The Prospects For Eye-Controlled Musical Performance

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ABSTRACT
Although new sensor devices and data streams are increasingly used for musical expression, and although eye-tracking devices have become increasingly cost-effective and prevalent in research and as a means of communication for people with severe motor impairments, eye-controlled musical expression nonetheless remains somewhat elusive and minimally explored. This paper (a) identifies a number of fundamental human eye movement capabilities and constraints which determine in part what can and cannot be musically expressed with eye movements, (b) reviews prior work on eye-controlled musical expression, and (c) analyzes and provides a taxonomy of what has been done, and what will need to be addressed in future eye-controlled musical instruments. The fundamental human constraints and processes that govern eye movements create a challenge for eye-controlled music in that the instrument needs to be designed to motivate or at least permit specific unique visual goals, each of which when accomplished must then be mapped, using the eye tracker and some sort of sound generator, to different musical outcomes. The control of the musical instrument is less direct than if it were played with muscles that can be controlled in a more direct manner, such as the muscles in the hands.

Keywords
Eye-controlled interfaces, eye tracking, human performance, music, musical expression, sensor interfaces.

1. INTRODUCTION
Despite a somewhat dramatic increase over the last few years in the use of new sensor technologies for musical expression (such as with the Kinect motion detector and the Wii Remote inertial measurement unit), as evidenced by the nature of papers presented in recent years at this conference, and even though eye tracking devices are getting cheaper and better, there remains relatively little work done to perform music with eye movements. There in fact appear to be only six successful projects to date. This paper attempts to understand why there has been such relatively little work in this area. The paper discusses the human processes that are involved in moving the eyes, summarizes the six prior eye-music projects, and characterizes the fundamental constraints of eye-controlled musical expression.

1.1 Why the Eyes Move
The eyes are used primarily to take in visual information—to see the world—and hence the muscular control that is required to rotate the eyeballs in their sockets is primarily used to bring visual items that are in the periphery into the high-resolution vision at the center of vision, the "point of gaze." A person's introspective experience of his or her eye movements is not that the eyeballs are rotating in their sockets but rather that new high-resolution visual information becomes available to visual perception.

Conscious deliberate control of the point-of-gaze is perhaps only possible to the extent that a person can consciously and deliberately pursue different specific visual-perceptual goals such as to bring a white dot into high resolution vision or, in everyday terms, to simply "look at" the dot. It is difficult, without practice, to *not* look at a dot that consistently appears on a computer screen just to one side of the point of gaze; there is a tendency to try to look at the dot, which causes it to move, and it gets chased off the screen [3]. Eye movements can only be controlled indirectly, by pursuing visual goals. To build an eye-controlled musical system, the instrument designer must create a set of visual-perceptual goals each of which can be accomplished by the performer and uniquely detected and mapped to a different musical outcome. The specific kinds of eye movements that people can make to achieve visual perceptual goals are discussed next.

1.2 How the Eyes Move
There are a limited number of distinct classes of eye movements that people can make, and thus that could be mapped to direct musical outcomes. These classes are summarized here, drawing from Rosenbaum [8]. Each class of movements has evolved in humans to support a different supporting role in visual perception.

Single point-of-gaze. Though we have two eyes, they typically point together at the same location, producing a single point of gaze. This assists visual perception by providing additional and redundant sensory information as well as distance information.

Saccades and fixations. The most typical eye movements are quick *saccades* that last on the order of 30 ms and which jump the point-of-gaze from one location to another. The gaze then typically stays at that new location for a *fixation* that lasts roughly 100 to 400 ms. The fixations permit high-resolution visual information to be collected for an extended period and for new gaze destinations to be considered.

Smooth pursuits. In a *smooth pursuit* the eyeballs rotate at a steady rate. This type of movement is typically produced only when there is a steadily moving object to lock onto. This permits vision to gather visual information from objects that are moving, or that are stationary when the head is turning.

Blinks. Blinks occur to moisten the surface of the eye and to protect the eye from approaching objects. Blinks have been used in some eye-controlled interfaces but are not typically used in such interfaces intended for people with severe motor impairments because many such users cannot control their blinks.

Jitter. During a fixation, the eyes do not hold perfectly still but instead make very small random movements on the order of 0.1° of visual angle. The jitter prevents receptor cells from becoming over-saturated and the image from fading.

