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Virtual Reality Musical Instruments: State of the Art, Design Principles, and Future Directions

Abstract: The rapid development and availability of low-cost technologies have created a wide interest in virtual reality. In the field of computer music, the term "virtual musical instruments" has been used for a long time to describe software simulations, extensions of existing musical instruments, and ways to control them with new interfaces for musical expression. Virtual reality musical instruments (VRMIs) that include a simulated visual component delivered via a head-mounted display or other forms of immersive visualization have not yet received much attention. In this article, we present a field overview of VRMIs from the viewpoint of the performer. We propose nine design guidelines, describe evaluation methods, analyze case studies, and consider future challenges.

In 1965, Ivan Sutherland described his idea of an ultimate display, conceived as a multisensorial virtual experience able to recreate the Wonderland where Alice once walked (Sutherland 1965). More than 50 years later, such ultimate display is nearly at hand. In the past couple of years, the rapid development of low-cost virtual reality displays, such as the Oculus Rift (www.oculus.com/rift), HTC's Vive (www.htcvive.com), and open-source virtual reality (www.razerzone.com/osvr), has boosted interest in immersive virtual reality technologies. Hardware devices once exclusive to high-end laboratories are now available to consumers and media technology developers. We define virtual reality (VR) as an immersive artificial environment experienced through technologically simulated sensory stimuli. Furthermore, one's actions have the potential to shape such an environment to various degrees.

In the fields of new interfaces for musical expression and sound and music computing, virtual musical instruments (VMIs) have been developed and refined in recent decades (see, e.g., Cook 2002; Smith 2010). Physical interfaces for musical expression, gestural control, and mapping systems between novel interfaces and sound synthesis algorithms have been at the forefront of development. Progress in interactive auditory feedback and novel control mechanisms has made great strides. On the other hand, the new interfaces for musical expression (NIME) community has not shown a wide interest in the visual aspects of VMIs. One of the reasons why virtual reality musical instruments (VRMIs) have not drawn more attention in this community might be the fact that musicians mostly rely on their auditory and tactile feedback and on the interaction with the audience. Another reason could be that low cost and portable visualization devices have only become available in the last five years.

Researchers working with interactive audio and haptic feedback have called their instruments VRMIs (see, e.g., Leonard et al. 2013); however, visual feedback was absent. In this article we distinguish, on the one hand, between virtual musical instruments (VMIs), defined as software simulations or extensions of existing musical instruments with a focus on sonic emulation, for example, by physical modeling synthesis (Välimäki and Takala 1996) and, on the other hand, virtual reality musical instruments (VRMIs), where the instruments also include a simulated visual component delivered using either a head-mounted display (HMD) or other forms of immersive visualization systems such as a CAVE

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(Cruz-Neira, Sandin, and De Fanti 1993). We do not consider those instruments in which 3-D visual objects are projected using 2-D projection systems, such as the environment for designing virtual musical instruments with 3-D geometry proposed by Axel Mulder (1998) and the tabletop based systems proposed by Sergi Jordà (2003). We focus instead on the examination of 3-D immersive visualizations from the viewpoint of the performer.

We believe that virtual reality shows the greatest potential when facilitating experiences that cannot be encountered in the real world. As Jaron Lanier envisioned in Zhai (1998):

> I have considered being a piano. I'm interested in being musical instruments quite a lot. Also, you have musical instruments that play reality in all kinds of ways aside from making sound in Virtual Reality. That's another way of describing arbitrary physics. With a saxophone you'll be able to play cities and dancing lights, and you'll be able to play the herding of buffaloes made of crystal, and you' ll be able to play your own body and change yourself as you play the saxophone (Heilbrun 1989, p. 110).

In line with Lanier's thoughts, immersive technologies enable new musical experiences that extend beyond those offered by traditional musical instruments. Immersive visualizations thus stimulate additional levels of abstraction, immersion, and imagination.

On the other hand, virtual reality research has focused mainly on the exploration of visual feedback, with other senses playing a secondary role. In some cases, the sole focus on visual domain can provide a powerful visual experience away from the daily life. Ben Shneiderman has stated that virtual reality offers a lively new alternative for those who seek immersion experiences via blocking out the real world with goggles on their eyes (Preece et al. 1994).

It is important to note that virtual reality can pose some challenges for the audience that witnesses a performer wearing head-mounted display for immersive visualization as stated by Berthaut, Zappi, and Mazzanti (2014). This is mainly because the audience is unable to share performer's experience. Berthaut et al. (2013) presented an attempt to expose the audience to the mechanisms of digital musical instruments using 3-D visualization. The topic of audience participation in virtual reality experiences lies, however, beyond the scope of this article.

Virtual reality musical instruments have the potential to bridge the fields of NIME and VMIs. Adding meaningful immersive visualization to a digital musical instrument can result in a new way of experiencing music. In the following sections, we present an overview and the current status of research and practice of VRMIs. We propose nine design guidelines, provide case studies, and discuss potential future challenges.

Background Work

Although research and development in VMIs has a long history and many examples can be found in the literature, the same cannot be said for VRMIs. In the following we propose an overview of the most significant VRMI research efforts.

Cadoz and colleagues have been developing their CORDIS-ANIMA system for many years. It is a modeling and simulation programming language for audio and image synthesis based on physical models (Cadoz, Luciani, and Florens 1993). Although to our knowledge the system has never been used in immersive virtual environments, it includes all the elements of immersive multimodal musical instruments, covering auditory, haptic, and visual feedback.

Mäki-Patola and coworkers reported on a software system designed to create virtual reality musical instruments (Karjalainen and Mäki-Patola 2004; Mäki-Patola et al. 2005). The team presented four case studies: a virtual xylophone, a membrane, a theremin, and an air guitar. The authors discuss the quality, efficiency, and learning curve as outlined by Jordà (2004). For example, low spatial and temporal resolution and latency decrease efficiency (Mäki-Patola et al. 2005). They suggest that existing technologies can improve these deficiencies and allow for more responsive instruments, expanding both design and performance possibilities.

One of the most important features of VR interfaces is their potential for visualization. Virtual

Figure 1. Virtual FM Synthesizer (a) and Virtual Air Guitar (b). Images are from http://mcpatola.com/almaproject/HUTTMLIndex.html, used with kind permission of Teemu Mäki-Patola.

