Thesis

Using Audio Cues to Support Motion Gesture Interaction on Mobile Devices

Submitted by

Sarah Morrison-Smith

Department of Computer Science

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Master's Committee:

Advisor: Jaime Ruiz

Christina Boucher
Chris Peterson

Abstract

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Motion gestures are an underutilized input modality for mobile interaction despite numerous potential advantages. Negulescu et al. found that the lack of feedback on attempted motion gestures made it difficult for participants to diagnose and correct errors, resulting in poor recognition performance and user frustration. In this paper, we describe and evaluate a training and feedback technique, *Glissando*, which uses audio characteristics to provide feedback on the systems interpretation of user input. This technique enables feedback by verbally confirming correct gestures and notifying users of errors in addition to providing continuous feedback by mapping distinct musical notes to each of three axes and manipulating pitch to specify both spatial and temporal information.

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CHAPTER 1

Introduction

Figure 1.1. The DoubleFlip gesture. The user holds the phone in his right hand. He rotates the phone along its long side so that the screen faces away and then back.

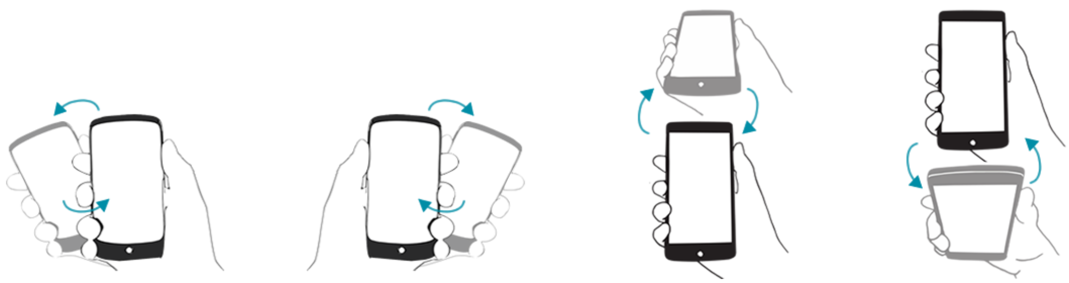

Figure 1.2. Additional motion gestures influenced by [36]. (a) FlickLeft, (b) FlickRight, (c) FlickUp, and (d) FlickDown.

The smartphone form factor is limiting in both input and output. To allow the device to fit into a pocket or purse, screens are small and keyboards are thumb-sized. On many devices, the thumb keyboard has been replaced by a soft-keyboard displayed on the screen to minimize the size and weight of the device. As a result, the primary interaction with a smartphone consists of a user tapping or swiping on the devices display. Recently, Ruiz et al. proposed taking advantage of the internal motion sensors (e.g., the gyroscope and accelerometer) commonly found in mobile devices to extend the input space [36]. Their work demonstrated how *motion gestures*, gestures performed by translating and rotating a mobile device in three-dimensional space, can be mapped to a device command allowing interaction without the use of the touchscreen. However, beyond rotating to change screen orientation [17] or shaking to shuffle songs, few motion gestures have been incorporated into typical users daily lives.

This disparity is surprising considering the many potential benefits granted by using motion as an input modality for mobile interaction. Recent research (e.g. [29, 30, 35]), has highlighted several of these possible advantages, including the potential to expand the input space for mobile phones, provide shortcuts for multi-step smartphone commands, and facilitate smartphone use while distracted.

The underuse of motion gestures for mobile input is a multifaceted problem with a variety of contributing factors. Negulescu et al. identified several crucial barriers to widespread adoption of motion gestures, including increasing user awareness of available gestures and providing opportunities to practice and receive feedback on gestures during the learning process [30]. While these challenges exist for all gesture interfaces [5], feedback and training are especially difficult for motion gestures due to the fact that the movement of the device is three-dimensional. Furthermore, motion gestures have an additional constraint in that a user must perform a gesture in a time-dependent manner.

To address the need of a training and feedback system for motion gestural input, we developed *Glissando*, a technique that assists in learning motion gestures by using audio characteristics to provide feedback on the system's interpretation of user input. This technique assists in training and provides feedback by (1) verbally confirming correct gestures, (2) notifying users of specific errors, and (3) providing additional continuous feedback by mapping distinct musical notes to each of three axes and manipulating audio characteristics to specify both spatial and temporal information.

The remainder of the paper is organized as follows: first, we give an overview of related work in Chapter 2. Next, we provide a description of Glissando in Chapter 3, followed by an exploration study to determine the optimal method for providing continuous feedback with Glissando in Chapter 4. We then evaluate the effectiveness of continual feedback in assisting users to learn the spatial component of the *DoubleFlip* gesture [35] (shown in Figure 1.1) with a pilot study in Chapter 5. This is followed by a brief exploration study in Chapter 6 to determine whether the time-dependent aspect of a motion gesture can be enforced using time limits. Next, we assess the effectiveness of using continuous feedback to express temporal information about the gesture in Chapter 7. These initial studies focus on use with the DoubleFlip gesture since recent work reported that users had difficulties performing the gesture when no feedback was present despite its relative simplicity [30, 29]. Finally, we evaluate Glissando in Chapter 8 by examining gesture memorability for users trained with and without the system using an expanded gesture set that includes several gestures inspired by a previous elicitation study [36] in addition to DoubleFlip: *FlickLeft, FlickRight, FlickUp, and FlickDown* (shown in Figure 1.2). We close with a discussion of findings and a synopsis of future work in Chapters 9 and 10.

CHAPTER 2

Related Work

2.1. Motion Gestures

Several researchers have explored various applications for motion gestures. Rekimoto [34] was the first to demonstrate how mapping device tilt can be used for selecting menu items, interacting with scroll bars, panning or zooming around a digital workspace, and performing complex tasks such as 3D object manipulations. Harrison et al. [15], Small & Ishii [37], and Bartlett [3] extended the use of tilt sensors to enable navigating through widgets on mobile devices. Additional potential applications of motion gestures have been developed, such as using tilt to allow a user to change screen orientation [17], navigate maps or images [34], input text [18, 32, 41], control a cursor [40], access data on virtual shelves around a user [22], and verify user identity [23].

Further research has explored the various aspects of designing gestures, including the development of systems to aid designers of systems that use motion gestures such as Exemplar [16] and MAGIC [2]. Ruiz et al. developed a taxonomy which described the attributes of smartphone motion gestures and the natural mappings of motion gestures onto smartphone commands [36].

Prior work has also examined the cognitive demands of using motion gestures. Negulescu et al. examined the relative cognitive demands of tapping the touchscreen, performing *surface gestures*—gestures performed on display surfaces—and performing motion gestures [30]. Results from this study showed that no significant difference in reaction time exists between the three types of input, meaning that using gestures does not result in an observable increase in cognitive cost. Additionally, it was shown that motion gestures result in significantly less time spent looking at the device screen while walking than tapping on the screen, even when the device interface is optimized for eyes-free input.

