VRMin: Using Mixed Reality to Augment the Theremin for Musical Tutoring

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ABSTRACT

The recent resurgence of Virtual Reality (VR) technologies provide new platforms for augmenting traditional music instruments. Instrument augmentation is a common approach for designing new interfaces for musical expression, as shown through *hyperinstrument* research. New visual affordances present in VR give designers new methods for augmenting instruments to extend not only their expressivity, but also their capabilities for computer assisted tutoring. In this work, we present *VRMin*, a mobile Mixed Reality (MR) application for augmenting a physical theremin, with an immersive virtual environment (VE), for real time computer assisted tutoring. We augment a physical theremin with 3D visual cues to indicate correct hand positioning for performing given notes and volumes. The physical theremin acts as a domain specific controller for the resulting MR environment. The initial effectiveness of this approach is measured by analyzing a performer's hand position while training with and without the VRMin. We also evaluate the usability of the interface using heuristic evaluation based on a newly proposed set of guidelines designed for VR musical environments.

Author Keywords

Virtual Reality, Mixed Reality, Music Pedagogy, Theremin

ACM Classification

H.5.1 [Information Interfaces and Presentation] Multimedia Information Systems—Artificial, augmented, and virtual realities, H.1.2 [Information Systems] User/Machine Systems—Human factors, H.5.5 [Information Interfaces and Presentation] Sound and Music Computing

1. INTRODUCTION

Developed in the 1920s by Leon Theremin while experimenting with radios, the *Theremin* is one of the earliest electronic music instruments and one of the few instruments that is performed without physical contact (and without the use of a computer). The continuous nature of the *Theremin* makes it one of the most expressive electronic music instruments for performers. However, this continuous nature also makes it one of the most difficult instruments to learn and play. While many musicians have used it as a novel addition to their compositions it was never fully adopted as a new musical voice, and only a few players have mastered it. Instead the theremin is mostly known for the eerie sounds of Sci-Fi movies of the 1950s. The theremin has, however, had a substantial influence on NIME.

One such area is the work on *hyperinstruments*, a term introduced by Tod Machover at MIT Media Lab [12]. Hyperinstruments are traditional instruments that have been augmented with sensors for real-time processing of performance data. They enable the type of computer control and music generation provided by digital instrument that is typically not available to performers of acoustic instruments. One of Machover and colleagues' most prominent hyperinstruments, the *Hypercello*, used similar electric field sensing techniques to the *Theremin* for the sensing of an augmented bow for the cello. The instrument, implemented by Machover's colleagues, Paradiso and Gershenfeld, was designed for Yo Yo Ma to perform Machover's composition *Begin Again Again...* [20]. The Hypercello, like many hyperinstruments since then, was specifically designed for a composition and required invasive augmentation with sensors of a specially designed cello. Such invasive modifications are expensive, hard to implement, and difficult to adopt by musicians. More recently researchers have used advanced and innovative sensors for non-invasive instrument augmentation [23]. New technologies for Virtual Reality (VR) and Mixed Reality (MR) afford more possibilities for augmenting instruments. While sensors allow for more gestural control, VR and MR add a new layer of visual affordances to the interaction. Instead of interacting with an intangible location within the performance space, VR can be used to add virtual objects to the environment providing visual cues to guide a musician's interaction with the instrument.

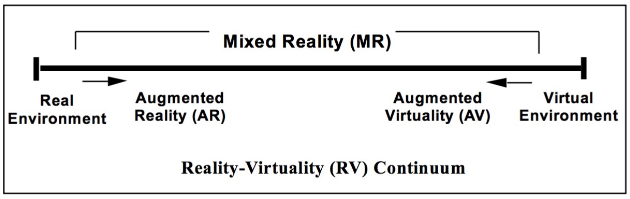

Figure 1: Milgram's Reality-Virtuality Continuum

VR and MR are similar concepts that vary in relation to the degree the user is immersed in a virtual environment. As Milgram proposed with his Reality-Virtual Continuum, shown in figure 1, MR is any environment that mixes real world components with a virtual environment, with augmented reality and virtual reality at the extremes of the continuum [14].

In 1992 Jaron Lanier (often thought to have coined the

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term Virtual Reality) performed *The Sound of One Hand*, a live improvisation of VR music instruments. One of the more notable aspects of his performance was that Lanier performed multiple instruments using only one hand, creating a performance that could not be accomplished with physical instruments [9]. Since then, however, there has been little research exploring the possibilities of performing music in immersive environments.

