On the Choice of Gestural Controllers for Musical Applications: An Evaluation of the Lightning II and the Radio Baton

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Abstract

This thesis evaluates the Lightning II and the Radio Baton gestural controllers for musical applications within two main perspectives. The first involves a technical specification of each in terms of their construction and sensing technology. This step, along with an analysis of the insights by long-term users on the controllers in question, provides an understanding about the different musical contexts each controllers can be and have been used in. The second perspective involves studying the Radio Baton and the Lightning within a specific musical context, namely that of a simulated acoustic percussion instrument performance. Three expert percussionists performed basic percussion techniques on a real drum, a drum-like gestural controller (the Roland V-Drum), the Radio Baton and the Lightning II. The motion capture and audio data from these trials suggest that certain acoustic percussion playing techniques can be successfully transferred over to gestural controllers. This comparative analysis between gestural controllers adds to the ongoing discussion on the evaluation of digital musical instruments and their relationship to acoustic instruments.

Resumé

Ce rapport de thése examine les contrôleurs gestuels Lightning II et Radio Baton selon deux perspectives principales. La premiere implique pour chaque contrôleur une specification technique en terme de materiel et de technologie sensorielle. Cette etape inclue tant une vue sur les possibilités et limitations de chaque contrôleur, que les avis de experts au sujet des differents modes d'utilisation. La second perspective concerne l'etude de l'utilisation du Lightning et du Radio Baton dans un context musical specifique : le jeu de percussion lie a une simulation audio-numerique. Ce context musical a ete experimente par trois percussionistes, executant ainsi des techniques de bases de percussion, alternativement sur une percussion reelle, un Roland V-Drum, le Radio Baton et enfin le Lightning II. Les resultats acoustiques et de capture de mouvement suggerent la possibilité de transferer certaines techniques de percussion aux contrôleurs gestuels. Cette analyse comparative des differents contrôleurs gestuels contribue ainsi a l'évaluation des instruments de musique digitaux et de leur rapport avec les instruments acoustiques traditionnels.

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Chapter 1

Introduction

1.1 Context and Motivation

As acoustic instruments have evolved over the centuries, various standards have arisen so that one can argue, for example, that one violin is of a higher quality than another or that a certain drum head design will have a certain musical effect. This was ostensibly achieved by musicians using the instruments for long periods of time, composers and their audiences listening and watching performances, and builders changing the physical designs.

The last twenty-five years has seen the rise of inexpensive and powerful computers, sensors, and digital sound synthesis implementations. These can be put together to create a **digital music instrument** (DMI). Digital music instruments are constantly being invented, used, and improved as well. Compared to acoustic instruments, however, there has simply not been enough time to answer questions of quality or develop a complete picture of device capabilities . Furthermore, as suggested by **Figure 1.1**, the physicality of the instrument and the sound it makes are separated by the mapping layer, each of which is variable, which may render established practices for acoustic instrument evaluation inadequate.

Taking into account the sheer number of new gestural controllers and general computer input devices that are released every year by the commercial and academic [1] communities, the problem of comparing interfaces becomes compounded. Given that the majority of commercial devices must be based on an existing musical skills so as to be quickly adopted and therefore profitable, these devices closely resemble acoustic keyboards, percussion, etc. On the other hand, the majority of devices from music input device research tend to have shortlived lives as prototypes only, and so otherwise innovative designs are forgotten. To begin looking at the question of gestural controller quality, a balance between the two extremes might be a fruitful place to look.