2.2. Visual Feedback Techniques

The need to provide feedback for gestural interaction is not limited to motion gestures. Surface gestures have the advantage of being readily displayed as two-dimensional diagrams, which, in addition to facilitating the communication of available gestures, facilitates the provision of continuous feedback by displaying the correct surface gesture alongside the user's input [3]. OctoPocus, developed by Bau and Mackay [4], utilizes this approach to provide continuous feedforward and feedback to learn, remember, and execute surface gestures. However, this method is difficult to apply to motion gestures due to inherent difficulties with projecting a three-dimensional gesture onto a two-dimensional surface. Additionally, the nature of motion gestures requires the user to rotate and translate the device, meaning that continuous visual feedback displayed on the device's screen is not always feasible since the screen may not be visible at all times.

Sodhi et al. [38] presented LightGuide, a visual continuous feedback system for *mid-air gestures*, gestures performed in three-dimensional space without holding a device (e.g. pointing and gestures performed using the Microsoft Kinect). LightGuide projects visual cues, such as arrows and colors, onto a user's hand to guide them in performing physical movements, such as moving their hand along a pre-determined path. The similarity between physical movements and motion gestures suggests that LightGuide can be easily adapted to provide feedback for motion gestures. However, while LightGuide's system mitigates occlusion of visual feedback by not using the mobile device's screen, we believe that this is not a viable solution for everyday use of motion gestures due to its reliance on additional devices (a projector and a depth camera).

Recent work by Kamal et al. [19] explored the effect of using various gesture representation systems, with and without visual feedback, on user performance of motion gestures. Methods for representing motion gestures included icons, videos displayed on the device screen, and a combination of Kinect and videos displayed on an external screen. Feedback consisted primarily of visualization of the distance between the ideal gesture and the user's attempt either through a numerical scale displayed on the device screen or by directly comparing the Kinect representations of the user's attempt and the ideal gesture. Results indicated that scaffolding techniques that rely only on the mobile device, with no additional devices or hardware, can be a feasible solution for training users to perform motion gestures.

2.3. Aural Feedback Techniques

Audio feedback may be appropriate for providing training and feedback for motion gestures since it has been successfully utilized for assisting various spatial and surface gesture tasks and does not rely on users being able to see the screen or possessing an additional device. Furthermore, concurrent auditory feedback has been shown to be more effective than visual concurrent feedback in enhancing learning of new skills [9].

Previous work has examined the use of audio characteristics as feedback for spatial tasks such as aiding navigation for blind users [39], determining radial direction [14], expressing 2-dimensional paths [14], enhancing target selection tasks [10, 26, 27, 25], enhancing tilt-controlled speed-dependent automatic zooming [11], and replacing joint and muscle sensory information for patients who lack proprioception [12].

Several researchers have explored the integration of continuous and end-of-gesture audio feedback for teaching and improving the accuracy of surface gestures [6, 24, 28, 31] and tasks similar to performing surface gestures [33]. Additional work has focused on the combination of audio feedback and surface gestures to promote accessibility [20], [21].

Notably, Andersen and Zhai explored application of audio feedback to pen-gesture interfaces, but concluded that it is difficult to achieve benefits with audio feedback [1]. However, the observed negative effect of audio feedback on gesture performance is likely due to the type of feedback provided. In this study, gestures were mapped to feedback characterized by complex tones using frequency, timbre, jitter, amplitude, and displacement [1], which likely provided too much information for the users to effectively utilize [9]. Additionally, users were only provided with a visual reference of the gesture and did not receive an audio reference that corresponded to audible feedback [1]. Furthermore, the authors' concern regarding the efficacy of audio feedback for gestures was partially based on the idea that audio feedback is too slow to improve handwriting [1]. However, it is unclear whether this conclusion applies to motion gestures.

Williamson and Murray-Smith developed a method for communicating high-dimensional, dynamic information to users interacting with systems via continuous audio feedback generated by asynchronous granular synthesis [42]. This audio feedback mechanism was postulated to be applicable to surface and motion gestures and was incorporated into a framework, SIGIL, designed for developing and testing gesture recognizers [42], [43]. However, there is no indication that this system is fully developed or examined in a user study. As such, we are unaware of any work implementing the use of audio as the sole feedback mechanism for training users to use motion gestures.

CHAPTER 3

Using Audio for Gestural Training and Feedback

In light of relevant work, we designed our gestural feedback system to meet the following design goals:

- **G1:** Minimize visual feedback since the device screen may not always be visible while performing motion gestures.
- **G2:** The system should not use any external hardware or additional devices in order to promote the mainstream adoption of motion gestures.
- **G3:** The system should be compatible with current generation smartphones to facilitate mainstream use.

3.1. Glissando

In addition to providing a reference, Glissando produces continuous concurrent feedback, allowing users to manipulate their input before an unsuccessful gesture has been detected. To enable continuous feedback in Glissando, we mapped distinct musical notes to each of three spatial axes; a change in note characteristics (e.g. pitch and/or volume) was used to specify the spatial information of rotating and/or translating the device around a specific axis. This mapped each gesture attempt to a unique audio representation with distinct characteristics. The resulting representation of the reference (ideal) gesture was available to be played to the user, as well as the representation of the user's most recent gesture attempt. Any differences in the characteristics of these representations indicated differences between the ideal gesture and the performed gesture.

Additionally, upon recognition of a complete gesture or detection of an extreme error, Glissando informed users that the gesture was correct or identified the user's error. Error messages included identifying when a user passed a threshold of movement in an undesirable direction. For example, if a user attempting to perform DoubleFlip tilted the phone sufficiently towards herself, Glissando simply said “too far up.” Additional error messages identified when a user failed to meet a threshold. For example, if a user tried to perform a gesture that required rotating the screen, e.g. DoubleFlip, and did not rotate the phone to the required threshold, Glissando stated “not far enough.” Finally, for our exploration study on enforcing strict time limits, Glissando included error messages that notified a user when they took too long to complete the gesture. In this case, Glissando stated “not fast enough.” For clarity, error feedback was designed to be verbal rather than nonverbal.

Glissando is designed for use in a training environment where the user is attempting to learn a specific, predefined gesture. This is opposed to normal, everyday use, where audio feedback would not be provided. As demonstrated by our final study, Glissando can be harnessed to assist a user in learning multiple gestures by tailoring implementations for each gesture in the set. For this use case, it is not necessary for Glissando to differentiate between multiple gestures since it is reasonable to specify which gesture will be performed.

Since Glissando relies on audio characteristics to represent spatial information, it is important to choose a characteristic configuration that allows the user to easily discriminate between different gestures. Furthermore, it is important to limit feedback to the manipulation of only a few characteristics since excessive feedback becomes an issue as feedback begins to exceed a learner’s ability to internalize and react [9]. Common audio characteristics include pitch, volume, timbre, tempo, and rhythm. Timbre was rejected as a potential characteristic for Glissando due to concerns that the limitations of the mobile device’s internal speaker would make discerning between different tones exceedingly difficult. Tempo, while easily discernible using the mobile device’s internal speaker, seemed uniquely suited to providing temporal information, such as gesture speed, and was reserved for that purpose. Rhythm, which seemed similarly suited to providing temporal information, will be of interest in future research. As such, to determine the appropriate configuration for Glissando, we considered the following four methods that utilized the remaining note characteristics, pitch and volume:

3.1.1. Wandering Pitch (WP). feedback consists of playing all notes mapped to an axis. Deviation from the reference gesture causes each note mapped to an affected direction to independently change pitch. Correct gestures result in all notes being played continuously without pitch change. For example, see Figures 3.1 and 3.2(a).