(a) (b)

reality musical instruments can stimulate intelligent visual feedback that may aid the player in performing. This expands the interaction with the physical instruments, where visual feedback is directly connected to the mechanism of sound production, for example, vibrating strings. Gelineck et al. (2005) proposed several physics-based VRMIs, such as a flute and drum. The instruments used a combination of physical models, 3-D visualizations, and alternative sensing techniques. Blowing into a plastic tube would trigger a dynamo motor, allowing a natural performance experience. The performer could see the virtual flute through a 3-D visualization. Gelineck and colleagues further detailed possibilities that could not be achieved in the physical counterpart, such as the ability to change the dimensions of the simulated instruments while playing them.

Similarly, the FM synthesizer and the virtual air guitar that were developed within the Algorithms for the Modeling of Acoustic Interactions (ALMA) project and presented by Mäki-Patola and coworkers sonically expand the theremin and guitar, respectively (Karjalainen and Mäki-Patola 2004; Mäki-Patola et al. 2005) (see Figure 1). Their visual representations, however, expand beyond the expected originals. The instruments are further described in the case studies section of the present article.

Examples of interactive multimodal VR environments were described by Rodet et al. (2005); these were a part of the project *Plateforme haptique d'application sonore pour l'eveil musical* (PHASE). The goal of the PHASE project was to provide musical game installations with auditory, haptic, and visual feedback. Multisensory interactions enabled a general audience to explore new musical possibilities.

Rob Hamilton (2009) proposed an understanding of virtual environments as enactive instruments in their own right, able to react to gesture and action. Hamilton suggested that just as the laws of physics can be set aside within a virtual space, so could the traditional methodologies of coupling gesture to sound within space. In this way, traditional relationships between gesture, sound, and space could be recontextualized and up-ended. Hamilton also stated that VR and VRMIs allow possibilities of extensions to the real world, which become particularly interesting in an artistic domain. Such possibilities have been only modestly explored, however.

Most VMIs have been developed as single-process instruments, i.e., instruments that allow control over only one synthesis or effect process or musical navigation tool. In the case of VRMIs, a principal advantage of graphical musical interfaces is the ability to handle multiprocess instruments. Based on visual feedback from the selected sound processes, Berthaut, Desainte-Catherine, and Hachet (2011) suggested relying on the concept of reactive widgets. The reactive widgets can be defined as complex 3-D objects associated with particular sound processes (Levin 2000).

The addition of visual feedback can aid the player in performance and can enhance the aesthetic experience. As an example, Xiao, Tome, and Ishii (2014) proposed to visualize music as animated characters walking on a physical keyboard, to promote an understanding of music rooted in the body, taking advantage of walking as one of the most fundamental human rhythms. Although not immersive, the visualization is an interesting way to support music learning and thinking through connecting individual keys into lines and sequences. Visual feedback thus assists in the conversion of performing discrete events to continuous piano playing.

Design Principles for VRMIs

Ge Wang (2014) presented a set of principles for visual design of computer music, inspired by principles for designing computer music controllers put forward by Perry Cook (2001, revised and expanded 2009). In particular, Cook's principle that "copying an instrument is dumb, leveraging expert technique is smart" (i.e., advice not to replace or copy existing instruments, but to consider controllers inspired by virtuosity: violins, trumpets, microphone stands, turntables, beat-boxers, ethnic instruments, and so forth) is relevant also to VRMIs.

Wang proposed a total of 13 principles, categorized either as user-oriented or aesthetic, with some additional observations. For the user-oriented principles, Wang advocates the need for real time, for the ability to design sound and visuals in tandem and seek salient mappings, for hiding the technology and making the viewer experience substance, for adding constraints, and for the use of graphics to reinforce physical interaction. For the aesthetic principles, Wang suggests that the designer simplify, animate, be organic, and have not only a function but a personal aesthetic sense. Other principles are iteration, visualization, and the possibility of being inspired by movies and computer games. Many of these principles, if extended as explained in the following, are also relevant for VRMIs.

Design principles for new interfaces for musical expression were also proposed by Garth Paine (2009). Paine in particular stresses the importance of the fact that relationships to sound are in part physical: musical instruments generally require the performer to blow, pluck, strum, squeeze, stroke, hit, or bow. For VRMIs, some principles from new interfaces for musical expression and visual design are still valid.

When designing VMIs based, for example, on physical models, a common assumption is that there is no need to simulate existing instruments, because the real counterparts are of higher acoustic quality and and can be more easily played. On the other hand, there are several reasons to build virtual musical instruments: for example, to provide software tools to musicians who do not have access to physical players of those instruments, or to understand the acoustics of such instruments though simulations.

Another interesting aspect of VMIs is the fact that, because the instruments are virtual, they allow the creation of possibilities that could not be achieved in the real world. To cite a just few historical creative examples from established composers, there is *Silicon Valley Breakdown* by David Jaffe, written in 1983, where the simulation of plucked string instruments, achieved by implementing extensions of the Karplus-Strong algorithm (Jaffe and Smith 1983), allowed the sonic reproduction of strings as long as the Golden Gate Bridge. Another example is Oxygen Flute (Chafe 2005), an installation in a gallery chamber made with bamboo and containing four continuously performing virtual flutes, where the visitors create the sounds by breathing. Patterns in levels of carbon dioxide measured inside the chamber created the music.

Kojs and colleagues have described more examples of augmentation (e.g., unfeasibly rapid performance on a stretched marimba), hybridization (e.g., plucking tubes and plates), and abstraction (e.g., bowing the conductor and belling the composition) of virtual musical instruments created with physical modeling techniques and their modes of interactions (Kojs, Serafin, and Chafe 2007; Kojs 2013).

