Design Concepts for Gaze-Based Digital Musical Instruments

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ABSTRACT

In recent decades, the introduction of new affordable non-invasive eye tracking technologies accelerated the development of new gaze interaction techniques. Some of these find an application in accessible human-computer interfaces operable by people with quadriplegic disabilities. Musical interfaces represent a possible benchmark for these techniques since they require high precision levels, speed, and minimal latency. Several software Accessible Digital Musical Instruments have been developed, experimenting with keys and visual cues suitable for this particular context. This paper proposes a review of different design techniques proposed in the literature for the design of gaze-based musical interfaces, as well as possible solutions for the Midas Touch Problem, a known issue in gaze-based interfaces. A summary of the physiology of the human ocular movement is also provided. The provided notions could inform the design of new gaze-based software musical instruments.

1. INTRODUCTION

Research on Digital Musical Instruments (or DMIs) has expanded over the past decades into the use of unconventional interfaces, interaction paradigms and channels. Such instruments are less constrained by physical limitations than their acoustic and traditional counterparts: this allowed for the exploration of new expressive possibilities and led to the need of partially revising what we culturally consider a musical instrument.

One of the possibilities offered by DMIs is to increase the accessibility of the world of musical performance, extending it to people with important motor disabilities such as quadriplegic users, which are paralyzed from the shoulders below, leaving only the neck and above, with all the related possible bodily movements as available interaction channels. The use of gaze as an interaction channel for musical interfaces can be a particularly simple and suitable solution for designing Accessible Digital Musical Instruments (ADMIs) dedicated to this particular target. This is also demonstrated by the amount of gaze-based accessible instruments found in the literature.

A 2019 ADMIs review of by Frid [1] shows that among the 83 instruments found in literature, dedicated to different types of user groups, disabilities and contexts, 2-3% exploited a gaze-based interface.

Gaze detection is now an established interaction method for different contexts in Human-Computer Interaction [2, 3]. This was also possible thanks to the introduction on the market of several low-cost eye trackers, such as Tobii (EyeX, 4C, 5) [1] and The EyeTribe devices (now discontinued). These eye trackers take advantage of non-invasive technologies based on Near Infrared (NIR) cameras that require a straightforward calibration procedures, whose detection performances have been evaluated in the past [4,5]. In this paper we refer to the characteristics of these eye trackers to describe interface design techniques and related interaction issues.

In a previous article we listed gaze as one of the possible interaction channels for ADMIs dedicated to quadriplegic users [6], then we carried out a comparison experiment between gaze tracking, head movement, breath and mouse in target selection tasks [7]. Compared to the others, gaze resulted to be a particularly fast interaction channel, although generally NIR eye trackers present unstable detection and noise.

The interfaces of acoustic musical instruments are usually designed to exploit the peculiarities of hand and finger movements. Similarly, a gaze-based musical interface should consider the characteristics of eye movements to guarantee comfortable and effective interaction. In fact, a simple imitation of the layout of a traditional musical instrument may be unsuitable for gaze interaction, thus requiring the implementation of specific solutions.

The goal of this paper is to provide theoretical background on design choices and techniques for gaze-based musical interfaces design, as well as a collection of related design cues. Many of these have been found and implemented by instruments found in literature and resumed here.

Some words should be spent to indicate that, despite some of the theoretical notions we're listing could be useful in designing any type of gaze based DMIs, focus is given to a particular category of instruments dedicated to real-time performance. In order to frame this category, we resort to Malloch *et al.* [8] conceptual framework, which classifies DMIs according to which kind of behavior is re-

[1] Tobii products on Tobii official website: *https://tech.tobii.com/products/*

quired to interact with them. In such framework, behaviors can be skill-, rule-, or model-based. Playing conventional acoustic instruments require skill-based behaviors, i.e. actions which take place partly without conscious effort, in an automated manner due to muscles memory training, to which the instrument immediately responds with feedback (e.g. acoustic) which impacts the performed music. In this paper we're focusing on this type of instruments, while rule-based or model-based gaze controlled musical interfaces (such as turntables, sequencers, algorithmic music composition, etc.) are instead not directly covered.

Sec. 2 provides an insight on the related state of the art. Sec. 3 describes how the eyes move from a physiological point of view. Sec. 4 lists a series of design cues and techniques which could be used to enhance interaction. Finally, Sec. 5 addresses the Midas Touch problem, a known issue in gaze-based interfaces design, and some possible solutions to tackle it.