3.1.2. Additive Pitch (AP). feedback starts by playing only notes mapped to the axes of desired movement. Notes mapped to axes along which or around which movement is undesirable are not played. The pitches of these notes change as the phone is moved. A correct DoubleFlip gesture results in the smooth transition of these notes ranging between a low-pitched note (C^4, 60 MIDI) and a high-pitched note (C^6, 84 MIDI). Notes mapped to axes along which or around which movement is undesirable are not played initially. However, these notes are played once a threshold is passed indicating error in the associated direction. For example, see Figures 3.1 and 3.2(b).

3.1.3. Wandering Volume (WV). feedback consists of playing all notes mapped to an axis (e.g. C^4, 60 MIDI, A^4, 65 MIDI, and F^4, 69 MIDI). Deviation from the reference gesture causes each note mapped to an affected direction to independently decrease in volume. Correct gestures result in all notes being played continuously without volume change. For example, see Figures 3.1 and 3.2(c).

3.1.4. Additive Volume (AV). feedback starts by playing only notes mapped to the axes of desired movement (e.g. C^4, 60 MIDI). The volumes of these notes change as the phone is moved. A correct DoubleFlip gesture results in the smooth transition of these notes ranging from 20% to 100% volume. Notes mapped to axes along which or around which movement is undesirable are not played initially. However, these notes are played once a threshold is passed indicating error in the associated direction. For example, see Figures 3.1 and 3.2(d).

Glissando maps each axis to one of three distinct notes comprising a major chord that meets the requirements of all the methods mentioned above. For example, an audible and undistorted adequate pitch range was required for AP, while AV and WV required all notes to remain above the lowest note that could be played at discernibly different volumes (C^4, 60 MIDI). A major chord was chosen because of its tendency to generate a positive effect [7] when resolving from an error chord (i.e., the chord heard due to a deviation in one or more axes) to the original chord in the WP and WV conditions. The use of the mobile device's internal speaker reduced the range of notes that could be played without distortion.

Options WP and WV were rejected during the initial design process due to difficulty discerning differences between the changes in audio feedback. The feasibility of options AP and AV were determined by the following exploration study.

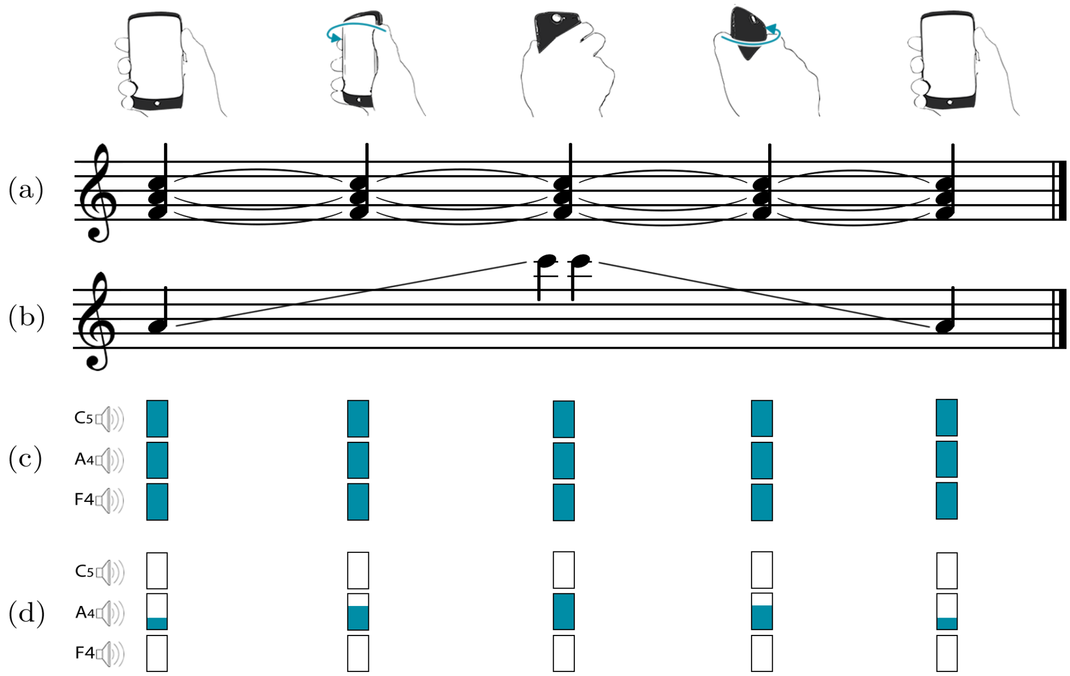

FIGURE 3.1. Examples of feedback for a correct DoubleFlip gesture for (a) Wandering Pitch, (b) Additive Pitch, (c) Wandering Volume, and (d) Additive Volume.

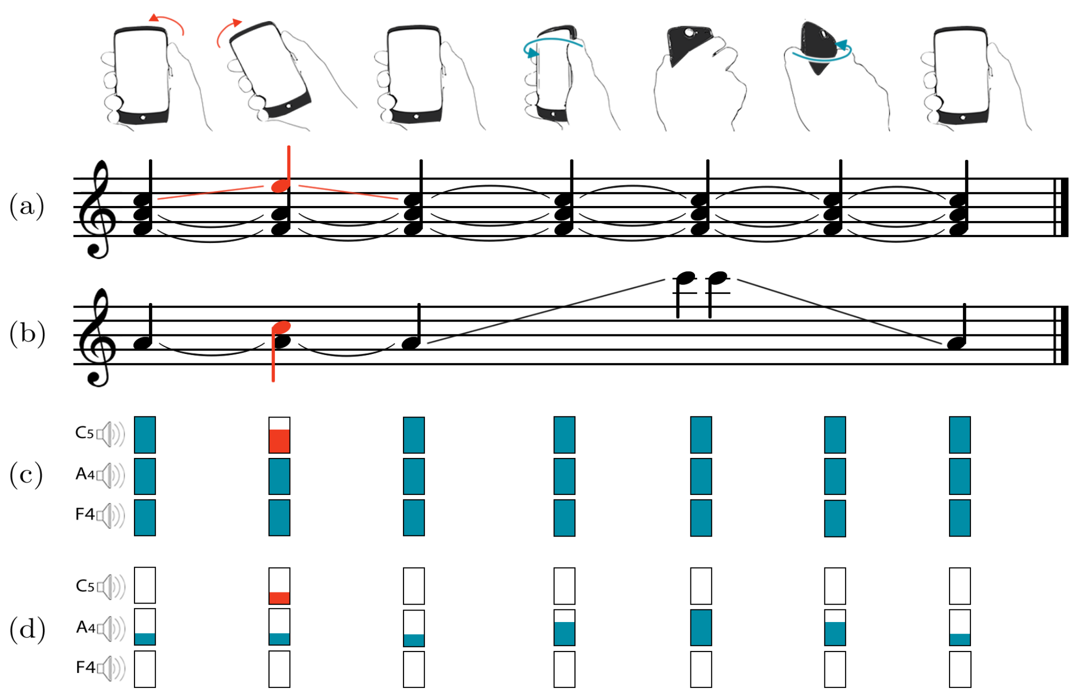

FIGURE 3.2. Examples of feedback for an incorrect DoubleFlip gesture for (a) Wandering Pitch, (b) Additive Pitch, (c) Wandering Volume, and (d) Additive Volume.