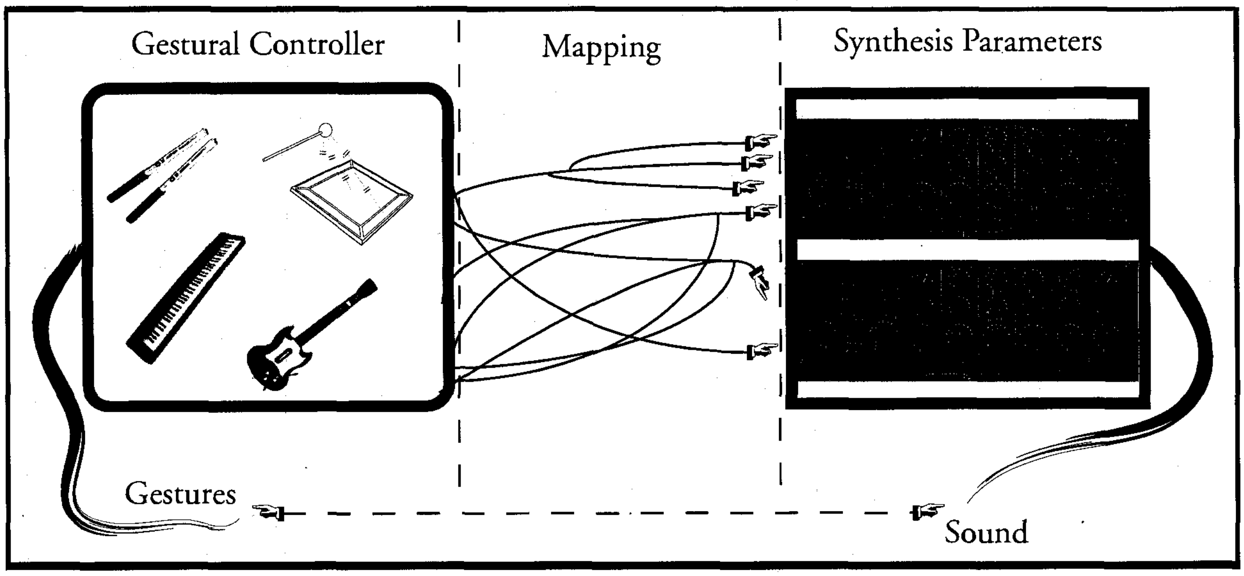

Fig. 1.1 Conceptual framework of a digital music instrument
The gestural controller is the user interface of the DMI and encapsulates the sensors. Sensor data is mapped to sound output parameters which control the sound engine. These parts can be integrated into one design or separated (for example, across several computers and controllers). In constrast, acoustic instruments have all these parts coupled together by their physical form. Adapted from [2].

A Case Study: The Radio Baton and The Lightning

Two gestural controllers that have relatively long histories include the Buchla Lightning (and its successor the Lightning II) and the Boie/Mathews RadioDrum, now called the Radio Baton. Each introduced near the beginning of the 1990s, they are still available for purchase today. The Lightning uses wireless infrared transmitters embedded in drumstick-like "wands" that are sensed by a separate receiving unit placed in front of the performer. The Radio Baton uses capacitive sensing to track wired mallets held by the performer over a receiving surface. Each has hardwired algorithms for capturing striking movements. Due to their use of sticks and their ability to capture ballistic movements, these controllers may be used as percussion instruments (see **Figure 1.2**).

Despite the similarities, the Lightning and the Radio Baton are not easily evaluated in terms of percussion instruments. At first glance, they resemble percussion instruments because their user interfaces are basically drum sticks, or perhaps mallets in the case of the Radio Baton; as such, the choice of control gestures can easily be ballistic in nature. It is natural to attempt hitting something to make a sound with these controllers. However, one important difference between these controllers and acoustic percussion instruments involves the separation of gestural controller and sound source, as mentioned above. The gestures can be smooth and slow as well