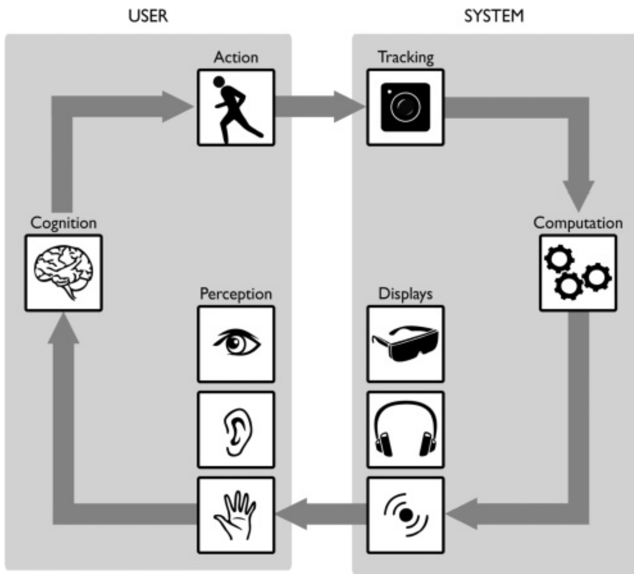
Figure 2 shows a general schematic representation of the components involved when designing virtual reality musical instruments. The player performs actions that are tracked and mapped to visual, auditory, and haptic feedback. The feedback is interpreted by the player, who performs the resulting actions in a feedback loop.

We now present our design principles in detail.

Principle 1: Design for Feedback and Mapping

We design for sound, visual, touch, and proprioception in tandem, and we consider the mappings between these modalities.

Figure 2. A general structure of the different input and output modalities required to design a virtual reality musical instrument.



For virtual reality musical instruments, it is not only relevant to design sound and visual in tandem, and to consider the mapping; touch and motion should also enter into the equation, as well as full body interaction. From the perspective of auditory feedback, virtual reality musical instruments have been presented through speakers or headphone-based systems. For virtual reality, 3-D sound is an especially relevant issue, because the location and motion of the visual virtual objects need to match the location and motion of the auditory objects (Begault 1994).

From the perspective of tactile and haptic feedback, several studies (e.g., O'Modhrain et al. 2000a,b; Marshall and Wanderley 2011), suggest that the development of musical skills strongly relies on tactile and kinesthetic cues. While performing on acoustic or electro-acoustic musical instruments, an intense haptic experience is not only unavoidable, it is highly relevant to the musical performance. Moreover, tactile feedback enhances playability of virtual musical instruments (O'Modhrain 2001). Haptic feedback can be delivered in free air, as in the case of the AIRREAL (Sodhi et al. 2013) or by using a tangible interface. One of the purposes of augmented visual feedback can be to help to create more intuitive, learnable instruments, as is the case in Jordá's FMOL and reacTable* (Jordà 2003) for table-based interfaces. Although the field of NIME has seen the proposal of several novel tangible interfaces and input devices, this is not the case for virtual reality. Most hand-based input devices for virtual reality are, as a matter of fact, still in the form of gloves, remote controllers, or joysticks. It might be beneficial for VRMI researchers to consider tangible interfaces developed in the NIME community to extend possibilities provided by traditional VR input devices. Lately, the Leap motion controller (www.leapmotion.com) has become a popular option in the consumer VR community, mainly for its ability to track and represent both hands in the 3-D world without the need for the user to wear any additional interface, such as gloves or joysticks.

Principle 2: Reduce Latency

All interactions should be smooth and have minimum latency. Because VRMIs are inherently multisensory, reduction of latency with respect to both sound and visuals is paramount. Particularly, synchronization between the arrival of stimuli in different modalities is known to influence the perceptual binding that occurs in response to an event producing multimodal stimulation (Kohlrausch and van de Par 1999). Thus, it is crucial that VRMIs represent timely and synchronized audiovisual feedback in response to the user's actions. More generally, it is crucial to reduce system latency, since it is believed to increase cybersickness (LaViola 2000), the topic of the next principle.

Principle 3: Prevent Cybersickness

Cybersickness, or VR sickness (Fernandes and Feiner 2016), may involve a range of different symptoms including, but not limited to, disorientation, headaches, sweating, eye strain, and nausea (Davis, Nesbitt, and Nalivaiko 2014). Although alternative explanations exist (Riccio and Stoffregen 1991; Bouchard et al. 2011), the most popular is known as sensory conflict theory. This theory stipulates that cybersickness arises as a consequence of conflicting information from the visual and vestibular senses; e.g., a user driving a virtual vehicle will be physically stationary while the visual stimuli suggests that movement is occurring. System factors believed to influence cybersickness include latency, display flicker, calibration, and ergonomics (Davis, Nesbitt, and Nalivaiko 2014). Aside from optimizing factors such as efficient tracking and high update and frame rates, developers of VRMIs should be mindful of how the user's movement around the virtual environment is made possible. Particularly, it is advisable to use a one-to-one mapping between virtual and real translations and rotations, and if the user has to move virtually while being physically stationary, accelerations and decelerations should be minimized as the vestibular system is sensitive to such motion.

Principle 4: Make Use of Existing Skills

This principle is related to Cook's notion that it is less interesting to copy existing musical instruments; what is more interesting is to be inspired by existing musical instruments and extend their possibilities. Virtual reality musical instruments have the potential to become interesting when they provide immersive experiences that are not possible in the real world. The role of virtual reality, e.g., the role of the immersive visualization hardware and software, is to enhance the overall multimodal experience. Virtual reality is a different medium than the physical world. Replicating interfaces of traditional instruments in VR may not bring about useful results unless we are extending existing instruments with additional control. Familiarity with a real-world counterpart helps to grasp the concept and supports playing in the beginning. But it may not be easy to find new ways of playing, which is needed as the instruments are different.

Users of traditional instruments may not even be interested in using virtual replicas, since the original ones work well. Instead, we should discover the kinds of interfaces that are best suited for the VR medium. Using metaphors derived from interactions existing in the real world offer interesting possibilities.

Principle 5: Consider Both Natural and "Magical" Interaction

In a continuation of the previous principle, and in line with general recommendations by Bowman et al. (2004) for 3-D user interfaces, creators of VRMIs should consider the use of both natural and "magical" interactions and instruments. In relation to VRMIs, either an interaction or an instrument will qualify as magical if it is not limited by real-world constraints, such as the ones imposed by the laws of physics, human anatomy, or the current state of technological development. On the other hand, interactions and instruments qualify as natural if they conform to real-world constraints. Notably, natural interactions can be combined with magical instruments and vice versa (e.g., the user may manipulate a physically plausible instrument located at a great distance using a nonisomorphic approach (e.g., the Go-Go interaction technique, Poupyrev et al. 1996), or the user may use natural gestures to manipulate an instrument that defies the laws of physics. The advantage of natural techniques is that the familiarity of such approaches may increase usability, whereas magical techniques allow the player to overcome the real-world limitations normally imposed on the musician and the instrument (Bowman et al. 2004). As an example, because the virtual body can be scaled, musicians could play instruments located outside of their normal reach.