The visual affordances of VR and MR can extend traditional instruments, and hyperinstruments, in a number of ways. With the emergence of depth sensors, such as the Kinect, that allow performers to interact with virtual space, VR and AR can be used to add visual signifiers to the space that provide visibility to the additional functionality of instrument. Additionally the visual signifiers could be used as training mechanisms for new musicians to learn the particular instrument. With this work we propose, *VRMin*, a system for the later case, in which we augment a physical theremin with visual objects to help new thereminists learn correct hand positioning and placement.

1.1 Hyperinstruments

Since Tod Machover's work on hyperinstruments there has been significant research on augmenting instruments with sensors and microcontrollers to extend the capabilities of traditional instruments. Young's *Hyperbow* uses sensors and custom hardware track the position, acceleration, force and angle of a violin bow. The sensor data affords musicians new expressivity in their performance by allowing the violinist to alter the acoustic sound of the violin in real-time using gestures from the bow [25]. Overholt takes augmenting the violin one step further by designing the augmented violin from the ground up building the hardware and sensors directly into the instrument [19]. The *Electrumpet* is a standard trumpet augmented with additional sensors and buttons for additional control of the acoustic output. While *Electrumpet* augmentation was not completely invasive to the original instrument it does require the technical expertise to work with microcontrollers for a musician to implement in their own instruments [10].

The release of RGB-D sensors such as the Kinect has led developments in non-invasive augmentation seen in Trail and collegues' work on augmenting pitched percussion instruments using a Kinect[23]. Using sensors like the Kinect affords more accessible and affordable instrument augmentation since all that is needed is a Kinect and computer running the special middleware. As sensors improve and Virtual and Augmented Reality become more prevalent we expect to see the emergence of hyperinstruments solely using these technologies to augment the capabilities of traditional instruments with virtual objects.

1.2 Virtual Reality Music Instruments

Advances in VR and MR technologies have expand the possibilities for creating New Interfaces for Musical Expression (NIME) and Learning. With the advent of VR, a new category of NIME is emerging, Virtual Reality Music Instruments (VRMI). VR adds a visual layer to the design of NIME and thus far there is little research on how the new visual affordances of VR can to be used for music interfaces.

One of the first published research experiments of VRMIs may be the work of Maki-Patola and colleagues. In this work the authors analyzed four VRMIs using Jorda's concepts of efficiency and learning curve [8]. In their findings, they reported that because VR is a different medium compared to a the real world, mimicking traditional instruments in VR may not result in better instruments unless VR is used to augment real instruments with additional control. Furthermore, they noted the potential of visualization for providing visual cues, teaching users and visualizing sound [13].

The majority of research of VRMI has led to interfaces in which a perform generates musical sounds through interactions with 3D musical objects using standard VR input controllers, for example Berthaut, Desainte-Catherine, and Hachet propose the use of 3D reactive widgets [1] and Moore and colleagues work on *The Wedge* in which users build their own musical performance space by adding note objects to space from a palette [15]. Instead of using standard input controllers for sound generation, Gelineck and colleagues proposed a VRMI for interacting with tangible controllers that can change dimensions of physical models in real-time through VR capabilities [2]. This work shows the potential for using VR technologies to create hyperinstruments. Although the controllers were not acoustic instruments (as is the case with hyperinstruments) their work shows how VR can be used to extend the physical world. For a more extensive overview of VRMIs see this year's survey from Serafin and colleagues. In this work the authors also proposed nine design principles for VRMIs used to develop an evaluation framework [22].

The bulk of research of VR for musical interfaces has been in the design of new digital music instruments. VR also opens the door for two other types of musical interfaces, augmented instruments (or hyperinstruments) and computer assisted music instrument tutoring (CAMIT) interfaces. Furthermore, MR has the potential to augment physical music controllers with new features and visual feedback in real time. In essence VRMIs have the potential for creating musical experiences not available in the real world.

1.3 Computer Assisted Music Tutoring

Learning to play a musical instrument is a challenging task that requires years of disciplined practice to master. Advances in technology have opened the door for computational methods for musical pedagogy that can make the process easier. Research in the field of Computer Assisted Music Instrument Tutoring (CAMIT) has created tools to improve this process by analyzing students' performance and providing personalized feedback [21]. These tools generally use audio signal processing to analyze the aural performance of the student. The success of companies like Yousician [1] shows that there is demand for tools to enhance the musical learning experience. There is not, however, a substantial amount of research in the area of CAMIT.

