audio experiences within the context of VR are an example of a step toward achieving the aims Lanier proposed some thirty years ago.

Conclusion and Future Research

This paper has identified that VR can provide a viable alternative to videoconferencing as a suitable visual platform for collaboration in an NMP. However, further research is needed on the use of VR in an RIA-style NMP. In this context, the following question remains unexplored: What are the key elements of performing in VR compared with videoconferencing? Studies that explore this area could help highlight what visual medium is most appropriate. A second question in need of examination is: How do aspects such as embodiment and the virtual environment affect participants' experience in a realistic interaction? Examining the role of presence and place in NMP

[55] Jack Atherton and Ge Wang, "Doing vs. Being: A Philosophy of Design for Artful VR," *Journal of New Music Research* 49, no. 1 (January 2020): 58, https://doi.org/10.1080/09298215.2019.1705862.

could help uncover additional considerations and options for collaborating online in the most effective manner.

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