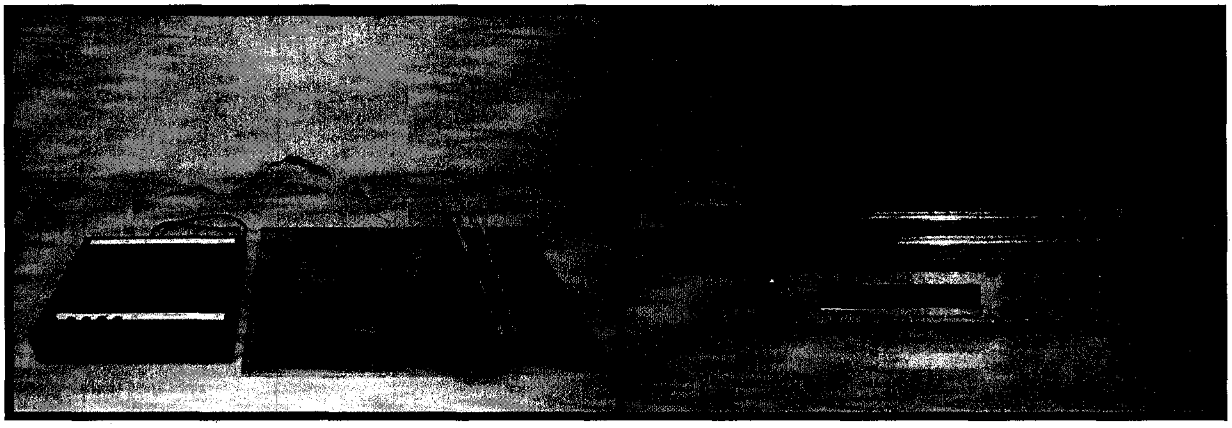

Fig. 1.2 The Radio Baton and the Lightning II
The Radio Baton (left) and the Lightning II (right)

as ballistic; these can in turn be mapped to either percussive or non-percussive sounds, sound sequences, or timbral changes.[1]

Given only the appearance of these or any other controllers, one would not have a complete idea of what their musical possibilities and limits might be. Since DMIs can be mapped in so many different ways, it might be impossible to come up with a universal method to evaluate and compare them for all settings. If there is such a method, the search for it must begin with the consideration of a particular design in more than one light.

1.2 Research Overview

This thesis aims to view the Lightning and the Radio Baton within two main perspectives. The first involves a low-level technical specification of each in terms of their construction and sensing technology. It is thought that this, along with an analysis of the opinions of the controllers in question by long-term users, may shed light on what these designs are capable of. As noted above, these two particular designs resemble acoustic percussion instruments. Assuming then that this particular musical context is well suited to these designs, the second perspective involves motion capture of percussive performance gestures using these devices. This comparative analysis between similar instruments will hopefully add to the ongoing discussion on the relationship between digital musical instruments and acoustic instruments.

[1]Indeed, they can be mapped to control any digital media, including video and 3D graphics.

1.3 Thesis Overview

The proposed comparison of the Lightning and the Radio Baton is composed of three parts:

The first deals with the history and construction, and hence the sensing strategy, used by each controller (see **Chapter 3**). There is a limit to the type and subtlety of performance gestures that can be captured by each controller that is a function of the construction of each device. This limit becomes important when choosing controllers for a particular musical effect.

The second part focuses on the relationship between the device and the user. Due to their longevity, experienced users were informally questioned on subjective performance characteristics such as expressivity and versatility (see **Chapter 4**). Musical instruments (of any kind) must in the end be used and adopted by musicians. The goal here is to a get a sense of what it means to play and adapt to these controllers in a performance setting over a long period of time.

The third part involves motion capture of performances on both controllers, a commercial drum controller[2], and a tom drum (see **Chapter 5**). Using the sound engine of the Roland V-Drum, a realistic tom drum sound can be mapped to the output signals of all three electronic controllers. Percussion studies[3] incorporating basic techniques were used. The performances by students of the Schulich School of Music's classical percussion program were captured using the Polhemus Liberty[4] electromagnetic tracking system and video cameras. The evaluation of kinematic characteristics of percussionist movements can shed light into whether percussion skills can be transferred to the performance of each device. Furthermore, these exercises place the evaluation of the controllers firmly within a particular music performance context.

1.4 Contributions

It is hoped that by comparing the Radio Baton and the Lightning in more than one setting, a more complete understanding of their musical possibilities might be attainable. It is assumed that this is a worthy task because, contrary to many digital musical instruments in the commercial and academic worlds, they are still, relatively speaking, widely available, undergoing continual revisions, and resemble yet are distinct from acoustic instruments. If this thesis is only able to renew interest in these worthy designs, it should be considered a success. It is also hoped this report will contribute to the discussion over the evaluation and comparison of digital music instruments.