2. RELATED WORKS

Relatively few gaze-based methods for playing music have been developed to date. Interesting analyses of strengths and weaknesses of these approaches, as well as limits and challenges that future solutions should address, can be found in the works by Hornof et al. [9, 10]. Vamvakousis [11] also provides a source for gaze-based instruments research.

Up to date, a few gaze-based instrument proposed different solutions for gaze-based musical performance. The EyeMusic system and related performances [12] are a first attempt at creating tools for generating sounds with the eyes, although they cannot be strictly considered real musical instruments. The Eye Play The Piano intrument [13] allows to select notes and chords by looking at hexagonal graphical shapes that control the keys of a real piano. EyeJam [14] proposes a method for note selection called "context-switch", where sound is produced only when the gaze crosses a horizontal line. Lumiselo [15], is probably the first to propose a hybrid method involving both gaze and breath (through a sip-and-puff controller): a note is selected by gaze, and then its actual playing occurs by blowing into a breath detecting sensor. Netytar [16,17] exploited the same idea of hybrid gaze-breath interaction, focusing on proposing a peculiar isomorphic layout designed to solve gaze interaction issues and providing fast detection through the avoidance of eye tracker data filtering. Netychords [18] used instead a gaze-head hybrid interaction paradigm to control chords performance. EyeConductor [19], and The EyeHarp [20] introduced pie-shaped interfaces in which the central area is mapped to silence (pauses). EyeConductor also exploits facial expressions, such as raising eyebrows or opening the mouth to change octaves or to control filters. The EyeHarp is a complete musical instrument that allows to play notes on several octaves and to control sound dynamics. Its interface contain gaze sensitive buttons with white dots used to guide the gaze, and the central area is exploited for both pauses and note repetition, through a dynamically mapped button. Clarion [21] instead proposes a solution based on customizable layouts. In this way, the interface could be customized according to the musical piece to be performed, renouncing however a general consistency that could affect the instrument learning process.

The design solutions provided by these instruments are reviewed, collected and compared in the following sections.

3. CHARACTERISTICS OF GAZE MOVEMENTS

Gaze point is the point in space (or the point on the screen) where the user is looking at.

Eyes generally move through *saccades*, which are jerky movements, lasting about 30 ms, during which the gaze point moves from one discrete point to another. These are interspersed with *fixations*, where the gaze point remains, indeed, almost fixed on a position. Usually a fixation lasts from 100 ms to 400 ms. Fig. 1 shows a visual representation of gaze point moving through saccades and fixations while reading a text.

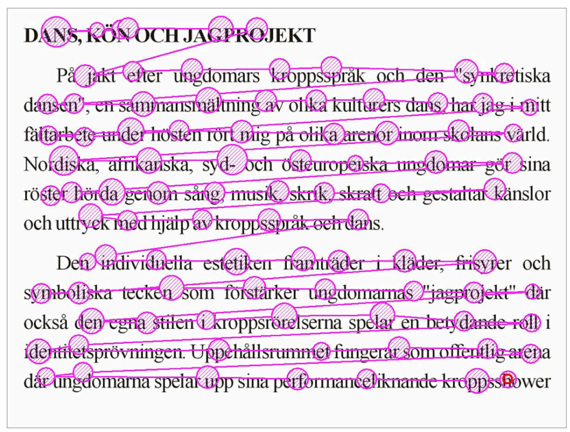


Figure 1: A *scanpath*, namely a visual representation of saccades (straight lines) interspersed with fixations (circles) while reading a text
Source: *Lucs-kho at English Wikipedia, Public domain, via Wikimedia Commons*

That said, the eye is unable to perform fluid movements unless it has a target to lock on: this is called *smooth pursuit*, a fluid movement which follows the movement of a target.

Blinks are sometimes not recommended as an interaction channel due to their potentially involuntary nature [2], but are listed in [6] as one of the residual movement abilities for a quadriplegic person. As they are very fast, however, blinks are employed in some accessible applications and instruments like Netytar [16], using some filter or rule to discriminate voluntary and involuntary blinks.

Finally, even during a fixation eyes are not perfectly still but make small random movements within 0.1° of the visual angle, called *jitter*.