Principle 6: Consider Display Ergonomics

All the devices necessary to create virtual reality experiences introduce the additional challenge of how to hide the technology to focus on the experience. The recently introduced HMD devices are improving from an ergonomic perspective. While wearing HMDs such as the HTC Vive or Oculus Rift, the user remains tethered and the weight of the two displays is noticeable, however. Thus, when creating VRMIs, developers should be mindful of the potential strain and discomfort introduced by wearing an HMD and of the issues currently introduced by wires (e.g., a 360-degree turn can leave the user entangled).

Principle 7: Create a Sense of Presence

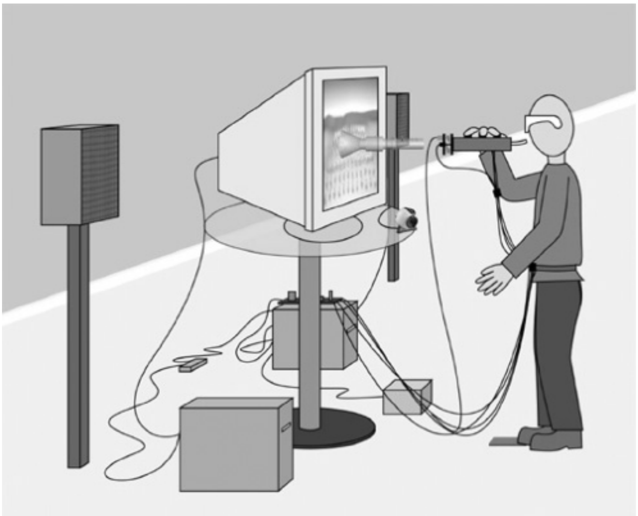
The experience of "being there" in a computer-generated environment is often referred to as the sensation of presence or "place illusion" (Slater 2009). The illusion is believed to be present in proportion to the degree of technological immersion offered by the system. The degree of technological immersion offered by a given system can be characterized by the range of normal sensorimotor contingences supported by the system. Particularly, Slater (2009) describes sensory motor contingencies as the set of actions a user will know how to perform in order to perceive something (e.g., moving one's head and eyes to change gaze direction, kneeling to get a closer look at something on the ground, or turning one's head to localize the position of an invisible sound source). Thus, it is advisable for developers of VRMIs to construct virtual instruments with the limitations of the system in mind, to discourage users from relying on sensorimotor contingencies not fully supported by the system. Beside depending on the range of normal sensorimotor contingencies, presence is also believed to be influenced by the illusion of body ownership, discussed next. In other words, seeing a body in the virtual environment that one feels ownership of contributes to the sensation that one is inside that environment.

Principle 8: Represent the Player's Body

One of the challenges of VR is the fact that people cannot see their own body represented in the virtual world, unless the real body is tracked and mapped to a virtual representation. The resulting sensation is called *virtual body ownership*, and several studies have shown that it is possible in VR to generate perceptual illusions of ownership over a virtual body seen from the first-person perspective, in other words, of a body that visually substitutes the person's real body (Gallagher 2000).

Kilteni, Bergstrom, and Slater (2013) show how differences between the real and virtual body have temporary consequences for participants' attitudes and behavior under the illusory experience of body ownership. Particularly, differences in body movement patterns while drumming were found

Figure 3. *A schematic representation of a virtual reality flute. The player blows on a controller that drives a physics-based sound engine for a flute and that animates a 3-D visualization presented on the screen.*



depending on whether the perceived body representation fulfilled expectations of what appearance was and was not appropriate for the context. This study has interesting implications because it shows that virtual reality can help to train and adapt movements and gestures of musicians.

The presence of a virtual body representation is also important to provide the necessary visual feedback to the player. Consider, for example, a virtual reality flute, as displayed in Figure 3: The instrument consists of a controller (a cylinder) with a breath-pressure sensor driving a flute physical model, together with 3-D glasses to visualize the flute. The flute controller is tracked, so the virtual visual flute matches the position of the physical controller. It is important for the player to receive visual feedback of the position of the hands; this is achieved by tracking the player's hands and displaying them in the virtual world. The lack of visual feedback breaks the sense of presence as described in relation to principle 7.

Notably, a study by Argelaguet et al. (2016) explored the effects of varying degrees of realism in visualizing players' hands and found that abstract and iconic hand representations produced a greater sense of agency than realistic representations. One potential explanation is that the realistic representation made the participants expect a more natural interaction than was offered by the Leap Motion device used for the study. Thus, although a virtual representation of the user is important, it may also be important that the appearance of this representation is appropriate for the precision of possible interactions.

Principle 9: Make the Experience Social

One of the fundamental aspects of music is its ability to create shared social experiences. On the other hand, as of this writing, virtual reality has merely been an individual activity where one person is immersed in one virtual world. This is mostly due to the occlusive properties of HMDs, blocking any visual communication with the outside world. Recent developments in VR technologies, however, are pointing towards the desire to create shared VR experiences. It is interesting to use other channels when the visual modality is blocked; in this case the auditory and tactile channel can create some interesting possibilities that have not been explored. This can create novel social musical experiences in virtual reality. An alternative to facilitating social interaction between individuals in the same physical space is for users to share experiences virtually and potentially experience social presence or "copresence" (Nowak and Biocca 2003). Examples of social applications of VRMIs include, among others: (1) using VRMIs for collaborative performances; for example, musicians transported together while playing the same or different instruments, and (2) using VRMIs for virtual performances; for example, the performance of the musician playing a VRMI is transmitted to an audience that shares the virtual environment with the performer. Finally, previous work has documented that when individuals are asked to present in front of an audience of virtual characters, they tend to respond similarly to how they would in a similar real-world situation (Slater, Pertaub, and Steed 1999). Thus, it seems possible that virtual reality can provide performers with a surrogate for actually being on stage while playing VRMIs or traditional instruments.