[2]V-Drum by Roland (www.roland.com). Accessed 30/08/07.
[3]These were chosen in part as a result of discussion with percussionist Fabrice Marandola.
[4]www.polhemus.com. Accessed 30/08/07.

Chapter 2

Background

2.1 Gestural Controllers as Input Devices

Input devices are the means by which a computing device receives information from the user. There is a large corpus of work in the field of Human-Computer Interaction that deals with evaluating and classifying general input devices for the computer (such as the keyboard and mouse) to improve their relationship with the human user. Since gestural controllers facilitate the input of musical control data, they can be thought of as a special type of input device as well. As such, there is HCI research that applies to DMI's and gestural controllers.

2.1.1 Research in Human-Computer Interaction

The focus in HCI has been on quantifying the role of input devices in the computer user's experience, especially in regards to the graphical interface.[1] The possibilities of this role are heavily moderated by the interaction model between the device and the application. The *WIMP* (Windows, Icons, Menus, and Pointers) framework [5], for example, is used in many text-based applications. However, as interaction complexity increases (e.g. video games, virtual reality), new models necessarily appear [6]. These tend towards "a set of continuous relationships" [7] between user and computer, a paradigm that more closely resembles music performance. The following section outlines research in HCI that can address some of the particularities of gestural controller design and evaluation.

Graspable User Interfaces

Graspable User Interfaces refers to an interaction model where specialized input devices are tightly coupled to virtual objects they manipulate or control. Graspable UIs physically resemble their

[1] For a general introduction to HCI, please see [3] and [4].

related objects on the screen and cannot directly control other virtual objects. This paradigm is called *space-multiplexing*, in contrast to *time-multiplexing* where, for example, a mouse performs several different functions for several different virtual objects over time. According to the authors, GUIs have a higher financial cost that comes with the greater number of physical devices and an increased cognitive load from dealing with several devices. However, the argument is made that this framework is already used extensively in automobiles and kitchens (and music). In the experiments reported in [8], Graspable UIs and a mouse were compared for their ability to allow the user to track objects on a computer screen. GUI's resembled the screen objects physically. It was found that space-multiplexed devices outperformed time-multiplexed devices in terms of learning time and tracking precision.

In a similar way, controllers are usually designed to address a specific musical performance context and allow for more gestural expression at the cost of generality of use. This is an important issue at this point in the development of DMI's; it can be said that laptop musicians, of which there are increasing numbers every year, more generally use a mouse or keyboard than a custom gestural controller [9], introducing repercussions on the amount of gesturality allowed in the performance.[2] The case of Graspable User Interfaces supports the idea that gestural controllers that focus on a single application allow "lower latency, higher precision, higher data rates,and a broader range of physical gestures" than general input device objects [10], i.e. the computer keyboard and mouse.

Evaluation Tasks and Fitts' Law

Bill Buxton [11] presented a set of tasks that correspond to common user demands on graphical user interfaces. These were to be used in experiments to establish objective evaluation methods. Of these, *Target Acquisition* has emerged as the most widely used task in HCI research; it has a quantitative formulation in Fitts' Law. Fitts [12] identified a formal relationship to describe the movement time of a stylus passing between two targets by a subject, a relationship that has been shown to hold for other similar tasks in aimed movements [13]. This was first used in HCI in [14], where several input devices were compared on a text selection task. It is formulated such that the movement time increases linearly with a ratio of the amplitude of the movement and the target width (see **Figure 2.1**). The utility of Fitts Law is in the quantification of the movement tradeoff: "The faster we move, the less precise our movements are, or: the more severe the constraints are, the slower we move." Though quantified in respect to target selection, modern applications now also employ trajectory-based interactions through drop down menus, curve drawing, and

[2]It should be noted that MIDI keyboards do not differ greatly from computer keyboards: in terms of gestural information both capture the selection of a key, in terms of construction they both resemble an array of discrete switches. MIDI keyboards also sense the velocity of a depressed key as a value between 0 and 127, which is a rough estimation of the piano hammer action.

navigation. Accot and Zhai [15] extend Fitts' Law to this type of interaction through mathematical extrapolation and empirical results that support it. Using these metrics provides target acquisition performance indices for various devices independent of the experimental conditions, therefore allowing for quantitative comparison of devices.