From among these classes of eye movements, fixations are the primary behavioral phenomenon that are used to issue direct commands to a computer because a fixation on or near an object is a visual-perceptual goal that can be easily motivated on a visual display and used to motivate an eye movement that can be detected by an eye tracker in a relatively straightforward manner. However, *all* of the

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(x, y) data that are reported by the eye tracker can potentially be mapped to musical outcomes, including the path of the eyes during saccades, and even the jitter. Even though there is little evidence that a performer has any direct or indirect control over these aspects of the data stream, all of the data can of course be used in a composition.

1.3 Eye Tracking Technology

Most eye trackers work by using specialized computer vision algorithms to convert a video image of the eye into the (x, y) coordinates of where a person is looking on a computer screen. The (x, y) location is typically reported between 30 and 1,000 times per second (30 to 1,000 Hz). In order to report the coordinates accurately, the algorithms are necessarily complex and, for commercial eye tracking companies, closely-guarded trade secrets.

One challenge when working with eye tracking technology is to get accurate data [12]. Reasonably accurate commercial eye trackers, such as by SensoMotoric Instruments (smivision.com) or L.C. Technologies (eyegaze.com), can report where a person is looking with reasonable accuracy, within roughly 1° of visual angle (which is roughly half the width of your thumb at arm's length). But these commercial systems also tend to be somewhat expensive, on the order of US$10,000. This presents a problem for computer musicians who would like to explore eye-controlled music but do not have access to accurate commercial devices. Cheaper commercial systems that cost on the order of US$200 are currently being introduced to the market but it remains to be seen how accurate and reliable these devices will be. Some open source eye trackers are available, such as the ITU Gaze Tracker (gazegroup.org), EyeWriter (eyewriter.org), and openEyes (thirtysixthspan.com/openEyes/), with the ITU Gaze Tracker perhaps the most advanced of the three. But these systems do not yet appear to have the accuracy of a good commercial system. The accuracy and reliability of an eye tracking system will directly affect the extent to which it could be used to control a computer, such as for musical performance.

The idiomatic interaction technique used in eye-controlled interfaces is to present a user with oversized buttons that the user can decisively select by looking at buttons for short periods of time. The buttons need to be oversized to compensate for the jitter in the eye movements and the error in the eye tracker. This interaction technique is relatively easy to implement because all that needs to be done to determine which buttons are pressed is to count the number of consecutive gaze samples that occur within each button region. Smooth pursuits are not typically used in eye-controlled interfaces because it is not as straightforward to move objects around a display such that the eyes could lock onto those distinct objects to issue distinct commands, but this would be an interesting area to explore in part because it would permit a range of aesthetically interesting visual components in an eye-controlled interface.

1.4 An Upper Limit on Eye-Controlled Performance

Given the idiomatic interaction technique of using fixations to control an interface with the eyes, we can establish an upper limit on the number of discrete eye commands that a person can issue in a given amount of time. In terms of how many fixations can be made per second, there is strong evidence that, even with practice and in the most optimal circumstances, such as simply moving the eyes back and forth between two buttons, people can make at most four specific, deliberate eye-controlled commands per second. Figure 1 shows the results of an experiment conducted in our lab in which participants used their eyes (and three different eye-controlled trigger methods) to tap along to a beat (alternating between eight beats of taps and eight beats of rest), and we found that 50% accuracy is only achievable for inter-beat intervals of 250 ms and higher, and that the best performance requires inter-beat intervals of 300 ms and higher. When the eyes are not simply bouncing back and forth between two points but instead moving to new intended locations with each

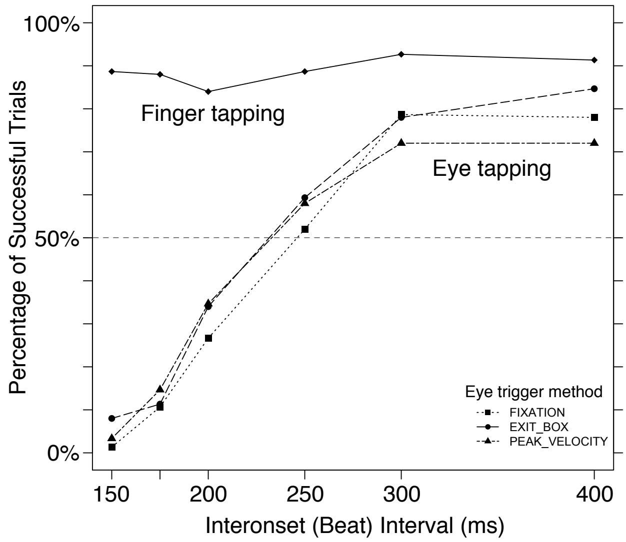

Figure 1. The percentage of successful tapping trials as a function of the inter-onset interval between the beats, a measure of an ability to tap a rhythm using eye movements.