Evaluation of VRMIs

Evaluation of digital musical instruments involves several different parties, including instrument makers, novice and skilled performers, and the audience. In this article we focus on performers. Even then, several aspects have to be assessed, from mere task performance, as carried out by Wanderley and Orio (2002), to the playability, user experience, and emotions, as outlined by O'Modhrain (2011).

Andrew Johnston proposed a practice-based design for the evaluation of new interfaces for musical expression (Johnston, Candy, and Edmonds 2008; Johnston 2011). The idea is a broader study into performers and their creative practice in the context of their use of new instruments. As an experience-oriented framework, MINUET considers evaluation as a central activity in designing musical interfaces (Morreale, De Angeli, and O'Modhrain 2014). Similar evaluation frameworks would also be useful for VRMIs. Fortunately, the nine design principles (DPs) outlined in the previous section can be converted to an evaluation framework, with three distinct layers.

The first layer concerns the modalities of interaction (Erkut, Jylhä, and Discioglu 2011). The alignment between each input and output modality (cf. Figure 1) would provide a good start in this layer (DP 1). After considering each modality in tandem, we can then proceed with perceptual integration and mapping (DP 1), based on perceptual, sensorimotor, and cognitive abilities and capacities of users. Such a structured approach has been previously used by Erkut, Jylhä, and Discioglu (2011) to evaluate a rhythmic interaction system with a virtual tutor (Jylhä et al. 2011) and to redesign the auditory and visual displays of the interactive system. Besides specific issues in each modality, the approach identified the effects of latency (DP 2), social factors (DP 9), and to some degree, the ergonomics of the display, in terms of fatigue (DP 6).

The second layer is VR-specfic, and considers evaluation of cybersickness (DP 3), virtual body representation and ownership (DP 8), and presence (DP 7). The VR-specific evaluation methods should be followed in this layer; see the related work in corresponding design principles. Latency (DP 2), for instance, which was considered in the previous layer for each interaction modality, should be revisited in the VR-specfic level as an integrated system property. It is clear that advances in VR display and tracking technologies keep reducing the latency. Note, however, that there is a perceptual and motor tolerance to latency that can positively impact the evaluation (Maki-Patola and Hämäläinen 2004).

The concept of presence (DP 7) needs also special attention in this layer. Previously defined as the sensation of being in the simulated space, or the perceptual illusion of nonmediation (Lombard and Ditton 1997), presence has recently been redefined as the combination of two orthogonal components: place illusion and plausibility (Slater 2009). Place illusion corresponds to "being there," the quality of having a sensation of being in a real place. Plausibility illusion refers to the illusion that the scenario being depicted is actually occurring. In the music domain, Charles Ford (2010) has given presence a different definition, referring in general to those qualities that make a performance outstanding, and are hard to quantify scientifically. From the player's point of view, it is probably more relevant for VRMIs to use engagement as an evaluation method, referred to as the ability of the player to keep interest in playing the instrument for a significant amount of time (Wessel and Wright 2002). A relevant element for VMIs is the concept of agency, e.g., the ability to take meaningful actions and see the results of one's decisions and choices (Herrera, Jordan, and Vera 2006).

The final layer focuses on the quality and goals of interaction and on the specific mechanisms involved, such as natural and magical interactions (DP 5), and leveraging expert techniques (DP 4) for musical expression. This layer focuses on higher design goals, embracing experience and "meaning-making" (Bødker 2006). The experience can evolve over time, particularly in social contexts (DP 9, cf. Bødker 2015). In this layer, evaluators should avoid breaks in presence; therefore, methods to assess the user experience without interruptions are desirable. One widely adopted way to assess user experience in virtual reality is by using posexperimental questionnaires, sometimes coupled with physiological measurements captured during the experiment (Meehan 2001). Extensions towards practice- and experience-based frameworks are also possible at this layer.

To summarize, an evaluation of VRMIs from the performer's point of view presents challenges similar to those with the evaluation of VMIs in terms of usability, playability, and engagement. But it also presents additional challenges introduced by the immersive visualization component, such as a sense of presence and the need of a virtual body representation to create agency. These challenges can be structured with a three-layer evaluation scheme: interaction modalities (the lowest layer), a VR-specific middle layer, and the highest layer aiming to evaluate the goals, practices, and experiences of VRMI players.

Case Studies

In this section we analyze VRMIs and examine selected instruments through the lens of our proposed design principles. We summarize this discussion in Table 1.

Virtual Membrane, Xylophone, and Air Guitar

Mäki-Patola and coworkers describe a number of VRMIs such as a virtual membrane, a virtual xylophone, and a virtual air guitar. We have described the virtual air guitar as an abstract instrument (see Figure 1) earlier in this article; here we focus on the virtual membrane and the virtual xylophone (Mäki-Patola et al. 2005; see also mcpatola.com/almaproject/TMLvideos.html). The instruments are depicted in Figure 4.

The virtual membrane is an instrument based on a physical model of a rectangular membrane. The player operates two virtual mallets, hitting the virtual membrane simulations at various locations. Such control and interactions were reported as intuitive and natural, as they are derived from the real-life situation. The location hit determines which of the particular modes of the membrane would be excited, thus enabling timbral differentiation associated with location. The pairing is well aligned with the behavior of a physical membrane. It is noteworthy that sufficient flexibility and complexity of the sound model allows for rich interaction and subsequent prolongation of the user's experience. Mäki-Patola and coworkers comment, however, that the lack of tactile feedback diminishes the speed and accuracy of the performance, and they suggest using a physical controller such as a MIDI drum set to compensate. Extending the interaction to feet controlling attacks would free the hands and thus deepen the connection between the player and instrument. This virtual instrument presents a 3-D audiovisual scenario focused on the reproduction of naturally observed interactions (a mallet hitting a membrane) and the resulting sonorities (sounds of an excited membrane). The ability to dynamically alter parameters such as dimensions, tension, damping, and material in real time also enables expansion of the existing instrument's sonic palette beyond what is possible in the physical world, however. The resulting sounds were described as potentially useful, for example, as special effects for film media. Latency was reported as a major problem (observed above a threshold of about 60 msec). Although cybersickness was not addressed in the analysis, the fact that the player's gestures would pass through the visualized membrane suggests an upsetting experience. The visual display consists of waveform animations traveling along a virtual plate. The player's body is not represented in the VR. The lack of the player's immersion in the VR environment suggests a weakened sense of presence. Although one can imagine a potential for shared experience, any social interaction is absent in the current iteration of the virtual membrane, since a single player operates the instrument.