There have been a few proposed systems for CAMIT in non immersive AR. Piano AR is an application for teaching piano by augmenting a physical piano with virtual fingers that a student would then follow [6]. Mora and colleagues use AR to correct poor body posture in piano players [16] and Liarokapis used non immersive AR for for guitar learning[11]. Johnson and colleagues proposed a system to analyze pianists' hand posture using computer vision with the goal of implementing an AR based piano tutor application [7]. While these works provide proof of concept for VR based musical tutoring more research is required to understand the effectiveness of this approach to learning an instrument.

In addition to using VR to teach traditional instruments, researchers of VRMI have seen the potential for using VR to teach users how to play VRMIs. As Maki-patola notes, "in addition to providing visual cues, visualization could be used to teach the user how to play an instrument. For example, the FM Synthesizer could include a scrolling musical

[1] `https://yousician.com/`

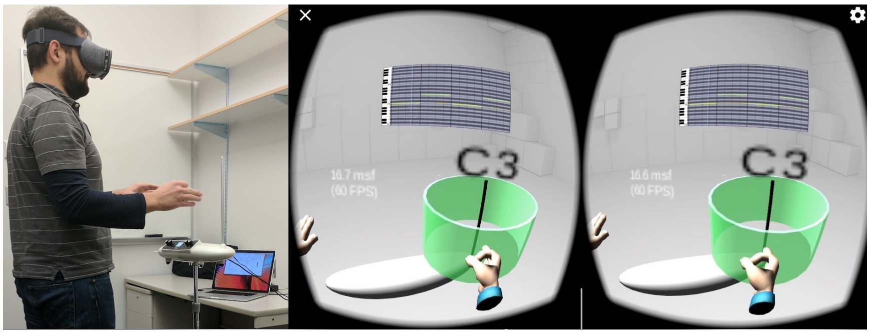

Figure 2: A student practicing the theremin using VRMin with capture of the view on the right

score that marks the correct position of the hand in the air" [13].

1.4 Heuristic Evaluation

Self evaluation of an interface is a critical step in the interaction design process to quickly evaluate the design before the intrusive process of a usability study. One commonly used method is Heuristic Evaluation (HE) in which an evaluator determines the good and bad aspects of an interface based on a set of guidelines, known as heuristics [18]. Many of these heuristics common for traditional user interfaces (see [17, 24]) are not be well suited to the design challenges presented for virtual interfaces and environments. As Gabbard, Hix, and Swan claim, "[these guidelines are] too general, ambiguous, and high level for effective and practical heuristic evaluation of VEs" [4]. Instead the authors proposed a framework of design guidelines developed specifically for VEs [3]. VR music environments (including both expression and learning environments) have different characteristics of than that traditional VE. Serafin and colleagues presented nine design principals specifically for for VRMI, a number of which are also relevant to our work on VRMin [22]. From a pedagogical standpoint, an optimal use of performance feedback is an important factor in the design of VEs. Research has been done in simulation based medical education (SBME) that shows how learning is affected by different types of performance feedback [5]. The ideas from each of these fields have informed our development of design guidelines for heuristic evaluation of MR musical pedagogy presented in section 3.

2. VRMIN

In this work we present, *VRmin*, a mixed reality CAMIT application intended to improve the process of learning the theremin. The main challenge that affects a user's ability to learn the theremin is a lack of affordances and constraints that provide guidance within the pitch and volume spaces. Furthermore, the theremin has continuous control rather than being composed of discrete notes. This makes it difficult for new thereminists to find the correct location of a given note. *VRmin* provides visual cues to guide the performer within the pitch space by augmenting the theremin with visual signifiers through the use of mobile VR. Figure 2 shows a student practicing the theremin with the VRMin environment.