saccade, such as when eye-typing, it appears as if eye-controlled buttons can be selected no faster than one button every 600 ms [6]. Working within the human and technology constraints discussed here, researchers and musicians have successfully developed a number of eye-controlled systems for musical expression, which will be discussed next.

2. A REVIEW OF EYE-CONTROLLED MUSICAL PERFORMANCE

To date, there appear to be just six published or publicized projects that have successfully developed eye-controlled musical instruments, compositions, or performances. This review captures the author's understanding of all such work based on reviewing the literature, searching the web, and communicating with researchers and practitioners. The projects are presented in an order that shows the natural progression of the development of eye-controlled musical expression.

2.1 Intuitive Ocusonics – Polli (1999)

The earliest work on eye-controlled music is the Intuitive Ocusonics system, and compositions created using this system [7]. Figure 2 shows some of the software components, and Figure 3 shows a performance using the system at SIGGRAPH in 2001. Intuitive Ocusonics used Steim's BigEye software as a low resolution video analyzer to monitor the position of the dark pupil and iris in comparison to the white of the eye, giving the composer roughly nine unique pupil-and-iris positions to work with, each of which was used to trigger different synthesized or sampled sounds. It appears that the system was somewhat prone to error, and that the performer did not have tightly-coupled control of the instrument and thus the sounds that were played, but also that the compositions were designed to use this error as a creative element. This is the only system discussed here that did not work in some way with the x and y positions of the gaze on the display, but instead directly interpreted the video stream of the eye itself. Though this would understandably be more error-prone and thus introduce more artifacts into the performance, Intuitive Ocusonics is arguably the first attempt to create a DIY (do-it-yourself) eye tracker and evidently the first attempt to use the eyes to control a musical performance.

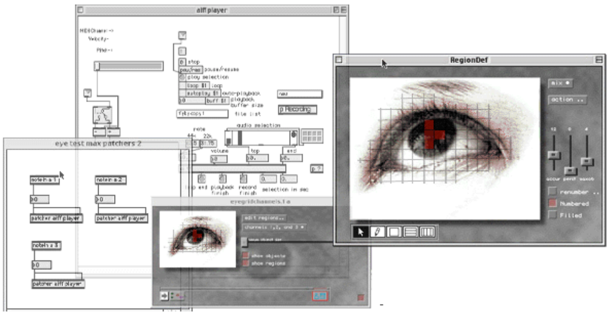

Figure 2. Andrea Polli's Intuitive Ocusonics system used Steim's BigEye to extract data from video images of the eyes and Max/MSP to convert these data into sound. (Image from www.andreapolli.com. Used with permission.)

Figure 3. A performance using the Intuitive Ocusonics system in 2001. (Image from www.andreapolli.com. Used with permission.)

2.2 Oculog – Kim et al. (2007)

Oculog [5] is another DIY eye-image tracker that, like Ocusonics, works directly with the video image of the eye, though Oculog uses computer vision algorithms to compute the relative horizontal and vertical position of the pupil in the camera frame (with no calibration to the computer's display). Because the change in the position of the pupil is relative to the camera, and the camera is fixed to goggles worn by the performer, the performer must move his or her eyes based on visual-perceptual goals that can be generated from the performer's immediate visual environment. This arrangement does mean that smooth pursuit movements can be evoked quite easily by simply fixating an object and then moving the head (though this effectively relegates the eye tracker to a reverse head tracker). In a composition entitled *Saccadic Variations* that was created using Miller Puckette's Pure Data software, the pupil coordinates are mapped to a tone generator, with the note number mapped to the x coordinate and the key velocity to the y coordinate. A progression through segments of the composition is controlled based on which of four quadrants (top left, top right, bottom left, or bottom right) the pupil is reported in after a blink is detected.