CHAPTER 4

Exploration Study: Determining Appropriate Audio Characteristics for Spatial Representation

Since Glissando relies on audio characteristics to represent spatial information, it is important to choose a characteristic configuration (such as AP or AV) that facilitates discrimination between correct and incorrect gestures. Thus, the goal of this exploration study was to determine the optimum continuous feedback configuration for Glissando, using DoubleFlip as an example gesture.

4.1. Conditions

As the DoubleFlip gesture comprises solely of rotation around the Y axis, AP was implemented such that a correct gesture resulted in the center note smoothly transitioning from A^4 (69 MIDI) to C^6 (84 MIDI) and back, as shown in Figures 3.1 and 3.2(b). Notes mapped to the Z and X axes were added once the gesture deviated 15° around either axis. The pitches of these notes retained their respective distances (–4 \+3 MIDI) from the center note pitch. The Y axis was mapped to the center note of the chord and the X and Z axes to the highest and lowest notes, respectively, to assist users in determining which direction needed correction.

AV was implemented so that a correct gesture resulted in only the center note smoothly transitioning from 20% volume to 100% volume and back, as shown in Figures 3.1 and 3.2(d). Notes mapped to the Z and X axes were added once the gesture deviated up to 15° around either axis. As described above, deviation from reference gesture resulted in independent volume changes for each note.

4.2. Design and Procedure

This evaluation study consisted of each participant using one of two feedback techniques (AV and AP) to perform a single correct DoubleFlip gesture. Participants were randomly assigned to each technique. The number of participants in each group was counter-balanced. The study began with the participant listening to a verbal description of the gesture and explanation of the technique. Each participant performed the DoubleFlip gesture while undertaking a think-aloud protocol. Since this was our first study, a think-aloud protocol was employed to provide participants with an opportunity to call our attention to any additional issues with the feedback mechanism. To prevent undue frustration, participants were stopped if they could not complete a gesture within 10 minutes.

4.3. Apparatus and Participants

Glissando was developed in Java using the Android SDK [13] and libpd library [8]. The study was performed using a LG Nexus 4 smartphone running Android 4.2. Eight participants aged 20-64 ($\mu = 31.0$, $\sigma = 14.9$, 4 females, 1 left handed) were recruited using a departmental email list.

4.4. Results

In one instance, a user was unable to discern correct gestures from incorrect gestures using AV due to similarity of high volume notes. Additionally, an older participant using AV reported difficulty discerning between differences in volume, especially for low volumes. AV was discarded due to these drawbacks. AP did not suffer from either of these problems, and one participant using AP reported that the task "seemed very easy."

4.5. Discussion

As a result of this exploration study, Glissandos continual feedback was provided using Additive Pitch. The effectiveness of continual feedback was examined in the following pilot study.

CHAPTER 5

Pilot Study: Evaluating Continual Feedback

The goal of this pilot study was to evaluate the effectiveness and feasibility of using continual concurrent feedback to provide audio feedback of motion gestures used for mobile interaction.

5.1. Design and Procedure

For this study, participants were asked to perform five correct DoubleFlip gestures using two implementations of our feedback technique: "Glissando," which provided continuous feedback using Additive Pitch, and "Control," which omitted continuous feedback and, consequently, did not provide a reference. Participants were split into two groups in order to determine which technique (Glissando or Control) they would use first. The number of participants in each group was counter-balanced.

The study began with the participant listening to a verbal description of the gesture and the first technique. Participants were then asked to complete five gestures. To prevent undue frustration, participants were stopped if they could not complete a gesture within five minutes. Then, participants repeated the task using the second technique. Finally, users participated in a brief (5-10 minute) semi-structured interview in which they were asked to identify the most helpful technique for learning the gesture.

5.2. Apparatus and Participants

Glissando was developed and run on the same hardware and software as our previous study. Thirty-two participants aged 18 - 55 ($\mu = 22.9$, $\sigma = 7.7$, 6 females, 3 left handed) took part in the study. Participants were affiliated with a local university.

5.3. Results

Two participants who initially used the control technique were unable to correctly perform a DoubleFlip gesture, but were able to complete the required five gestures using Glissando. Both participants requested to stop their control trial early out of frustration. One participant was unable to complete a gesture using either technique. The majority of our participants (90.63%) were able to use both techniques to accomplish the task, suggesting both provided adequate feedback.

When asked which technique they preferred, 26 out of 32 participants (81.25%) indicated a preference for Glissando, while two participants preferred the control technique and four participants had no preference. A CHI-squared test showed that technique order had no significant effect on preference. Participants stated that Glissando was especially helpful when determining the direction and magnitude in which to rotate the phone. Several participants commented that Glissando was more helpful because it provided "more complete feedback." Additionally, one participant reported imagining the sounds generated by Glissando while subsequently using the control technique.

5.4. Discussion

Results from this pilot study indicated that while both Control and Glissando provide adequate feedback to users, users prefer continuous feedback. Although temporal constraints were not imposed during this study, we observed that participants attempted to match the speed of the reference gesture while using Glissando. This calls into question whether or not a need to provide an explicit temporal constraint existsour observation implies that the implicit temporal information provided by listening to the reference gesture may be sufficient.

The strict enforcement of temporal constraints was investigated in the following exploration study.

CHAPTER 6

Exploration Study: Enforcement of Strict Temporal Constraints Using Time Limits

Considering that motion gestures must be performed by the user in a time-dependent manner, it is important to ensure that information regarding the temporal aspect of the gestures is adequately communicated to the user. The goal of this exploration study was to investigate the potential for including temporal feedback by imposing strict time limits.

6.1. Design and Procedure

A version of Glissando was implemented to examine hard temporal constraints during audio feedback. This "timed" version added a constraint that required the user to complete the gesture within 3 seconds. Since the provided reference gesture was 2 seconds long, 3 seconds was considered sufficient time to complete the gesture. Anything longer might result in high false positive rates. If a user failed to complete a gesture within the allotted time, the application stated "out of time."

Participants were asked to use this feedback technique to perform a single correct DoubleFlip gesture. The study began by the participant listening to a verbal description of the gesture and explanation of the technique. Each participant performed the DoubleFlip gesture while undertaking a think-aloud protocol. To prevent undue frustration, participants were stopped if they could not complete a gesture within 10 minutes.

6.2. Apparatus and Participants

Glissando was developed and run on the same hardware and software as our previous studies. A handful of subjects affiliated with a local university took part in the study.

6.3. Results

Participants using the timed version of Glissando overwhelmingly expressed frustration regarding not having enough time to learn the gesture. No participants were able to complete a gesture.

6.4. Discussion

As a result of the frustration expressed by participants in the exploration study, it became clear than an alternative to enforcing hard time constraints was needed to express temporal information. It is possible that all of the participants in this study found the DoubleFlip gesture to be too difficult to perform. However, we hypothesize that users in this study were unable to perform the gesture as a result of the strict enforcement of temporal constraints given the low failure rate exhibited by our previous study. Since we observed participants in the previous study attempting to match the speed of the reference gesture while using Glissando, we explored the incorporation of implied temporal information in the following pilot study.