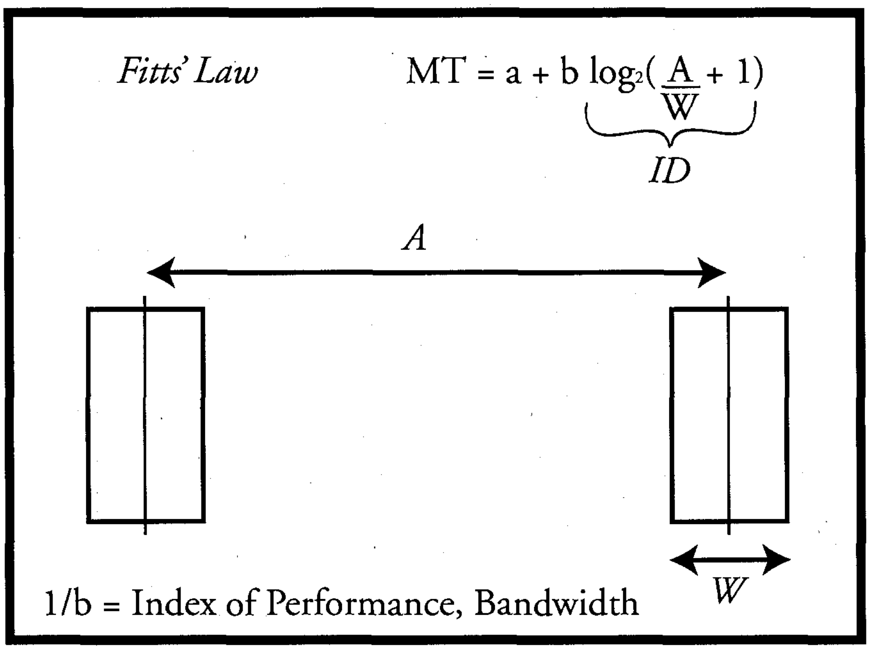

Fig. 2.1 A summary of Fitts' Law
Fitts' Law states that the movement time (MT) required to acquire a target with a continuous linear controller is a function of the distance (A) divided by the target width (W). ID refers to the Index of Difficulty. (The equation shown is actually called *Shannon's Formulation* and is a variation of Fitts' original formula [16].) A higher ID implies a higher movement time. The Index of Performance (1/b) is the amount of information per second (bandwidth) allowed by the device and is used in device comparisons.

Applying Fitts' Law or its derivations to devices of 3 or 6 Degrees of Freedom (DOF) can be less informative as the devices typically perform user tasks in which the idea of speed and accuracy may be spread across several dimensions and dependent on more than one dimension at a time. In [17], the authors propose efficiency as a possible variable for device comparison, where efficiency is an optimal path, including rotation, through a 3D space. The task is target pursuit on a display using one free movement device and one that involves the measurement of elasticity to control the rate of the display cursor with some haptic feedback. The free movement device produces faster completion times but less efficient trajectories. This study is relevant in that it departs from the classical HCI evaluation techniques in order to deal with more exotic input devices. Music controllers usually control many dimensions and continuous variables simultaneously [18].

Even in classic HCI, however, generality of results is difficult to achieve. If, for instance, the target shape of a test using Fitts' Law is word text or a circular target, it cannot be directly compared to tests using a vertical-bar target [19]. Furthermore, the commercial devices used differ in resolution, sampling frequency, form factors, sensor technology, and the transfer functions between the hardware and software. This is the case with DMI's in that materials and mapping strategies vary greatly. Rather than attempt normalizing all these variables, in [19] the assumption is made that the commercial devices were optimized for the majority of users and instead test the performance of these devices for a particular task that is thought to mirror common user actions. This approach is also used in this study. This does not however address the first difficulty which is determining appropriate general tasks that can be used for comparison across DMI designs. The following section examines HCI research specifically oriented towards digital music instruments.