2.3 *EyeMusic v1.0* – Hornof et al. (2006)

The EyeMusic system [2] connected a commercial eye tracker to computer music software, specifically a 60 Hz L.C. Technologies Eyegaze system to Max/MSP. Custom Max objects were created using C/C++ to make the eye tracking data available to Max/MSP in real time. After a number of informal studies, the multimedia composition *EyeMusic v1.0* was produced [4]. Figure 4 shows the stage setup for *EyeMusic v1.0* and Figure 5 highlights the various display components used in a performance. The multimedia composition is designed so that the performer could pursue visual-perceptual goals that are translated into a visual experience that is controlled by the performer and shared with the audience. The performer controls a small white dot, a gaze cursor, that corresponds to where he or she is looking. The cursor is repositioned on the display based on every (x, y) coordinate that is reported by the eye tracker (60 times per s) and this data is also used to create a granular synthesis of click-sounding samples that are spatialized to play near the gazepoint on the display by using stereo panning. A secondary display shows a video of the eye, permitting the audience to see and hear that the eyes are moving the gaze cursor. Visual events, such as the gaze cursor colliding with moving red balls, are mapped to musical elements such that the audience can see how the eyes are being used to play the instrument. The performer moves through segments of the composition with eye blinks, each of which is sonified as a sudden, loud, slamming sound. *EyeMusic v1.0* was performed at SEAMUS 2006 and NIME 2007.

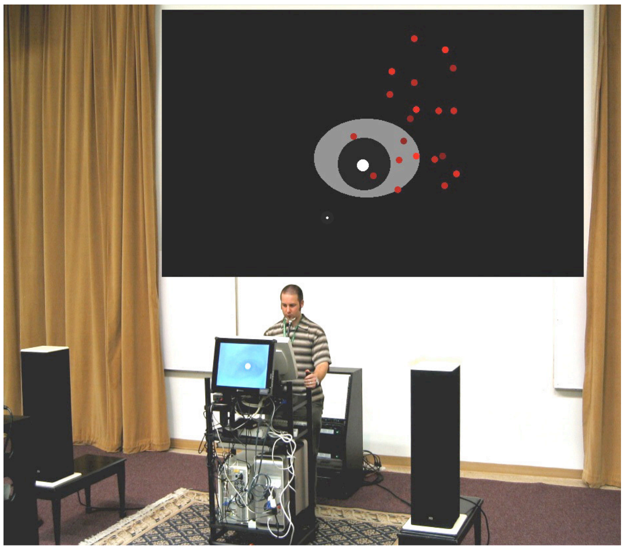

Figure 4. The staging for *EyeMusic v1.0*. The projection (inset) is the same image that the performer viewed to play the piece (though flipped horizontally).

Figure 5. The display components used in *EyeMusic v1.0*. The audience and the performer each see a large view of the control surface, and a small video feed of the eye image.

2.4 The EyeHarp – Vamvakousis (2011)

EyeHarp [10] was developed using the EyeWriter open source eye tracker (www.eyewriter.org) and then transitioned to use the ITU Gaze Tracker (gazegroup.org) open source eye tracker [11], each of which appears to report with reasonable accuracy the (x, y) coordinate on the display where a person is looking. EyeHarp presents the user with a complex interface with extensive functionality, though numerous human factors considerations serve to tame the complexity. For example, Figure 6 shows how rather than laying out the buttons in the configuration of a piano keyboard, which was demonstrated to be somewhat problematic for the eyes, the buttons are arranged in a *pie menu* [1] with the center of the pie the standby gaze location, and hence the eye-image status display is at that location (though much smaller than the status display in the center of the display for *Duet for Eyes*). Small white dots are positioned in fixed locations across the visual control surface to help create the visual-perceptual goals that are needed to move the eyes to these locations, similar to [3]. Though EyeHarp was not designed in collaboration with or specifically for people with disabilities, the author did conduct an informal evaluation of EyeHarp with people with cerebral palsy, as shown in Figure 7.