CHAPTER 7

Exploration Study: Using Tempo to Include Temporal Information

Given our observations of participants during the previous study, the goal of this exploration study was to determine whether the audio representation of a reference gesture created by Glissando provides sufficient temporal constraints to ensure that a user performs motion gestures in a time-dependent manner, without enforcing strict time limits.

7.1. Design and Procedure

Participants were asked to perform a DoubleFlip gesture five times correctly using one of four techniques: "Control" (an implementation of Glissando that omitted continuous feedback and thus provided no implied temporal information), "Glissando Slow" (implied gesture time of 4 seconds), "Glissando Medium" (implied gesture time of 2 seconds, identical to the speed of the representation in our previous pilot study), and "Glissando Fast" (implied gesture time of 0.5 seconds). The reference gesture representations for Glissando Slow and Glissando Fast were obtained by scaling the original reference gesture representation from our previous pilot study to the desired length. The number of participants using each technique was counter-balanced.

Participants first listened to a verbal description of the DoubleFlip gesture and application use. Specifically, participants in the experimental groups were asked to match the sound and speed of the reference gesture. The reference gesture was available to be played throughout the study at the user's discretion. Participants in the control group were simply asked to perform the gesture. To prevent undue frustration, participants were stopped if they could not complete a gesture within three minutes. Each gesture attempt was timed, in milliseconds, by the application.

7.2. Apparatus and Participants

Glissando was developed and run on the same hardware and software as our previous studies. Sixty-eight participants aged 18 - 61 ($\mu = 25.8$, $\sigma = 9.1$, 14 females, 3 left handed) took part in the study. Participants were affiliated with a local university.

7.3. Results

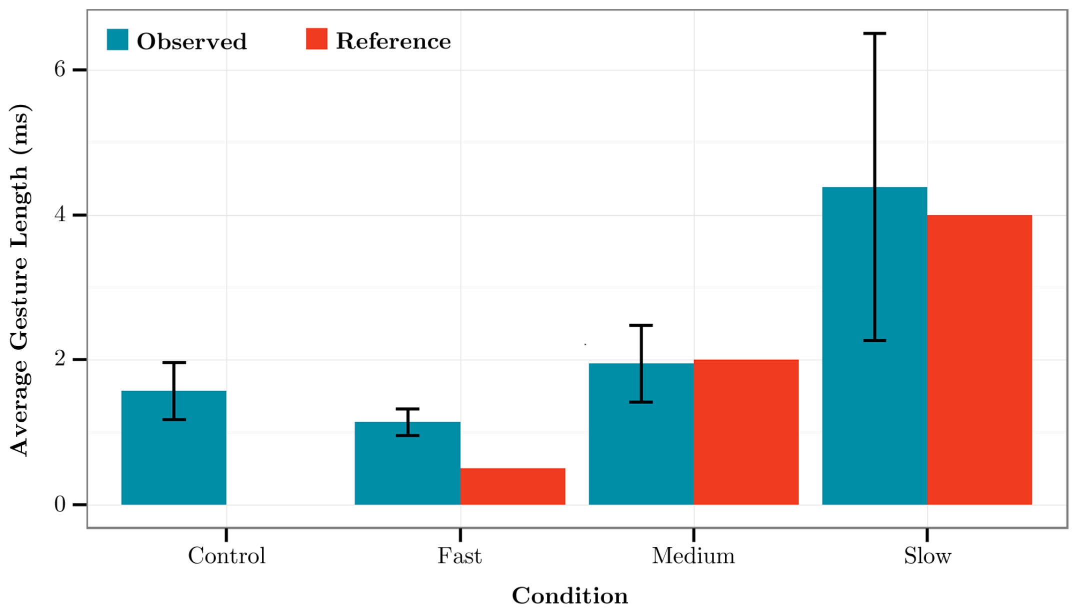

Figure 7.1. Mean length and corresponding reference gesture length (where appropriate), in milliseconds, by condition. Whisker bars indicate one standard deviation.

Figure 7.1 illustrates average gesture length, in seconds, by condition. As shown in Figure 7.1, Glissando Slow resulted in gestures with the longest length ($\mu = 4.37s$, $\sigma = 2.14s$) followed by Glissando Medium ($\mu = 1.94s$, $\sigma = 0.52s$), Control ($\mu = 1.65s$, $\sigma = 0.65s$), and Glissando Fast ($\mu = 1.14s$, $\sigma = 0.19s$).

Factorial analysis of variance (ANOVA) was performed on technique (Control, Glissando Slow, Glissando Medium, Glissando Fast), gesture attempt number (first attempt, second attempt etc.), and individual participant's average correct gesture length. We observed a significant main effect for condition on gesture length ($F_{3,314} = 136.4$, $p < 0.001$), but no significant main effect for gesture attempt number on gesture length ($F_{19,260} = 0.748$, $p > 0.1$).

Post hoc comparisons using Bonferroni correction showed a significant difference on gesture length between all Glissando conditions ($p < 0.001$ in all cases). It also showed the control technique to be significantly faster than Glissando Slow ($p < 0.001$). However, there was no significant difference between Control and Glissando Fast ($p > 0.3$) or Glissando Medium ($p > 0.7$).

Four participants were unable to perform a correct DoubleFlip gesture within 3 minutes. However, the majority of participants (94.12%) were able to complete the task.

7.4. Discussion

Our observations regarding gesture length in the above study indicate that Glissando's audio representations of motion gestures significantly influenced the speed at which users attempted to perform a gesture. It is important to note that while our results show that there is no significant difference between the control technique and Glissando Fast or Glissando Medium, this is acceptable since it is natural for users performing the gesture without being prompted for speed to achieve gestures with lengths somewhere between very slow (as in Glissando Slow) and very fast (as in Glissando Fast). Additionally, our results show that the difference between Glissando Fast and its reference is larger than the differences between Glissando Medium and Glissando Slow and their respective references. This is likely because the reference gesture for Glissando Fast is exceedingly short (0.5 seconds) and therefore likely too quick for users to reproduce accurately. The fact that the observed gestures for Glissando Fast were significantly shorter than the corresponding gestures for Glissando Medium is sufficient to indicate the speed of the reference gesture had the desired effect.

This indicates that the speed at which participants perform motion gestures can be manipulated by changing the speed of the reference gesture, which provides a method of ensuring that motion gestures are performed in an appropriately timely manner without either enforcing strict time limits or including an additional characteristic, such as amplitude [1], to the audio feedback.

CHAPTER 8

User Study

The goal of our final user study was to evaluate Glissando by examining memorability by comparing error rates and temporal correctness of recalled gesture (defined by Equations 1 and 2) for users trained with and without the system.

8.1. Design and Procedure

For this study, participants were trained to perform each of the five gestures described in Figure 1.2 five times correctly while using one of two techniques: “Glissando” and “Control”. In this case, the Control technique was an implementation of Glissando that omitted continuous feedback and replaced detailed verbal feedback with either “correct” or “incorrect” to better approximate performing the gestures in a real-world scenario where users only know whether or not their input was accepted. The control technique was designed in this way since, at the time this research was conducted, there were no other training techniques for motion gestures that did not additional hardware (such as a Kinect [19]).