2.1.2 HCI Research in Music Controllers

The design of digital instruments for musical expression has proceeded in two markedly different directions. The commercial market has by and large rested on digital reproductions of acoustic instruments, analog mixers, and now turntables [20], [21].[3] The academic computer music community has instead created a variety of different controllers [22], [23]. The advantage in this is that there is a great wealth of designs that explore new ways of making music; the downside is that designs are many times limited to one prototype and are not available for the general public to try [24]. As such, the evaluation and acceptance of these designs is difficult to achieve [25] [23].

This is in opposition to the evaluation of general input devices in HCI.[4] Although there have been attempts at leveraging HCI techniques for instrument design, there are some important differences between traditional (WIMP-based) applications and music systems. Specifically, from [18]:

- There is no fixed ordering to the human-computer dialogue.
- The human takes control of the situation. The computer is reactive.
- There is no single permitted set of options (eg.choices from a menu) but rather a series of continuous controls.
- There is an instant response to the user's movements.
- Similar movements produce similar results.

[3] see www.createdigitalmusic.com for an idea of the current trends in commercial controller design

[4] It should be noted that Bill Buxton, prominent HCI researcher, has called HCI a "failed science" [24] due to the continued dominance of the keyboard and mouse.

- The overall control of the system (under the direction of the human operator) is the main goal, rather than the ordered transfer of information.
- The control mechanism is a physical and multiparametric device which must be learnt by the user until the actions become automatic.
- Further practice develops increased control intimacy and competence of operation.

These differences cover a set of interaction requirements that DMI's are operated within, this set being very different from what traditional HCI research usually concerns itself with. For example, the musical analog to Fitts' Law has not been successfully postulated yet, the difficulty lying in finding an abstract, elemental musical task [25]. Instead, different researchers have chosen a particular musical context, i.e. perspective, from which to evaluate DMI's. The various contexts or "metaphors for musical control" [26] proposed in [25] include:

- sound processing control
- note-level control
- score-level control
- musical instrument manipulation
- interaction in a multimedia installation.
- HCI-related tasks e.g. navigation through a timbral space [27]
- dance/music interfaces
- musical games

Input devices can be used in more than one context, and may be suited to one more than another. This has led to different evaluation methods that are difficult to compare. On the other hand, users have a wide variety of methods to choose from.

DMI Classification: Taxonomies

Acoustic instruments have a long history of classification studies [29]. This has focused on studies of single instruments and also the comparison of different instruments. Western European work has focused on the means of sound production or the physical form to define categories. Kvifte instead considers playing technique, using the fact acoustic instruments control sound according to a certain correspondence between gesture and sound: bowing, plucking, or striking a