2.5 *Duet for Eyes* – Donegan et al. (2007)

Perhaps the most exciting application of eye tracking for real-time input to a computer is when eye tracking can be used to provide people with severe motor impairments a means of operating a computer and communicating with other people. In this role the technology is referred to as *assistive technology* or *augmentative communication*. *Duet for Eyes* is one of several musical performances made possible by a collaboration of musicians, performers with severe motor impairments, augmentative communication experts, and others. The team used off-the-shelf augmentative communication equipment and software (Tobii eye trackers running The Grid by Sensory Software) to configure eye-controlled buttons so that the performers could use these buttons to play sound files that the performers selected in advance from large collections of sound files. Figure 8 shows a screenshot of the gaze-controlled musical palette that was used by the performers. The arrows on the eye-controlled buttons serve as memory aides and as visual targets for eye movements made from one side of the screen to the other. Figure 9 shows *Duet for Eyes* being performed in 2008 at Trinity College in Dublin. Performers included James Brosnan, Katie Gillian, Colm O'Snodaigh, Eoin O'Brien, Robbie Perry, and others. Mick Donegan and Lizbeth Goodman directed the project, with Donegan providing eye tracking expertise [9].

It is noteworthy that *Duet for Eyes* was developed in collaboration with its intended end-users. In the screenshot shown in Figure 8, the black rectangle with the two white dots shows the user where the two eyes are currently positioned in the camera frame, and whether each eye is currently being successfully tracked (the white dot for each eye disappears if that eye is not being tracked). Providing tracking status in a prominent part of the display is an example of how collaborating directly with people with disabilities in the design of assistive technology will likely lead to a more user-friendly design for that population. This clear salient visual feedback permits self-monitoring and assists with the of making compensatory voluntary head movements to keep the eyes in range of the cameras, as is needed for users with motor impairments who have involuntary head movements that periodically move their eyes out of range.

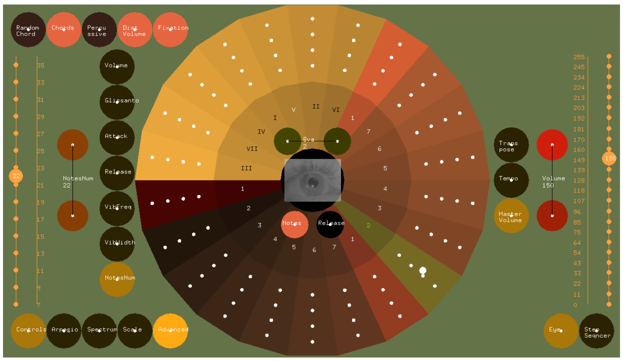

Figure 6. One of the two control surfaces in the EyeHarp interface [10]. The eyes are currently playing a note on the bottom right of the wheel.

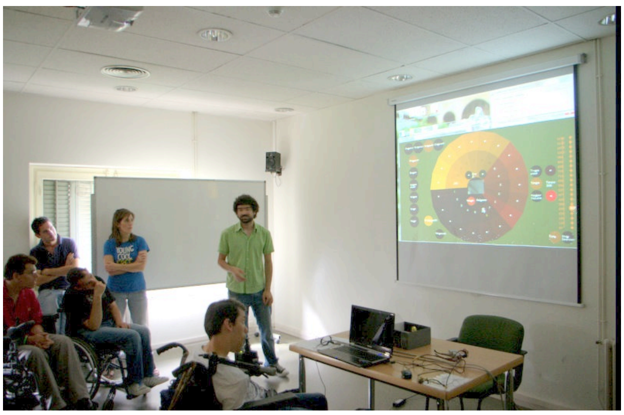

Figure 7. EyeHarp tested by users with cerebral palsy. (Images from [10]. Used with permission.)

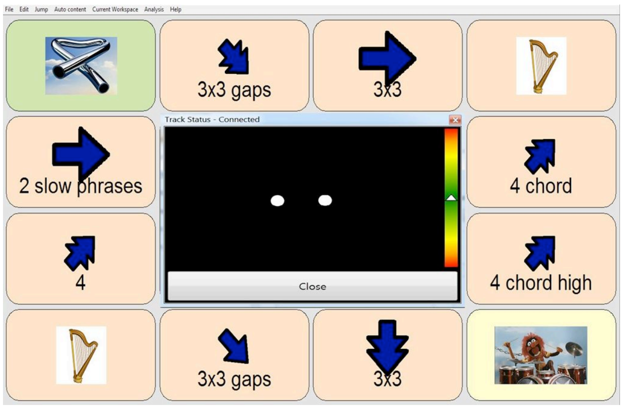

Figure 8. The gaze-controlled musical palette constructed for *Duet with Eyes* by Donegan and collaborators using The Grid from Sensory Software running on a Tobii eye tracker. (Screenshot courtesy of Mick Donegan.)

Figure 9. *Duet for Eyes* being performed in 2008. (Image from illustriouscompany.co.uk. Used with permission.)