Glissando was modified to display a short video of the gesture being performed along with the audio representation for this training session. The Control technique displayed the same videos as Glissando, but without the corresponding audio representations. The training session was separated into five tasks, one for each gesture, with a corresponding implementation of Glissando or Control that was tailored to that specific gesture. Gesture videos were available to participants throughout each corresponding training session task. Participants first listened to a verbal description of application use and then were asked to perform each task.

After completion of the training session, participants in the Control group were asked to rate the helpfulness of the video demonstration in learning the movement and timing of the gesture. To do this, participants answered six Likert-type questions using a visual analog scale ranging from 0 to 10, with 0 being “strongly disagree” and 10 being “strongly agree.” Participants in the Glissando group were given an additional six questions to rate the audio feedback. Both groups were asked to rate the likeliness that they would use the technique to help them learn motion gestures.

Participants were then asked to return seven days later and again perform each of the five gestures described in 1.2 five times correctly, in the same order. This return task was required in order to assess how well the gestures had been put into long-term memory. For this task, all participants were given a version of the Control technique that did not include the video in order to best approximate performing the gesture in a real-world scenario. The return session was separated into five tasks, one for each gesture, with a corresponding implementation of Control that was tailored to that specific gesture.

After completion of the return session, participants were asked to rate the helpfulness of the training session in learning the gestures, the easiness of learning the gestures, and easiness of performing the gestures by answering four Likert-type questions using the same visual analog scale from the initial questions.

Participants were randomly assigned to each technique. The number of participants using each technique was counter-balanced. As this was a between-subjects design, participants performed each gesture in the same order for both the training and return session: FlickLeft, FlickUp, DoubleFlip, FlickRight, and then FlickDown so that potential learning affects would average out. To prevent undue frustration, participants were stopped if they could not complete a gesture within five minutes. Each gesture attempt was timed, in milliseconds, by the application.

8.2. Apparatus and Participants

Glissando was developed using the same software as our previous studies. The study was performed using a LG Nexus 5 smartphone running Android 4.4. Thirty-eight participants aged 18 - 40 ($\mu = 21.66$, $\sigma = 4.8$, 10 females, 3 left handed) took part in the study. Participants were affiliated with a local university.

8.3. Results

For each gesture, we calculated the error rate (ER) as: $ER = \frac{number\_of\_incorrect\_gestures}{number\_of\_attempts}$. We also calculated the temporal correctness of recalled gesture (a.k.a. gesture error (GE)) as: $GE = |(user\_gesture\_length) - (ideal\_gesture\_length)|$.

8.3.1. Training Session.

We observed a mean error rate of 11.7% ($\sigma = 13.4\%$) for the control group and 9.0% ($\sigma = 10.1\%$) for Glissando. We did not observe a significant effect for condition or gesture on error rate.

Figure 8.1 illustrates GE (in milliseconds) by condition and gesture for the training session. As shown in the figure, use of the Glissando technique resulted in gestures with smaller temporal deviation from the reference gestures. Analysis of variance (ANOVA) performed on GE indicated a significant main effect for condition on ($F_{1,36} = 21.03$, $p < 0.001$). We did not observe a main effect for gesture performed on GE ($F_{4,144} = 0.37$, $p > 0.8$)

We found no differences between conditions in participant ratings of technique helpfulness, or likelihood of future use from the training session.

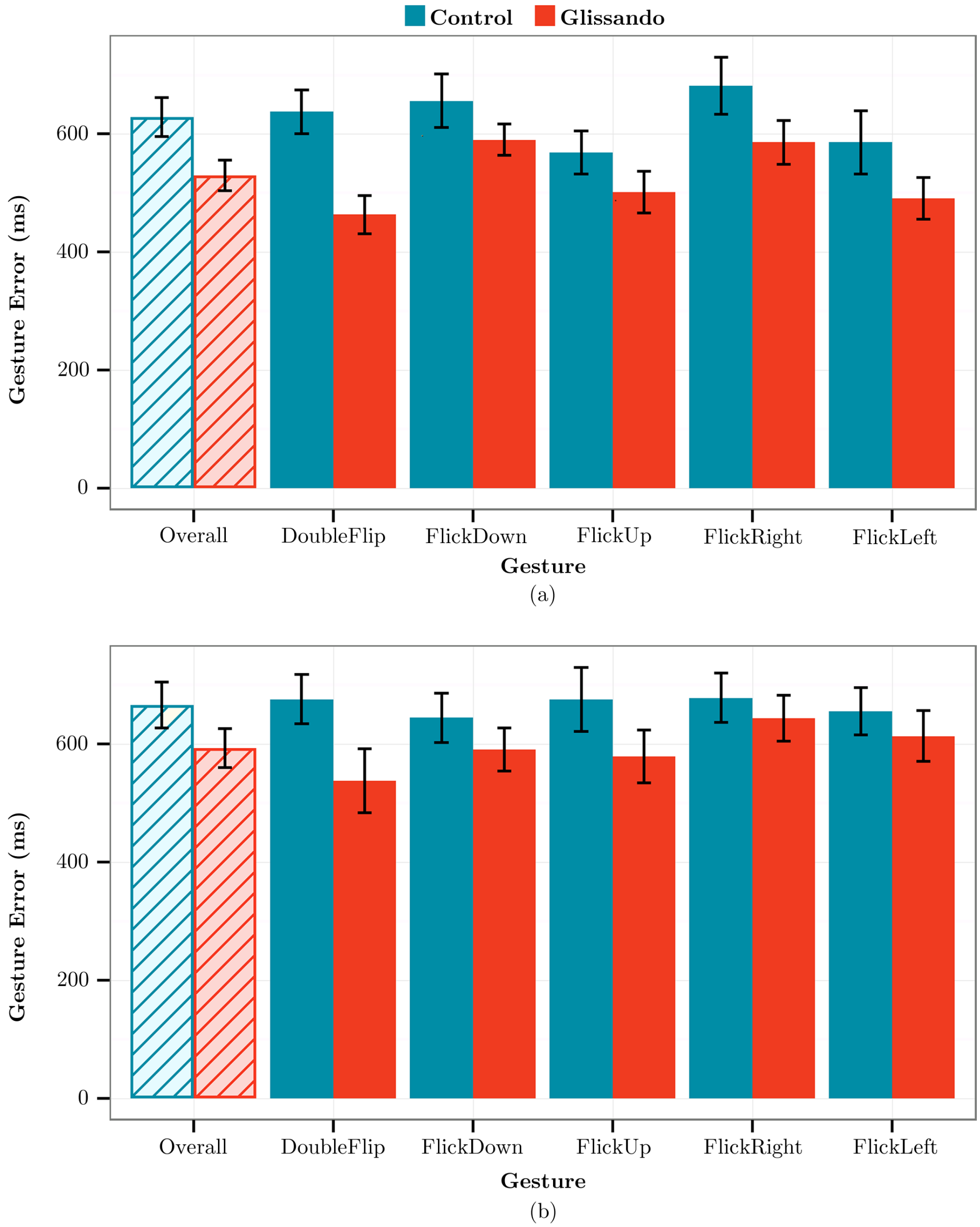

FIGURE 8.1. Gesture error (GE) for (a) training session and (b) return session, in milliseconds, by condition and gesture. Error bars represent standard error.