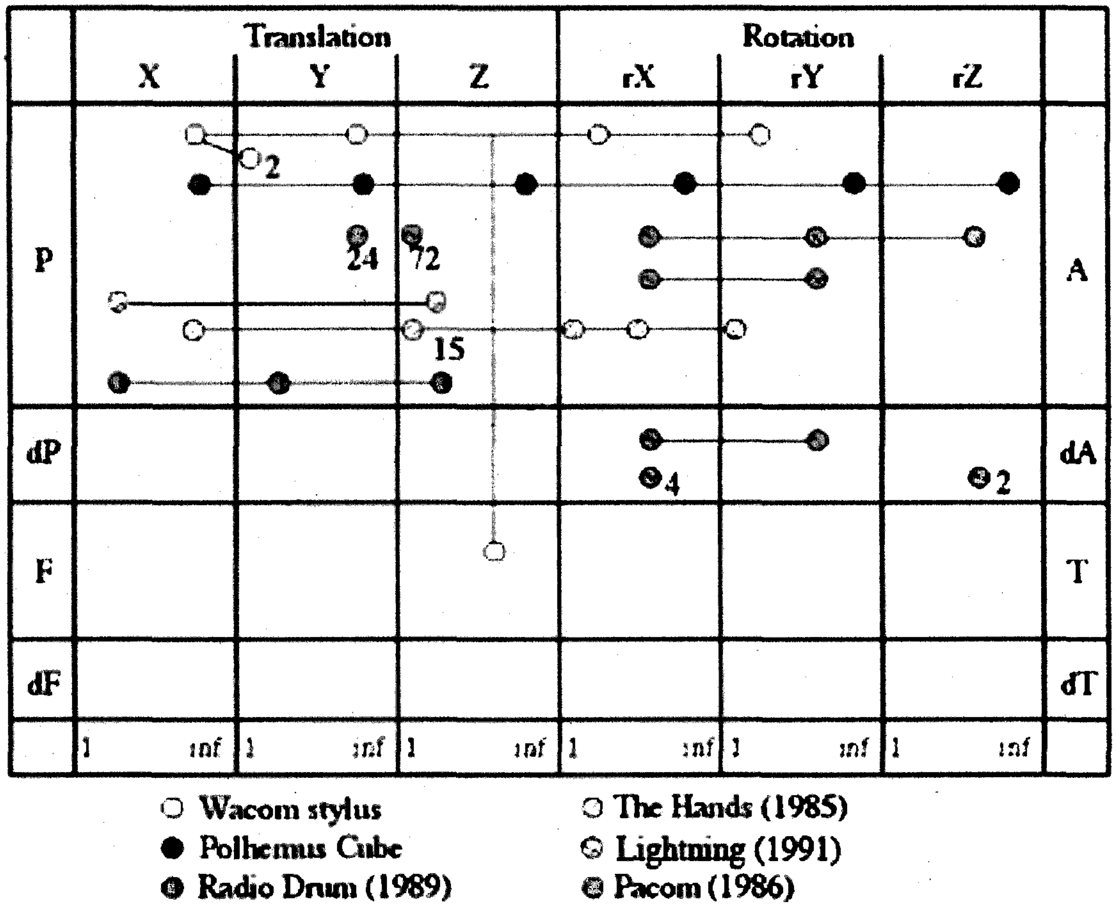

Fig. 2.2 Gestural controller taxonomy from Wanderley (2001)
Of the six devices listed here, the Radio Drum, the Hands, the Lightning, and the Pacom are gestural controllers designed for music performance. The Wacom Stylus and the Polhemus Cube are general input devices. The Radio Drum and the Lightning resemble each other within this classification scheme, differing by only one variable. Modified taxonomy from [28]

string for example. Furthermore, the playing technique of an instrument greatly influences any subsequent improvements to the design. This approach becomes difficult to apply to gestural controllers because the mapping used can change the playing technique, although it remains viable for completed DMI's that have non-evolving mappings.

Having said this, digital music instruments can be classified according to the control paradigms of conventional acoustic instruments. Acoustic instruments that are augmented with sensors can be classified as *extended instruments* while DMIs that emulate existing instruments are *instrument-like controllers.* Designs that borrow concepts from acoustic instruments but do not seek to emulate them may be deemed *instrument-inspired controllers* while those that do not share any similarities in control surface to existing instruments are *alternate controllers*. These designations are somewhat arbitrary. They can be seen as the product of a higher-level distinction, namely whether the design leverages an existing gestural vocabulary (in the case of the first three categories) or whether it eschews any attempt to use some predefined instrumental practice [25].

Input devices can be classified according to their sensing characteristics. When this information is visually plotted, comparisons regarding the technical characteristics can be made more quickly. [11] introduced a taxonomy based on how position, motion, and pressure is sensed in the three cardinal dimensions. This was used in [28] for six gestural controllers. **Figure 2.2** shows the Radio Baton and the Lightning (added by this author) in comparison to other gestural controllers from the same period. The plot allows for the comparison of sensing characteristics at a glance. However, since it's focus is translation and rotation, this taxonomy cannot be applied to controllers that measure other types of movement, such as postural changes or facial expressions, without changing the taxonomy criteria. Buxton's taxonomy was refined in [30] by using the resolution of position and force and their derivatives sensed within the six possible degrees of freedom.