The virtual xylophone is an extended reproduction of the traditional xylophone, and, like the virtual membrane, it is played with mallets. The first version of the instrument had a traditional, linear key layout (see Figure 4b), whereas the plates can be moved in 3-D space in the second version (see Figure 4c). The performer can customize the plates using an interface designed for this purpose. In this way, the instrument follows DP 4, which prefers leveraging expert techniques to copying existing instruments.

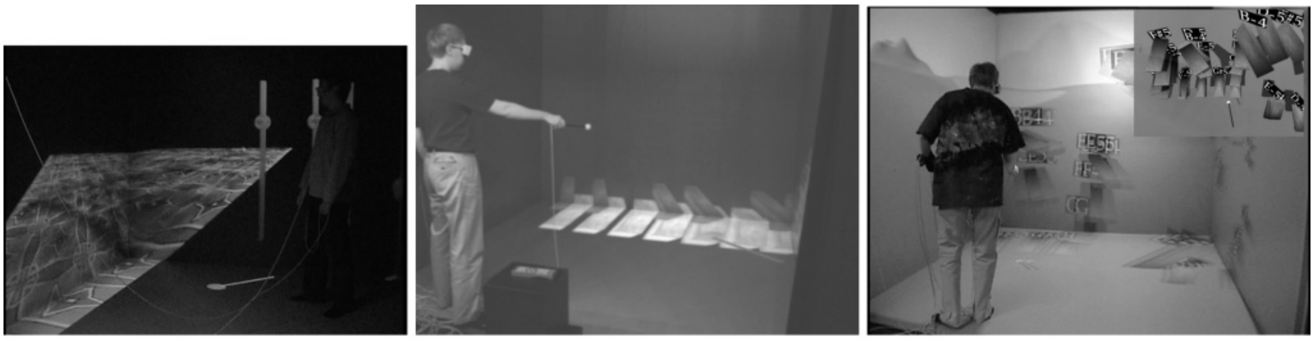
The virtual air guitar is a digital reproduction of a traditional electric guitar using an extended Karplus-Strong model for the sound production

Table 1. Summary of VRMIs Described in Case Studies

VRMI	*DP 1: Feedback and Mapping*	*DP 2: Latency*	*DP 3: Cybersickness*	*DP 4: Do Not Copy*	*DP 5: Interaction*	*DP 6: Ergonomic Design*	*DP 7: Sense of Presence*	*DP 8: Body Representation*	*DP 9: Social Experience*
Virtual membrane	AV in tandem no haptic but tactile feedback	Ca. 60 msec	Not addressed	Copy	More natural, some magical	Yes	Weakened by the lack of tactile feedback	No	No: single player
Virtual xylophone	AV in tandem no haptic but tactile feedback	Ca. 60 msec	Not addressed	Not a copy	More natural	Yes	Weakened by the lack of haptic feedback	No	No: single player
Virtual air guitar	AV in tandem	Ca. 60 msec	Not addressed	Not a copy, but an extension	More natural	Yes	Weakened by the lack of tactile feedback	No	No: single player
Gestural FM synthesizer	AV in tandem no haptic no tactile feedback	Not noticeable	Not addressed	Extension	More natural	Yes	Weakened by the lack of tactile feedback	No	No: single player
Crosscale	AV in tandem	Not noticeable	Potential	Extension	Natural triggering	Standard VR Oculus plus Hydra	Through interaction	No	No: single player
ChromaChord	AV in tandem	Not noticeable	Potential	Not a copy or extension	Not natural	Standard VR Oculus plus Leap Motion	Through hands	Hands	No: single player
Wedge	AV in tandem	Not noticeable	Not addressed	Not a copy or extension	Mostly natural	Standard VR Oculus plus Leap Motion	Through hands	Hands	No: single player
Cirque des Bouteilles	AV in tandem	Not noticeable	Not addressed	Copy	Not natural Not magical	Standard VR Oculus plus Leap Motion	Through hands	Hands	No: single player

AV = audiovisual.

Figure 4. The virtual membrane (a) and the virtual xylophone in two versions (b and c). Images are from http://mcpatola.com/almaproject/HUTTMLIndex.html, with permission of Teemu Mäki-Patola.



(a) (b) (c)

engine (Karjalainen et al. 2006) but without tactile feedback. Mäki-Patola and colleagues reported it to be the most successful among the VR instruments, principally because of the popularity of its physical counterpart, the electric guitar.

Gestural FM

The gestural FM synthesizer, also developed by Mäki-Patola et al. (2005) and described earlier, is an extension of the theremin instrument (see www.theremin.info for more information). A complex FM synthesizer replaces the simple frequency spectrum of the original theremin. The visual feedback was reported to increase playability as compared with the original theremin instrument, where the only feedback is aural.

Crosscale

Crosscale (Cabral et al. 2015; see also youtu.be/9ecZIPQnDXQ) uses an Oculus Rift HMD and a Razer Hydra, a joystick-like interaction device to play a set of notes displayed as colored spheres on the screen. The intention is to perform notes in a 3-D space (chords can be controlled on the *z*-axis), instead of the linear left-to-right convention of a traditional keyboard. In contrast, the use of both hands enhances the parallel between piano playing and playing the virtual Crosscale. The performer's gestures trigger discrete events (single sounds); these do not evolve dynamically as would be expected on an acoustic instrument, however. The absence of both a sustain pedal and any resonance of the simulated instrument's body further limits the expressivity of performance. Furthermore, the digital display resembles a game environment more than an instrument. Although latency is not observed, the speed of interaction is limited to the performer's arm movement. This is because distances between target points on the screen are larger than those observed on a physical keyboard, and the arm movement replaces the nuanced finger control. Cybersickness may become a problem with extending an arm forward and retracting it, since the sense of depth is not stimulated by any sense of vibrotactile feedback. Moreover, increased speed of gestures may cause a sense of nausea and physical fatigue, as the parallelism between arm movements and traveled distances between the actual points on the display are disproportionate. Natural interaction between reaching and triggering is successful, although, this is precisely where the limitation of the magical appears. Enlarging the sound bank and using the dynamic properties of the arm motion would enable further expansion of expressive potential. Oculus Rift and Razer Hydra provide a typical level of ergonomic comfort by today's standards. The body image is not present in the system. Finger triggering and arm movement are the principal vehicles that enable a sense of internal presence. Although this project was designed for a single user, one can imagine a participatory experience with multiple users performing complex sequences on the instrument.