8.3.2. RETURN SESSION. Error rate for the control group ($\mu = 9.7\%$, $\sigma = 8.0\%$) and Glissando group ($\mu = 9.6\%$, $\sigma = 7.0\%$) were nearly identical. Similarly to the training session, use of the Glissando technique resulted in gestures with smaller temporal deviation from the reference gestures for the return session (shown in Figure 8.1). Analysis of variance (ANOVA) performed on GE indicated a significant main effect for condition on GE ($F_{1,36} = 6.78$, $p < 0.05$). Again we did not observe a main effect for gesture performed on GE ($F_{4,144} = 0.13$, $p = 1.0$).

As in the training session, we found no differences between groups in participant ratings of technique helpfulness, easiness of learning the gestures, or easiness of performing the gestures.

8.3.3. Discussion. Although the participants in the Glissando group rated the audio feedback neutrally ($\mu = 6.36$, $\sigma = 2.48$ for "I found the audio feedback helpful"), technique seemed to have an unconscious significant effect on users ability to match the timing of the gestures. This indicates that adding audio feedback conveys temporal information better than visual demonstration alone. This is significant because motion gestures heavily rely on temporal information to discriminate noise from input.

CHAPTER 9

Discussion

9.1. Implications for Designing Audio Feedback for Motion Gestures on Mobile Devices

In this paper we presented several user studies that examined appropriate audio characteristics for spatial representation, effectiveness of continual audio feedback, effect of enforcing strict temporal constraints, incorporation of implied temporal information, and effectiveness of audio feedback in assisting memorability. Together, the findings of these studies presented in this paper provide insight into what developers need to consider when designing an audio feedback system for training users to use motion gestures on mobile devices:

1: **Feedback should be designed with the limitations of current generation smartphones in mind since distortion can interfere with the user's ability to receive feedback.** This was exemplified during the initial design process of Glissando, when differences in audio characteristics could not be discerned for Wandering Pitch and Wandering Volume due to the quality of the device's internal speaker. Furthermore, observations during the initial exploration study indicate that users become frustrated when they can't hear or understand feedback and want to quit attempting to learn the gesture.

2: **Feedback should avoid excessive use of volume, as users may have difficulty hearing or discerning between volumes at the edges of the spectrum.** Results from the initial exploration study showed that two users had severe difficulty discerning between differences in very high and very low volumes. It is therefore important to control the use of volume since overuse will likely lead to user frustration and inhibit the adoption of motion gestures.

3: **Developers should refrain from imposing strict time limits on users without providing additional assistance in learning the gesture.** Our second exploration study demonstrated that users became overwhelmingly frustrated with strict time limits when attempting to learn the gesture for the first time. Furthermore, participants in this study were unable to complete gestures while strict time limits were imposed. It was observed that, in part, users appeared to have difficulty with the time limits because they were still trying to learn the spatial aspect of the gesture. For this reason we highly recommend that developers avoid imposing strict time limits on users who are unfamiliar with the gesture in question.

4: **Developers should consider providing continual feedback when teaching motion gestures as users strongly prefer the inclusion of continual feedback to receiving feedback only after making an attempt.** We believe that this is particularly important when teaching gestures such as DoubleFlip that require users to meet a specific threshold before changing direction. It was observed during our evaluation of continual feedback and incorporation of temporal information that users frequently were unable to tell when they had rotated the phone far enough without continual feedback. Furthermore, we observed that users who were unfamiliar with the gesture often used Glissando's continuous feedback to determine in which direction they should begin movement. Additionally, there were instances where users were unable to perform a gesture without continual feedback, but could perform the gesture with continual feedback. Finally, our final studies indicated that temporal information could be imparted through the use of continual feedback.

Our preliminary evaluations indicate that this system is a strong technique for providing feedback and assisting users in learning motion gestures. Furthermore, since this project's feedback relies only on the smartphone and all provided instructions can be easily recorded and stored on the device for playback by the user, our system is suitable for use outside of a research laboratory. In light of this, we hypothesize that this system has the potential to help benefit millions of smartphone users by promoting the mainstream adoption of motion gestures.

9.2. Limitations

Our initial prototypes and evaluations were performed using the only the DoubleFlip gesture. However, our final evaluation demonstrates that Glissando can easily be applied to other gestures.

Although our final studies indicate that continuous feedback can be successfully used to convey temporal information, strict temporal constraints were not imposed. Further research will need to be done to determine whether continuous feedback can be used in conjunction with other techniques to teach users to perform gestures that meet specific time requirements.

CHAPTER 10

Conclusion and Future Work

In this paper we explored the use of audio characteristics to provide spatial and temporal feedback to users performing motion gestures. We described and evaluated a technique for motion gesture input, Glissando, which used audio to provide feedback on the system's interpretation of user input. This technique enables feedback by verbally confirming correct gestures and notifying users of errors, in addition to providing continuous feedback by mapping distinct musical notes to each of three axes and manipulating pitch to specify both spatial and temporal information. Extra effort was used to support all design decisions on how to present audio feedback for motion gestures on mobile devices through experimentation. Results from our first pilot study demonstrated that Glissando provided adequate feedback to users both with and without continuous feedback, though provision of continuous feedback is more preferred. Our second exploration study and pilot study show that while users have difficulty with strict time limits, temporal information can be provided via Glissandos continual audio feedback by manipulating the tempo of the reference gesture. Our final study shows that adding audio feedback conveys temporal information better than visual demonstration alone.

10.1. Future Work

Further work includes evaluating Glissando by comparing user performance during ideal and distracted use (e.g. walking) after using Glissando and after using other scaffolding techniques. Additionally, given the nature of motion gestures and our use of audio feedback, we plan on exploring the use of motion gestures and Glissando to support mobile interaction for vision-disabled users.

Bibliography

[1] Andersen, T. H., and Zhai, S. "writing with music": Exploring the use of auditory feedback in gesture interfaces. *ACM Trans. Appl. Percept. 7*, 3 (June 2008), 17:1–17:24.

[2] Ashbrook, D., and Starner, T. Magic: A motion gesture design tool. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, ACM (New York, NY, USA, 2010), 2159–2168.

[3] Bartlett, J. Rock 'n' scroll is here to stay [user interface]. *Computer Graphics and Applications, IEEE 20*, 3 (May 2000), 40–45.

[4] Bau, O., and Mackay, W. E. Octopocus: A dynamic guide for learning gesture-based command sets. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology*, UIST '08, ACM (New York, NY, USA, 2008), 37–46.

[5] Bragdon, A., Zeleznik, R., Williamson, B., Miller, T., and LaViola, Jr., J. J. Gesturebar: Improving the approachability of gesture-based interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, ACM (New York, NY, USA, 2009), 2269–2278.

[6] Brewster, S., Lumsden, J., Bell, M., Hall, M., and Tasker, S. Multimodal 'eyes-free' interaction techniques for wearable devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '03, ACM (New York, NY, USA, 2003), 473–480.

[7] Cook, N. D. The sound symbolism of major and minor harmonies. *Music Perception 24*, 3 (2007), 315–319.

[8] Create Digital Music. libpd. http://libpd.cc/.

[9] Edwards, W. *Motor learning and control: From theory to practice.* Cengage Learning, 2010.

[10] Eslambolchilar, P., Crossan, A., and Murray-smith, R. Model-based target sonification on mobile devices. In *In T.Hermann and A.Hunt, editors, Proceedings of Interactive Sonification Workshop* (2004).