2.1 System Description

VRmin is a Mixed Reality (MR) system that integrates a Moog Theremini[2] for sound generation with mobile VR technology for visual augmentation. Implementing the system using mobile VR increases accessibility as devices become more readily available. For this implementation we use the Google Daydream platform[3] and a Google Pixel XL. We found that the use of the Daydream controller was intrusive to the interaction with the theremin, as a thereminist's hands should be free to better control of musical output. With that in mind, we've designed VRMin so that all control is performed through interaction with the theremin instead of the native Daydream controller. This also affords for a system that is extensible to other VR and MR platforms including mobile VR, such Google Cardboard and Samsung Gear VR, and more powerful platforms, such as the Oculus Rift and Microsoft HoloLens.

The Theremini outputs MIDI CC messages for both the pitch and volume antennae which we use as input for controlling the MR interface. The pitch control values are easily scaled to frequency based on the frequency range of the theremin. The frequency range of the Theremini is configurable and for the sake of this work, we have configured the Theremini with a frequency range of 65.40 Hz (C2) to 493.8 (B4) Hz.

The Theremini is connected to a computer running a Pure Data patch acting as middleware for converting MIDI CC messages to OSC for simplified network communication. Additionally the middleware handles simple gesture detection to add functionality to the theremin. Messages containing the pitch and volume control data, as well as detected gestures, are sent from the middleware to the VR device which is running an OSC server implemented with Unity. The received messages are then used to control interface elements, as described in the next section.

2.2 User Interface

The VRMin environment, shown on the left in Figure 2, contains visual representations of the physical elements that comprise the performance space, in this case the Theremini and the user's hands. These are augmented with visual elements not present in the real world, a visual note signifier and a virtual piano roll. The visual elements are controlled through input from the middleware allowing the Theremini to act as the controller. The pitch and volume values control the locations of the hands relative to the antenna and gesture messages are used to control interactions with the tutoring interface.

Within the VE we try to map the physical elements as closely to the real world as possible in both their dimensions and their positions. The theremin is represented with a simple 3D model with dimensions that replicate the physical theremin within the performance space. 3D hand models are used to represent the location of the user's hands relative to each antenna. Each hand is modeled in a pos-

[2]`https://goo.gl/zJNP5E`

[3]`https://vr.google.com/daydream/`

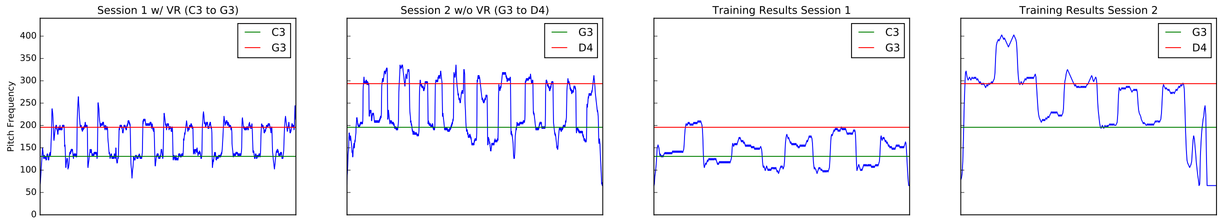

Figure 3: Performance analysis plots of practice sessions with and without VRMin

ture similar to one a thereminist would typically use; the pose of right hand is similar to the ”OK” sign and left hand uses a horizontally oriented flat hand. Using the ”OK” sign also mitigates an issue the authors found in which a vertically oriented flat hand occludes the tip of the middle finger from the field of view. This posed a problem because of the precision required to correctly play a note with a theremin.

The location of notes within the pitch space can be represented with circles since all points are equidistant from the antenna. For a 3D representation of notes we use hollow cylinders to indicate the location of a note relative to the antenna within the pitch space. Each note is also accompanied by text indicating the name of the note for additional feedback. Notes are transparent so that the user has constant feedback as to the location of the tip of virtual hand even as their hand passes through the cylinder. To play a displayed note, a user moves their hand such that the position of the tip of the virtual hand is located at the center of the two concentric circles that comprise the hollow cylinder. To further enhance performance feedback the cylinder's color changes to green when the tip of the middle finger is in the correct location[4].

The interface also contains a piano roll to display a score during the performance session. The piano is positioned just above the pitch antenna and is rotated along the Y axis by 30 degrees. This positioning provides the best view of the piano roll that is not obstructed by any portion of the theremin or note indicators. The user is able to easily view the piano roll by slightly tilting their head up. This placement also keeps a view of the right hand and virtual note in the user's periphery as they view the score. The piano roll includes a pitch indicator line to provide additional performance feedback as the score is being viewed.