ChromaChord

ChromaChord (Fillwalk 2015; see also youtu.be/5C1O1MvouXc) is a system that combines the Oculus Rift headset with a Leap Motion controller attached to it in order to create an immersive 3-D environment. The Oculus Rift allows a performer to view a three-panel visual interface with a black background that includes a pane with two rows of coloured rectangles, a white oval-centered display with particle-flocking around the central oval, and a white-and-gray table consisting of three rows. Performers can navigate between the three panels by turning their head. A performer uses both hands and fingers to interact with the interface. The Leap Motion Controller supports hand tracking, and gestures such as point, pinch, swipe, grab, etc., result in specific interactions. Musical effects generated and processed in Max/MSP complete the interaction loop. Pointing at the colored pane enables performance of single notes and gray arrows facilitate octave transposition. Melodic sequences can be controlled with a single hand. Grabbing and pointing gestures enable the performer to expand and reduce the amount of modulation on the synthesized sound via the white oval-centered panel. The three-row table display enables key and chord selection. Although interaction with the three-pane interface will appear obvious to those performers familiar with today's touchscreen interfaces, players with less computer experience may find the interaction more difficult to learn; the gestures for triggering chords, in particular, may seem unclear. Fast and precise movement may be difficult to track with the Leap Motion, resulting in involuntary note triggering. Fast movements may result in slight latency and a sense of cybersickness. The display is both panel- and keyboard-oriented, somewhat similar to that of CrossScale. Given the "vintage" nature of synthesized sounds, it is plausible that the authors intended a display corresponding to early synthesizer computer keyboards. Hands (fingers, palms, and wrists) are visualized in three dimensions, using white solid color on black background. The sense of hands detached from the body and suspended in the black space is intriguing. It simultaneously enables and denies a sense of presence in different ways. That is, players are aware of their body parts, yet the hands are detached from the rest, undermining the sense of realism. Attaching the Leap Motion to Oculus Rift is an elegant solution, yet it adds a small amount of weight and awkwardness to the interface. The project was designed for a single user, although it would be reasonable to consider a version in which multiple players share the proposed virtual musical space.

Wedge

The Wedge musical interface, designed by Moore et al. (2015; see also youtu.be/tPxdVSrEC1U), also utilizes bimodal interaction and 3-D visualization using the Leap Motion controller and an Oculus Rift DK2 headset. Inside–out tracking allows for 360-degree control and bimanual visualization and interaction. Wedge is conceived as a customizable environment for composition and performance. Utilizing the 3-D surroundings, a performer is able to move and arrange virtual rectangular blocks with assigned pitches and MIDI note numbers. A virtual image of a robotic hand operates in two modes, called "build" and "play." In build mode, palm and index finger are oriented sideways, allowing for organization of notes into sequences and snapping them into chords laid out on the *z*-axis. The palm and index finger point upwards in play mode. For the most part, the tip of the index finger is used for alignment, arrangement, and triggering of sounds. The FluidSynth synthesis engine affords a variety of instrumental sounds that can be selected from an additional virtual scroll-down menu overlaid over the virtual blocks. This solution is effective, although, it can cloud the performance space. Perhaps moving it to a side would be more efficient. Because occlusion of the blocks and vibrotactile feedback are missing, the hands pass through the objects without resistance. This may cause cybersickness and problems with sense of presence. Single-finger interaction is effective, yet limiting to the speed and precision of the gestures. The VRMI is suspended in a planetary environment, which gives it a sense of depth. The hand is modeled with 3-D joints, giving it a sense of robotic veracity and scale superimposed onto the quasi-science-fiction 3-D environment. The blocks emerge from the layer of atmospheric space, further enhancing the sense of presence. Interaction modes rely heavily on natural gestures, and the resulting sounds do not push beyond the boundaries of the expected. The Oculus Rift and Leap Motion constellation supports standard ergonomic practices. Similarly to the previous projects, Wedge was designed for a single performer, although, it is clear that a social interaction with multiple users can be implemented.

Cirque des Bouteilles

In Cirque des Bouteilles (described by its authors as "The Art of Blowing"), the player performs on bottles, creating an audiovisual feedback loop (Zielasko et al. 2015; see also youtu.be/l-4TJsU5Gb8). The system is realized with the aid of an Oculus Rift headest for visualization and a Leap Motion controller for gesture tracking. A virtual space is set up as a 3-D visualization of a recording studio room, complete with door, glass window separation from the recording booth, some audio equipment, a floor rug, and a mixing console whose size and color match the physical desk at which the performer sits. Virtual ambient lighting and shadows are added for enhanced realism. Simulations of seven bottles are located on the desk in place of a mixer, showing the playful spirit of the designers. Each bottle has a label indicating the frequency it plays, and the percentage of liquid in it, together presenting a collection of a musical scale. Seated at the desk, performers can look around to situate themselves in the environment. In performance, both hands are in action and tracked by a Leap Motion unit placed on the desk. Simulations of palms and fingers are designed with focus on an animation of the bone structure. Additionally, hands are color-coded: the left hand in solid red and the right in solid green.

The left hand can grab the bottles, one by one, and place them closer in front of the player. Upward and downward movements of the right hand with the index and middle fingers extended forward are used to tune the bottle. Immediate changes of frequency, pitch, and liquid percentage parameters are displayed on the label, creating a direct motion–visual-feedback loop. Pointing to the opening of the bottle and virtually touching it with the right hand produces the sound of a blown bottle. While the bottle is excited, an accompanying visualization of the bottle turning a gray color with a gust of air coming out of it enhances the veracity of the situation.