2.6 Ableton-Live-adapted – Margulies and Anderson (2012)

Eye-controlled deejaying was successfully implemented by adapting the music production software Ableton Live so that it could be used via the eye-controlled mouse emulation that is built into the Tobii CEye assistive technology eye tracker (discussed at 1blinkequalsyes.com). This integration was developed collaboratively by Jon Margulies and David Anderson after David became disabled by amyotrophic lateral sclerosis (ALS). Figure 10 shows a screenshot with the eye-controlled mouse emulation palette overlaid on top of Ableton Live. Figure 11 shows David using the system to deejay a New Year's Eve party at the end of 2011. Ableton Live was adapted by identifying all of the musical tasks that a deejay needs to do, such as launching a song or fading a song across eight bars, and by creating a separate button for each task in Ableton Live's Session View, which can be populated with a grid of buttons, with each button triggering a separate musical task. All actions were quantized to start on the next bar. The key technical insight that made this adaptation possible was that, although some of the tasks such as launching a song were already implemented within Ableton Live, others such as fading across eight bars could be accomplished by launching MIDI events (that appeared to Ableton Live to be external MIDI events) and which then sent the appropriate commands to Ableton Live. This permitted all of the interactions such as adjusting on-screen faders with a click-drag-click (which is difficult to do with eye movements) to be converted into button presses which could be issued with eye movements. (Jon Margulies, personal communication.)

Figure 10. The Tobii eye-controlled mouse emulation buttons overlaid on top of Ableton Live. (Image from http://1blinkequalsyes.com/)

Figure 11. A deejay diagnosed with ALS uses an eye tracker connected to Ableton Live to mix the music at a party. (© 2013 Nityia Photography. Used with permission.)

3. ANALYSIS

This paper will now provide a taxonomy of the work that has been done to date to create eye-controlled musical instruments and musical expression, and briefly ponder likely future developments in this performance and design space.

3.1 A Taxonomy of Eye-Controlled Musical Performance

Eye-controlled musical instruments and compositions can be classified by asking a number of questions about each project.

Dimension 1: What is the motivation for the project?

The projects discussed here had three motivations:

(a) To create avant garde music and multimedia, as in Intuitive Ocusonics, *EyeMusic v1.0*, and EyeHarp.
(b) To explore the technical and practical possibilities with eye-controlled music, as in Oculog and EyeHarp.
(c) To create and deliver a tested working interface to people with disabilities, as in *Duet for Eyes* and Ableton-Live-adapted, the only two systems that were developed in partnership with such target users.

Dimension 2: What are the visual objects on the control surface that are used to motivate the visual-perceptual goals that a performer will use to play the instrument?

The "control surface" is the screen that the performer looks at to control the instrument. Recall that the eyes cannot be controlled as directly as the hands, but are instead moved by pursuing visual-perceptual goals, such as to look at specific objects. These projects have three types of control surfaces:

(a) No control surface, as in Intuitive Ocusonics and Oculog.
(b) A screen of large stationary buttons that primarily serve a functional role, as in EyeHarp, *Duet for Eyes*, and Ableton-Live-adapted. Each button has a visual object at its center, which creates a visual-perceptual goal. The targets are words, symbols, pictures, or small white dots.
(c) Large visual objects that move on the screen in the context of a time-based multimedia composition, as in *EyeMusic v1.0*, in which the visual-perceptual goals are to move the gaze cursor to explore a black screen, collide with red circles, and create an audio-visual narrative.

Dimension 3: Is a gaze cursor displayed on the surface?

The gaze cursor is a small visual object that appears where the eye tracker reports that a user is looking. It helps to show the performer and possibly the audience how the eye tracking data are driving the performance. Some implications for showing or now showing a gaze cursor are discussed in Dimension 6(e). Do these compositions use them?

(a) Yes. *EyeMusic v1.0* and EyeHarp show a gaze cursor.
(b) No. *Duet for Eyes* and Ableton-Live-adapted do not appear to show a gaze cursor.

Dimension 4: Can the control surfaces be shown to the audience to help them understand that the eyes are controlling the instrument?