Since VRMin has the design constraint of avoiding a separate controller, we have implemented simple gestures for interacting with the system using each antenna as a trigger. To activate a trigger a user simply places a hand in the near position of the antenna for a period of time that is longer than the hand would typically be in that position during performance. For example, the volume antennae is used as a trigger to start and stop each practice session by holding a hand in the near position of the antennae for two seconds. Additionally, the user is able to change the score used for the practice session similarly using the pitch antenna trigger. A third trigger is available (but not currently implemented) by placing hands at the near position of both antenna at the same time.

2.3 Performance Analysis

To improve the analysis of practice sessions, we have implemented performance logging in VRMin. The logging system records the OSC messages and values sent to VRMin. This data could then be used to replay a practice session for a visual analysis of the performance (similar to reviewing video recordings). More importantly, teachers can gain insight into a student's progress through a quantitative analysis of the data by using plots similar to figure 3.

The plots in figure 3 show the results of two pitch matching practice sessions, one using VRMin and one without. In each session, the student attempts to match computer generated tones and hold the tones for five seconds each. In this case the student is practicing moving between intervals of a perfect fifth. After each session, the performer attempted to perform the same tones without VRMin or the corresponding pitch playing in the background.

In figure 3 the red and green lines represent the pitches the thereminst was instructed to play as part of a pitch matching practice session. The first two charts show the results of the student during the pitch matching training sessions and the last two show data from the student attempting to play the notes on their own. While these are by no means conclusive, we do see that when using VRMin the user is much more precise during the practice session as there is much less vibrato and it was easier to find the correct location. Post pitch matching, however, it appears the user trained without VRMin was better able to recall the locations of the notes after a bit of adjustment.

3. HEURISTIC EVALUATION

The goal of this work is to design a tool that supports musical pedagogy in VEs; thus the guidelines chosen for the evaluation of VRMin have a focus on interface aspects that lead to positive user experiences for learning in a VE. For the sake of brevity we will not go into full detail about each guideline, we save that for future work as we refine the guidelines (we also direct you to the references for more detail about a specific guideline). Instead we discuss the high level guidelines we've found most important for the task of learning musical concepts and mention the supporting guidelines.

First we must make the distinction between two types of feedback for learning systems, *performance feedback* and *interface feedback*. *Performance Feedback* relates to the feedback given to a user to based on an analysis or their musical performance. This type of feedback is analogous to the feedback a music teacher would give while watching a student perform a scale. While *interface feedback* is feedback presented to a user based on the results of a given interaction with interface elements. An example of interface feedback is a visual signifier indicating that an action, such as loading a new score, was successful.

Based on the research discussed in 1.4 and our experience designing VRMin, we have established the following categories of design guidelines for VR based musical pedagogy systems.

1. **Guidelines for performance feedback** - these guidelines help design performance feedback that optimizes learning and minimizes the over reliance on feedback [5].

[4]see a video demo at `https://goo.gl/DxvSqK`

(a) Visual feedback shouldn't prevent a user from focusing on aural feedback
(b) Reduce cognitive load by limiting the amount of concurrent feedback [5]
(c) Provide terminal performance feedback upon completion of the practice task [5]

2. **Guidelines for VE design** - these guidelines are used to guide design decisions about the VE for the practice space promoting an enriching and comfortable experience. A properly environment also increases the usablity of the virtual interface.
   (a) Visibility of system status [17]
   (b) Choose metaphor(s) that naturally match the application task space [3]
   (c) Match between system and the real world [17]
   (d) Create a Sense of Presence [22]
   (e) Consider Display Ergonomics [22]
   (f) Consider Controller Ergonomics
   (g) Represent the Player's Body [22]
   (h) Ensure that users' avatars provide a familiar, accurate, and relevant frame of reference [3]
   (i) Allow users to alter point of view, or viewpoint [3]

3. **Guidelines for interaction in VR pedagogy** - while some interaction with the interface may be required during practice it should be limited to reduce user's cognitive load affording more mental capacity for learning new skills.
   (a) Limit nonessential interaction during practice
   (b) Recognition rather than recall [17]
   (c) Make use of existing skill [22]

3.1 Findings

Performing an heuristic evaluation requires a user task to guide the evaluation of the interface. For this case study we use an ear training practice task for beginning thereminists. During the practice session VRMin plays an aural tone of a specific pitch according to the practice score. The user's goal is to match the the pitch by moving their hand to the correct location relative to the pitch antenna. While wearing the VRMin display the user is presented with visual signifiers to help guide them to the correct location. Some initial findings from applying an HE while performing the practice session are listed in table 1.