These movements can be activated voluntarily, but many can occur involuntarily and unconsciously. Involuntary saccades, for example, occur on a regular basis even during

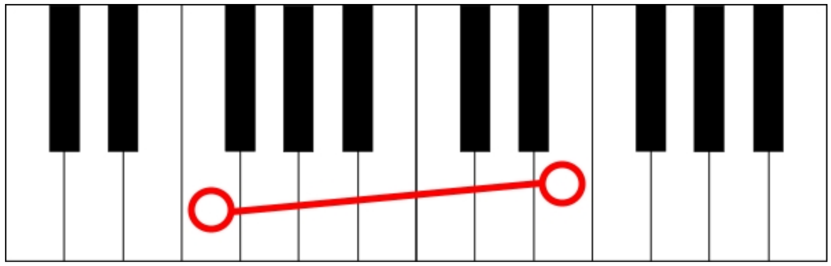


Figure 2: Gaze scanpath on a piano keyboard. When gaze moves from the F key to the E key, intermediate keys are crossed.

fixations [22]. Those may preclude musical performance, which requires very precise control. There is evidence for gaze anticipating physical movement [23] and interactions in virtual environments [24], a behavior which the performer must learn to avoid during gaze-controlled musical performance. In gaze controlled instruments, those may lead to the anticipated performance of notes with respect to the prescribed tempo, unless the introduction of filters to compensate by creating latency. Such behavior was noticed during the evaluation of The EyeHarp [20, Sec. 2.2.2]. Instruments like EyeJam, Netytar and Netychords, as a counterexample, does not use filters in order to improve the precision at higher tempos [16], thus not providing any aid to avoid anticipations.

The rhythmic capabilities of eye movements are limited. Hornof [10] provided an eye-tapping experiment which shows that eyes are unable to deliberately perform more than 4 saccadic movements per second (approximately one saccade every 250 ms). According to the author, this seems to be an upper limit which cannot be overcome, not even through training. In systems where notes are selected through gaze pointing, this translates into a maximum limit in note changing speed. More trained people could however manage to maintain fast tempos with greater precision. In [17] we discussed and proposed a training method to possibly reach this goal through exercising.

4. VISUAL CUES AND TECHNIQUES

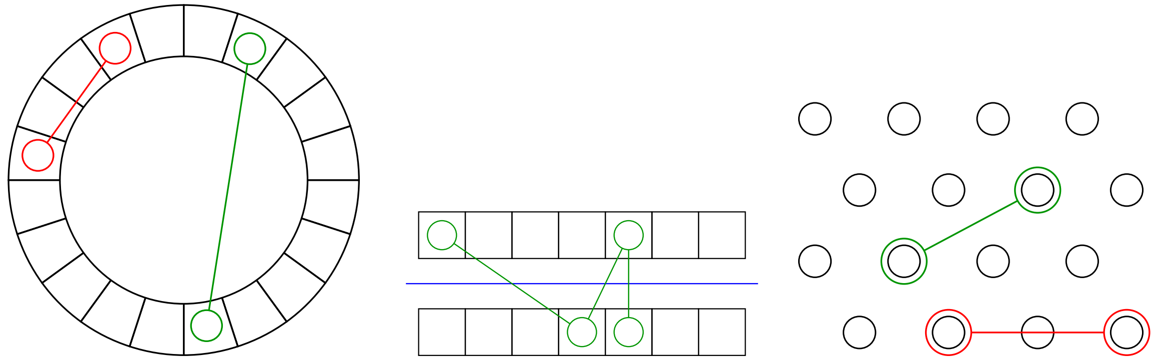
The following are some techniques which can be considered and combined while designing a gaze-based musical interface.

Color. When using a gaze-based musical interface, an eye movement can result in a involuntary interaction. This leaves little space for the user to explore the interface, and usually the performer needs to know in advance where the next gaze movement should happen. While many musical interfaces employ differently shaped keys (e.g. a normal piano keyboard) or spatialization (e.g. in The EyeHarp's interface [20]) to help note localization, color can be used strategically to enhance interaction and partially solve this problem. It has been proven that the areas of sight outside the fovea (the central area of human vision), corresponding to peripheral vision, are particularly sensitive to contrasting color variations [25].

Cursors. Although showing a cursor is a classical way to give a visual feedback to the user for the current pointing position, its usage in gaze-based interfaces could be problematic since it could distract the user. It has been shown, through experiments on primates, that involuntary gaze movements can be caused by moving objects [26]. Furthermore, given the general imperfect accuracy and precision of eye tracker data, even a slightly different position of the cursor with respect to the fixation point could frustrate the user and feel unnatural. It can be argued that the use of visual feedback may not be necessary to indicate the user's gaze position. When using a pointing device such as a mouse, a cursor is required as the pointed position would otherwise not be known to the user. In the case of gaze, the position is already known since the user who knows where their gaze point lies. There are however alternatives to cursors to return visual feedback on selecting items: one of these is to highlight the selected element through a different color, a flash or a different shape when the gaze point enters its area. Alternatively, it is possible to implement "discrete cursors" (e.g. as the one proposed by Netytar's interface [16]), which instead of moving in a continuum can only assume a limited number of positions (e.g. centered on gaze sensitive elements).