[11] Eslambolchilar, P., Williamson, J., and Murray-Smith, R. Multimodal feedback for tilt controlled speed dependent automatic zooming. In *In: UIST04: Proceedings of the 17th annual ACM symposium on User interface software and technology, (ACM* (2004).

[12] Ghez, C., Rikakis, T., Dubois, R. L., and Cook, P. R. An auditory display system for aiding interjoint coordination. In *in Proc. Int. Conf. On Auditory Displays (ICAD* (2000).

[13] Google Inc. Android open source project. http://www.android.com.

[14] Harada, S., Takagi, H., and Asakawa, C. On the audio representation of radial direction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, ACM (New York, NY, USA, 2011), 2779–2788.

[15] Harrison, B. L., Fishkin, K. P., Gujar, A., Mochon, C., and Want, R. Squeeze me, hold me, tilt me! an exploration of manipulative user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '98, ACM Press/Addison-Wesley Publishing Co. (New York, NY, USA, 1998), 17–24.

[16] Hartmann, B., Abdulla, L., Mittal, M., and Klemmer, S. R. Authoring sensor-based interactions by demonstration with direct manipulation and pattern recognition. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '07, ACM (New York, NY, USA, 2007), 145–154.

[17] Hinckley, K., Pierce, J., Sinclair, M., and Horvitz, E. Sensing techniques for mobile interaction. In *Proceedings of the 13th Annual ACM Symposium on User Interface Software and Technology*, UIST '00, ACM (New York, NY, USA, 2000), 91–100.

[18] Jones, E., Alexander, J., Andreou, A., Irani, P., and Subramanian, S. Gestext: Accelerometer-based gestural text-entry systems. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, ACM (New York, NY, USA, 2010), 2173–2182.

[19] Kamal, A., Li, Y., and Lank, E. Teaching motion gestures via recognizer feedback. In *Proceedings of the 19th International Conference on Intelligent User Interfaces*, IUI '14, ACM (New York, NY, USA, 2014), 73–82.

[20] Kane, S. K., Bigham, J. P., and Wobbrock, J. O. Slide rule: Making mobile touch screens accessible to blind people using multi-touch interaction techniques. In *Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '08, ACM (New York, NY, USA, 2008), 73–80.

[21] Kane, S. K., Morris, M. R., Perkins, A. Z., Wigdor, D., Ladner, R. E., and Wobbrock, J. O. Access overlays: Improving non-visual access to large touch screens for blind users. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST '11, ACM (New York, NY, USA, 2011), 273–282.

[22] Li, F. C. Y., Dearman, D., and Truong, K. N. Virtual shelves: Interactions with orientation aware devices. In *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology*, UIST '09, ACM (New York, NY, USA, 2009), 125–128.

[23] Liu, J., Zhong, L., Wickramasuriya, J., and Vasudevan, V. User evaluation of lightweight user authentication with a single tri-axis accelerometer. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '09, ACM (New York, NY, USA, 2009), 15:1–15:10.

[24] Lumsden, J., and Brewster, S. A paradigm shift: Alternative interaction techniques for use with mobile & wearable devices. In *Proceedings of the 2003 Conference of the Centre for Advanced Studies on Collaborative Research*, CASCON '03, IBM Press (2003), 197–210.

[25] Marentakis, G., and Brewster, S. A. A comparison of feedback cues for enhancing pointing efficiency in interaction with spatial audio displays. In *Proceedings of the 7th International Conference on Human Computer Interaction with Mobile Devices &Amp; Services*, MobileHCI '05, ACM (New York, NY, USA, 2005), 55–62.

[26] Marentakis, G. N., and Brewster, S. A. A study on gestural interaction with a 3d audio display. In *Mobile Human-Computer Interaction - Mobile HCI 2004, 6th International Symposium, Glasgow, UK, September 13-16, 2004, Proceedings* (2004), 180–191.

[27] Marentakis, G. N., and Brewster, S. A. Effects of feedback, mobility and index of difficulty on deictic spatial audio target acquisition in the horizontal plane. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '06, ACM (New York, NY, USA, 2006), 359–368.

[28] Müller-Tomfelde, C., and Steiner, S. Audio-enhanced collaboration at an interactive electronic whiteboard. In *In Proc. ICAD 2001. ICAD* (2001), 267–271.

[29] Negulescu, M., Ruiz, J., and Lank, E. A recognition safety net: Bi-level threshold recognition for mobile motion gestures. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services*, MobileHCI '12, ACM (New York, NY, USA, 2012), 147–150.

[30] Negulescu, M., Ruiz, J., Li, Y., and Lank, E. Tap, swipe, or move: Attentional demands for distracted smartphone input. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, AVI '12, ACM (New York, NY, USA, 2012), 173–180.

[31] Oh, U., Kane, S. K., and Findlater, L. Follow that sound: Using sonification and corrective verbal feedback to teach touchscreen gestures. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '13, ACM (New York, NY, USA, 2013), 13:1–13:8.

[32] Partridge, K., Chatterjee, S., Sazawal, V., Borriello, G., and Want, R. Tilttype: Accelerometer-supported text entry for very small devices. In *Proceedings of the 15th Annual ACM Symposium on User Interface Software and Technology*, UIST '02, ACM (New York, NY, USA, 2002), 201–204.

[33] Plimmer, B., Reid, P., Blagojevic, R., Crossan, A., and Brewster, S. Signing on the tactile line: A multimodal system for teaching handwriting to blind children. *ACM Trans. Comput.-Hum. Interact. 18*, 3 (Aug. 2011), 17:1–17:29.

[34] Rekimoto, J. Tilting operations for small screen interfaces. In *Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology*, UIST '96, ACM (New York, NY, USA, 1996), 167–168.

[35] Ruiz, J., and Li, Y. Doubleflip: A motion gesture delimiter for mobile interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, ACM (New York, NY, USA, 2011), 2717–2720.

[36] Ruiz, J., Li, Y., and Lank, E. User-defined motion gestures for mobile interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, ACM (New York, NY, USA, 2011), 197–206.

[37] Small, D., and Ishii, H. Design of spatially aware graspable displays. In *CHI '97 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '97, ACM (New York, NY, USA, 1997), 367–368.

[38] Sodhi, R., Benko, H., and Wilson, A. Lightguide: Projected visualizations for hand movement guidance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, ACM (New York, NY, USA, 2012), 179–188.

[39] Talbot, M., and Cowan, W. On the audio representation of distance for blind users. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, ACM (New York, NY, USA, 2009), 1839–1848.

[40] Weberg, L., Brange, T., and Hansson, A. W. A piece of butter on the pda display. In *CHI '01 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '01, ACM (New York, NY, USA, 2001), 435–436.

[41] Wigdor, D., and Balakrishnan, R. Tilttext: Using tilt for text input to mobile phones. In *Proceedings of the 16th Annual ACM Symposium on User Interface Software and Technology*, UIST '03, ACM (New York, NY, USA, 2003), 81–90.

[42] Williamson, J., and Murray-Smith, R. Audio feedback for gesture recognition, 2002.

[43] Williamson, J., and Murray-Smith, R. Sonification of probabilistic feedback through granular synthesis. *IEEE Multimedia 12*, 2 (2005), 45–52.