Table 1: Findings from a Heuristic Evaluation (italics indicate a potential design issue)

ID	Comments
1.a	*By trying to match the position of the hand to a visual element a user's attention is directed to the visual feedback rather than the auditory feedback from the theremin.*
1.b	Performance feedback during practice is limited to one element at at time.
1.c	*Performance analysis graphs are available but are not integrated into the VRMin interface*
2.b	All current interaction is performed using the only the theremin. Also the piano roll is a common
2.d	Presence is promoted by matching the real world to the VE and by integrating real objects with virtual objects.
2.e	The Google Daydream is a comfortable display but *has a small field of view making it difficult to view the aspects of the theremin that happen to be in the periphery*
2.h	The hands are in postures used by a number of renowned thereminists but *not all thereminists use the same hand posture.*
3.a	After starting a practice session there are no additional interactions required that are not directly tied to practice.

3.2 Discussion

By performing evaluation on VRMin using the above heuristics we have identified several potential design issues. Furthermore, we have established new questions about the VE to be answered through a formal usability study. Below we discuss the design issues listed in table 1 that we feel are most important to address either through interface changes or through usability studies.

First, design guideline 1.c suggests to provide terminal feedback upon completion of the practice task. Currently VRMin does not provide terminal feedback to the user after the practice session. This can be addressed by designing a new view to include data from the performance loggling simliar to the charts figure 3. One question that arises is how best to present this data to the student. Should the visualization be presented directly in the VE or would it be best to allow the student to view and analyze the data on a standard display? Additionally it would be interesting to find new visualization methods that take advantage of the visual affordances of VR.

Contrary to guideline 2.h, the hand postures of the virtual hands in VRMin are static and do not necessarily represent how a student may pose their hand during their performance. While we choose a hand posture that is commonly used, there are multiple techniques with varying hand postures. To ensure that the virtual hands provide an accurate representation of the user we plan to modify the interface so the user is able to change hand posture to reflect their playing style. An alternative would be to implement robust hand tracking which would require an additional sensor be added to the system, such as the Leap Motion. We prefer not to increase complexity unless it shown that exact real to virtual mapping improves the learning process.

Finally the most significant design challenge (as is the case with any pedagogical system) will be finding the proper balance of performance feedback to minimize the chance of users becoming over reliant on feedback. While performing pitch matching, one of the authors felt that his attention was focused more on adapting hand position based on the visual cues rather than focusing on the auditory feedback of the theremin. This required the user to expend cognition that could have been used to focus on listening to difference in pitch. The visual feedback does, however, provide valuable information for those that have trouble hearing pitch. By placing cues where hands should be located for given pitches, the user can be confident that they are playing the correct pitch, increasing the efficiency of their practice. It has yet to be seen how the extra strain on cognitive load from visual feedback affects students' growth over time. As a user gains experience with the interface the increased practice efficiency may compensate for the high cognitive load in the beginning. Finding the proper balance will take a comprehensive user study that evaluates students' growth over time with and without VRMin.

4. CONCLUSION

This paper describes the design and formative evaluation of *VRMin*, a mixed reality environment for learning the theremin. Specifically our work focuses on designing a system using the visual affordances of MR for enhanced theremin practice while minimizing the reliance of feedback. With this goal in mind, we have established a set of design guidelines for heuristic evaluation of MR environments for musical pedagogy. Using these guidelines we performed an evaluation of VRMin to uncover potential design issues in the environment. The issues will either be addressed directly through design modifications or will require a more formal usability study to better understand their effects on the learning process. While we have presented VRMin as a tool for pedagogy, the system also lays the foundations for an MR environment for musical expression.

Our initial evaluation of VRMin taught us that the attention spent focusing on the visual feedback increases the cognitive load during practice making it more difficult to focus on aural feedback leading to the potential of a student becoming over reliant on VRMin. The data from figure 3, however, indicates that the time spent practicing with VRMin may be more efficient for the student. To better understand the effects of real-time visual feedback in this sense we plan to perform a user study in which users will attempt to learn the theremin with different configuration of the VRMin environment including one without the use of visual augmentation through VR.

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