Visual elements to enhance precision. Given the aforementioned jittering nature of eye movements and gaze detection by eye trackers, some visual elements can be introduced to enhance interaction precision. Other than increasing the dimension of the gaze sensitive elements, they can be equipped with "visual hooks", such as dots, to help the user concentrate fixations on the center of their area. The EyeHarp [20], for example, presents a series of points on keys and external areas (which are used for pauses).

Auto-scrolling. Netytar [16] and Netychords [18] introduced an auto-scrolling feature and approach. The view on the virtual keyboard moves automatically, so the currently gazed key is smoothly placed on the center of the visualization area. The speed at which the interface moves is proportional to the square of the distance between the observed point and the center of visualization area on screen. This allows to have a theoretically infinite playing region available, regardless of screen size. This solution could also increase detection accuracy, as gaze detection provided by eye trackers based on Near Infrared technology is usually more accurate in the central screen area [27].



(a) Pie-shaped layout (b) Context switch based layout (c) Layout presenting spacing between keys

Figure 3: Three possible keys layouts to tackle the Midas Touch problem. In a pie-shaped layout (a), the red colored scanpath crosses intermediate keys, while the green colored one does not. In a context switch based layout (b), the green colored scanpath does not cross intermediate keys, since it passes through the blue rows separator in the middle. Spacing between keys (c) can solve the problem for some intervals (green scanpath) but not for others (red scanpath).

5. THE MIDAS TOUCH PROBLEM

One of the most known issues to be addressed in the creation of gaze based interfaces, occurring also while designing other types of interfaces based for example on gestural controls, is the so-called "Midas Touch" problem [3, 28, 29]. It consists of the fact that, if the act of passing gaze point through the area of on an interface element triggers an event such as its activation (as often happens in gaze-based musical interfaces), any exploratory or involuntary gaze movement can potentially cause an unwanted interaction. Jacob [2] summarizes the problem with the following sentence:

"Everywhere you look, another command is activated; you cannot look anywhere without issuing a command."

One very important consequence in musical interfaces is that keys layout design is a non-trivial problem which requires an additional effort. Traditional acoustic musical instrument layouts may not be suitable for gaze-based interaction. Let us take as an example a piano keyboard. In order to perform any given musical interval which requires a jump between two non-adjacent keys, other keys should be crossed (Fig. 2). Even if a saccadic movement is very fast, the sampling frequency of modern eye trackers is high enough to detect intermediate positions, causing an involuntary activation of intermediate keys. While fingers can be lifted from a keyboard, it is not possible to control the musical performance in the same way with gaze.

Various solutions have been proposed to this problem in the literature, for both musical and general purpose gaze-based interfaces.

Dwell time. A possible solution to this problem is to apply a delayed selection method. Using dwell time, an interface element is selected by gaze entering its area, but activated after the expiration of a given time interval [30, 31]. In musical terms, however, this might not be a very efficient solution since it introduces a Delayed Auditory Feedback (DAF) between the action of the physical input and the generation of the related sound. A DAF may alter the quality of a musical performance, impeding correct play of rhythmic pieces [32]. According to Wessel and Wright [33], 10 ms are an acceptable upper bound for a delay on audible system reactions during live computer music performances.

Filtering. Another solution is applying a filter to discriminate saccadic movements from fixations, and enable activations only when a fixation occurs. An implementation is provided by The EyeHarp [20]. However, even in The EyeHarp a DAF was observed which could preclude the performance of rapid sequences of notes [16].

Hybrid interaction. Using an extra physical channel in addition to gaze allows to decouple the note selection from its performance. As an example, the already cited Lumiselo [15] and Netytar [16] exploit breath to control note onsets and sound intensity: when no breath is emitted, gazed keys are not activated. Netychords [18] exploits instead head rotation along the yaw axis to trigger chord strummings and control sound intensity. It has to be noted, however, that introducing further interaction methods In addition to gaze could hinder the usability of the instrument to users with more restricted motor capabilities (such as those affected by total locked-in syndrome [34].