In all projects, simply projecting a video of the performer's eyes will help to emphasize that the eyes are playing the instrument. Intuitive Ocusonics and *EyeMusic v1.0* both did this. For the compositions that use control surfaces, could it also be helpful to project these surfaces for the audience to see? The answer is three shades of "yes":

(a) Definitely yes. For *EyeMusic v1.0*, the control surface is an integral component, and the gaze cursor shows the performer playing the instrument.
(b) Probably yes. For EyeHarp, skillful playing on its minimalist visual layout is compelling and captivating to watch, especially when the gaze cursor is visible and annotated with explanations of what each eye-command is

doing. For Ableton-Live-adapted, it makes sense to show the control surface but only in the vicinity of the deejay booth, consistent with how deejay activities can typically be observed in a nightclub but only near the deejay booth.

(c) Possibly yes. As *Duet for Eyes* was staged, the performer's faces were projected. A second projection of the control surfaces alongside their faces could possibly make the mappings from eye movements to sounds more clear to the audience (especially if the control surfaces are flipped horizontally to maintain left-to-right consistency between the eyes and the surfaces from the audience's perspective).

Dimension 5: How does each composition deal with the timing limitations of eye-controlled interfaces and yet still create an interesting composition and performance?

Recall that the eyes can issue at most two to four decisive eye-controlled commands per second.

(a) All of the eye-controlled compositions address this in part by incorporating substantial pre-recorded or pre-programmed material into the composition such that these musical elements could continue playing for a period of time after each eye-command.
(b) *EyeMusic v1.0* includes audio-visual components that continue somewhat independently of the eye movements.
(c) The EyeHarp incorporates an eye-programmable sequencer such that, over the course of the performance, the performer can first program the sequencer to play a background harmony, and then play the foreground melody directly.
(d) *Duet for Eyes* is played in concert with conventional musicians who continue to play between eye-commands.
(e) Two of the compositions, Oculog and *EyeMusic v1.0*, use the continuous flow of all of eye data, not just the data from the performer-initiated eye commands, to generate sounds.

Dimension 6: How does the system manage the error and jitter that are inherent in eye tracking data?

Eye-controlled interfaces need to accommodate the error in eye trackers, and the jitter in fixations. These compositions accommodate it in five different ways:

(a) By moving the composition forward somewhat independently of the eye movements. Intuitive Ocusonics does this to the greatest extent, using the eye data to just nudge the audio.
(b) By using the relative rather than the absolute position of the eyes. Oculog does this.
(c) By creating oversized visual targets. All four of the systems with control surfaces do this, as does Oculog.
(d) By sonifying *all* of the raw data such that the jitter creates a musical texture of its own. Oculog and *EyeMusic v1.0* both do this. *EyeMusic v1.0* uses the error and jitter as both an audio and visual element, with the jitter bringing the gaze cursor to audible and visible life, and the error creating visible-narrative tension as the audience can see the performer working to compensate for error.
(e) By showing the gaze cursor on the display. *EyeMusic v1.0* and EyeHarp both do this. When a gaze cursor is displayed, it is typically a short distance from the actual point of gaze due to error in the eye tracking device. This permits a performer to learn how to compensate for the error in real time, such as by learning to look slightly *next to* a target. That *Duet for Eyes* and Ableton-Live-adapted do not show a gaze cursor makes the systems easier to user for novices who would be distracted by the cursor, but may also prevent expert users from learning how to anticipate and work with the error and master an eye-controlled instrument.

None of the systems appear to reduce error by using *smoothing*, which is to report, rather than the raw (x, y) data, a running average of the last n samples, such as the last 0.25 s of samples. To not smooth the data is a sensible design decision given that smoothing introduces a control delay, and in general a musician wants his or her instrument to respond as quickly as possible.

3.2 The Future of Eye-Controlled Music

Eye-controlled musical expression remains relatively unexplored because of the numerous constraints imposed by how and why the eyes move and because of the limits of eye tracking technology. It is hoped that articulating these constraints and challenges, in the context of the few successful projects that *have* been completed, will make it easier to plan for the challenges in the design of future eye-controlled musical instruments and compositions. As the cost of eye trackers continues to drop and as consideration of eye tracker accuracy continues to rise [12], it is becoming easier to explore the potential for eye-controlled musical expression, and more exciting work will certainly be done. We will likely see the development of software libraries for connecting eye trackers to multimedia authoring toolkits, for creating the visual-perceptual objects needed in eye-controlled interfaces, and for automatically detecting when the performer pursues these visual-perceptual goals to issue commands in the context of eye-controlled musical expression.

4. ACKNOWLEDGMENTS

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