Thanks to a certain playfulness of Cirque des Bouteilles, the project encourages the engagement of a variety of performance styles. Grabbing, pointing, and sliding bimanual gestures enable a sense of partial body presence. Using the natural interaction of blowing would certainly increase the sense of presence, aligning the natural and virtual actions. Perhaps this was not an objective of this project, however. The project's character is primarily humorous, and thus touching the bottle instead of blowing it is, in this case, deliberately unnatural. As a result of this misalignment (continuous blowing excitation replaced by pointed triggering), the attack and release of the sounding samples seem too abrupt, producing unnatural fade-ins and cut-offs. Latency is not noticeable; the precision in initiating the sound can be troublesome, however. This is due to the fact that excitation point (the opening of the bottle) is rather small. Performance calibration while playing on multiple bottles can be extremely challenging, even at a moderate tempo, and it can induce cybersickness. The desingers' crafting of the 3-D environment, hands, and bottles enhances the sense of presence. Although the current iteration is designed for a single user, it is clear that a shared performance could lead to lively musical explorations and social interactions.

Summary

Crosscale, ChromChord, The Wedge, and Cirque des Bouteilles were among the instruments entered in the 2015 3DUI contest (http://3dui.org/2015/contest_awards.htm, accessed 6 July 2016), which was part of the International Symposium on 3-D User Interfaces (3DUI) held in Arles, France, 23–25 March 2015. The state-of-the-art symposium focused on providing an opportunity for industrial and academic researchers in the field of 3DUI to present their products and exchange ideas. The sixth contest, named 3DUIIdol, was conceived to highlight innovative and creative solutions to challenging 3DUI problems. The requirements included: expansion beyond the mouse and keyboard interaction with VRMI; playing a sequence of notes, scales, and chords; the ability to learn and operate the system by those who can read music with ease; and the versatility to perform other scores. Additionally, the contestants were asked to prepare a performance of "Frère Jacques" in a live demo. (See http://3dui.org/2015/contest.htm for the complete guidelines.)

Out of six finalists, a single winner was chosen. Although the competition did not specifically require the use of immersive visualization, out of those six finalists, five included an immersive visualization via head-mounted displays. Surprisingly, the winner of the competition was the digital Intonarumori, a physical interface lacking any immersive visualization and developed by the authors of this article. The interface is a reproduction of the original Intonarumori instruments developed by Luigi Russolo and coworkers ([1913] 1967). An earlier prototype of such instruments was presented at the New Interfaces for Musical Expression conference (Serafin et al. 2006). At the end of the article, we will discuss why this interface was judged as the most successful. Crosscale was the runner-up in the contest.

Based on these case studies, it is safe to state that the VRMI design is still in its infancy. It is not surprising, however, as future VRMI designs will spring forward precisely from the tension between imitating the physical world while attempting to detach oneself from it. Historically, the theremin and the Intonarumori have already paved a path.

For the moment, the difficulty of completing the basic musical task of performing a melody with conviction on most of the described instruments reflects such tension. Because most of the instruments lacked a vibrotactile feedback, performance was imprecise and cybersickness was introduced. Relying on crude arm and finger movements in situations that required precision and speed posed further challenges in accomplishing the task. Latency did not hinder the performance experience. Positioning the instrument in a crafted 3-D environment did enhance the sense of presence. The predominant combination of Oculus Rift and Leap Motion units showed the reliance on commercially available technologies, which raise some precision and mapping problems as well as being somewhat bulky interfaces.

Developing a virtual object is typically a process rather than an abrupt change (Levy 1998). In the end, challenges arise from enabling the imagination to guide the musical exploration. Establishing performance practice, repertoire, and lasting technologies will complement the process. Perhaps additional development of shared experiences in VR can become a playground for future explorations.

As a final remark, it is worth considering why the winner of the competition was, as previously mentioned, the Digital Intonarumori (Serafin et al. 2015). This is a successful anomaly given that the instrument lacked any augmented visual feedback. The instrument captured attention, however, because of the use of a physical controller with enhanced tangible presence and an elaborate synthesis engine that enabled complex sound production. The performer's gestures stimulate a continuous flow of change, thus providing auditory feedback not based on discrete points. Perhaps the most successful features of the instrument were mapping, natural playing technique, and intuitive control.

As for its construction, the instrument consists of a lever and crank. The lever movement controls frequency of the resonator and rotational speed of the crank provides continuous excitation for the instrument. We have been working on implementing an option that would allow the performer to select different classes of instruments directly from the tangible interface. Further addition of visual feedback is also being considered. The physical interface enabled us to minimize the latency, making the audio–tactile feedback loop smooth and believable. While measuring cybersickness, body representation, sense of presence, and VR medium inclusion did not apply to this iteration of the project, visualization of the different hand positions while operating the lever and crank as well as an animated resultant frequency display are being crafted for a future version of the instrument.

In this case the visual augmentation would work as an additional aid to the player, to better understand where to position the lever to achieve a desired sonority.

Potential versions for augmented reality and virtual reality systems, in which the the performer would operate a 3-D lever and crank, are being considered. The solid physical design defines the set of performance gestures; however, the flexibility of switching classes of instruments in the software enables surprising magical interactions. The same physical gestures could thus initiate diversely contrasting sonic processes. Expanding on Russolo's ingenious design, the Digital Intonarumori physical interface manifests ergonomic features that enable easy access and operation of the instrument. Although the instrument was designed for a single performer, a social experience could be stimulated through an ensemble of instruments.

Conclusion

Virtual reality technologies have provided new possibilities for exploration of musical interaction. Development of new techniques, graphic displays, immersion methods, and navigation systems has been crucial in advancing research and applications.

We believe that the main challenge is to develop sophisticated VRMIs that expand on the currently available VR musical installations and musical toys. In order to achieve this goal, continuous physical interactions and multimodal feedback with the instrument will need to be established. The challenges include understanding the unique potential that VR and any other immersive technologies can bring to the design strategies.

Learnability and training are yet another area for investigation and improvement. As we know, it takes years of practice to master a traditional instrument. We believe that such practice could also be beneficial in the case of NIME and VRMIs. Substantial time dedicated to practice and iterative design would be greatly beneficial to sustaining any VRMI. Such commitment, however, needs to be initiated and maintained by both designers and performers. Then transformation from musical toys and gadgets to fully developed instruments will become joyfully realistic.

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