Keys displacement. Passing through intermediate keys during the performance of different musical intervals can be avoided, in part or completely, through an adequate keys positioning. Various solutions have been proposed in literature, all having pros and cons, being partially capable of solving the problem.

- **Pie shaped layouts**. A layout where the keys are arranged in a circular fashion, as illustrated in Fig. 3a, can partially solve the problem. As shown in the figure, ideally many musical intervals do not require crossing keys in between. However, with finite-sized keys, some intervals may still require passing through intermediate keys. One drawback of using this solution is that the space is not fully exploited and, since the eye tracker detection limitations re-

Problem	**Solutions**
(3) *Involuntary movements (saccades, jitter)*	?
(3) *Anticipated performance of notes*	Introduction of filters to create latency
(3) *Limited rhythmic capabilites of the eyes*	?
(4) *Impossibility to explore the interface without issuing commands*	Strategic use of color to exploit color sensitivity outside fovea
(4) *Cursors can be distracting and suffer eye tracker's inaccuracy*	Highlight the gazed elements with color, flashes, shape changes; Use a "discrete cursor"
(4) *Eye movements and eye tracker's detection is jittery*	Equipping gaze sensitive elements with "visual hooks" (e.g. in the center of the area); Enlarging the gaze sensitive areas
(4) *Limited dimension of the screen*	Introduction of auto-scrolling, exploiting smooth pursuit
(5) *Midas Touch problem*	Dwell time (which introduces DAF); Fixation discrimination filters (which introduce DAF); Hybrid interaction (gaze + another interaction channel); Keys displacement (pie shaped layouts, context switching, spacing between keys).

Table 1: A list of problem treated in this paper with relative solutions. Numbers between parentheses indicate the section in this paper where the problem and the solutions are investigated. Question marks denote actually open challenges.

quire the use of large keys, it is not possible to represent more than a given number of notes on the screen. It is also not easy to implement solutions such as auto-scrolling (Sec. 4) for this type of layouts. The aforementioned Eye Conductor [19] and EyeHarp [20] make use of pie-shaped layouts.

- **Context switching**. A particular and original solution, called "context switching", has been proposed by the instrument EyeJam [14]. The solution, summarized by Fig. 3b, consists in placing two rows (or columns) of keys mapped to the same notes. The two rows should be separated by an area non-sensitive to gaze. Any activation should be preceded by the act of crossing this area. Any gaze movement which does not follow this rule is substantially ignored. In this way, an up-and-down motion of the gaze is required, but intermediate keys crossing is avoided.
- **Spacing between keys**. Another solution to tackle this problem amounts to using a 2D layout where keys are interspersed with non-sensitive areas and placed in a strategic way to avoid intermediate keys crossing for common musical intervals. This is obtained by reducing the size of keys and/or setting the gaze sensitive area associated with each key (often called "occluder") to have a different dimension than the key itself, as for example happens in Netytar [16], whose layout design is exemplified in Fig. 3c.

6. DISCUSSION AND CONCLUSIONS

In this paper we have summarized techniques and cues found in literature which can inform the design of gaze-based musical instruments.

Table 1 presents a list of problems and solutions addressed in this paper. For some issues, a solution is yet not present in literature, or solutions are partial and not sufficient. Those have been denoted with a question mark in the table.

Involuntary eye movements for example are part of the physiology of gaze movement, but can present an additional difficulty to take into account while designing gaze-based interfaces. Experiments like Eye Music from Hornof *et al.* [12, 35] circumnavigate this problem by sonifying these movements and making them part of the musical experience.

Although eyes move fastly, saccadic movement frequency limits can hinder the performance of fast pieces and virtuosities, and no solutions have been proposed so far to stem this issue, leaving another question mark on the "limited rhythmic capabilities of the eyes" problem. Although training could help to reach the physiological limit, solutions to map multiple effects to a single eye movement (e.g. a sequence of notes) could be introduced.

Some interaction problems that have been tackled in previous remains unresolved, keeping related discussions and the need to develop new techniques open. As an example, although several solutions have been summarized to tackle the Midas Touch problem, each of them involves different limitations on the note keys layout. Noise introduced by the image-based nature of the eye tracking hardware involves the need to use filters, which introduce input lag, or larger keys, which reduce the number of displayed gaze-sensitive elements.

Since musical interactions require both high spatial accuracy and temporal resolution, it results to be a very demanding testing ground for gaze-based interaction techniques. A solution for these common problems could allow the development of gazed-based interfaces suitable for different applications in the general areas of accessibility and Human-Computer Interaction.

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