In [31], the idea of a design space was introduced. This is a multidimensional plot of an interactive system according to several configurable criteria that can be continuous, discrete, ordered, etc.. When used for several devices, similar to visual taxonomies, quick comparisons are possible. [32] structured criteria to quickly distinguish between DMI's, installations, and musical toys. This was an improvement on similar work in [33] and [22]. As a result of taking a broad perspective, when used to compare two similar devices, such as the Radio Baton and the Lightning (**Figure 2.3**), the design spaces are quite similar.

DMI Classification: Evaluation and Features

Vertegaal, Ungvary, and Kieslinger [34] presented a set of guidelines for mapping fundamental musical functions to various transducer types commonly used in controllers and DMI's. They presented three musical functions:

- *Absolute Dynamical Functions* - e.g. absolute selection of pitch, amplitude or timbre.
- *Relative Dynamical Functions* - e.g. modulation of a given pitch, amplitude or timbre.
- *Static Functions* - e.g. selecting pitch range, duration range, scale or transposition.

A set of transducers were then presented as being better or worse for a particular function. This was partially validated by Wanderley et al. [33]. The experimental approach required subjects to perform a simple pitch selection task (Absolute Dynamical function) followed by a vibrato

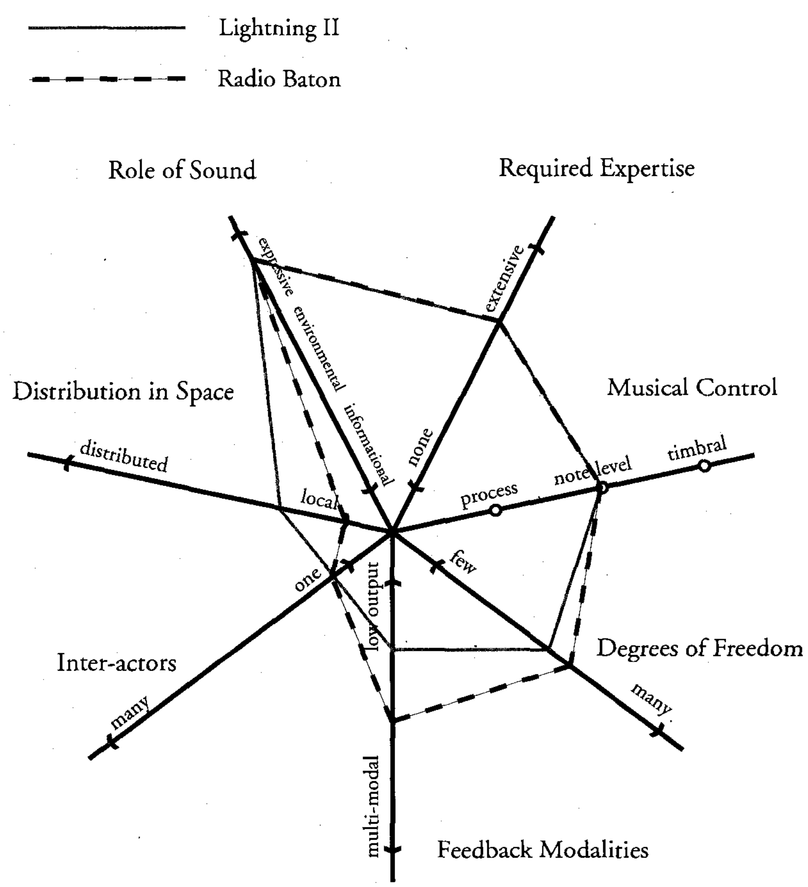

Fig. 2.3 Dimension space analysis of Lightning and Radio Baton
Dimension space analysis of Lightning using criteria from [32]. The differences lie in that the Radio Baton senses one extra degree and gives nominal haptic feedback while the Lightning sensing space is larger.

(Relative Dynamical function) using a mouse, a force-sensitive resistor, and Wacom tablet stylus. The authors found that several of the proposed function-transducer relationships were both favored by users. However, the general applicability of the guidelines remains to be determined, partly because the functions are considered too general when compared to normal performance practice.

Poepel presented work comparing three string-based interfaces [35]. He used cues for musical expressiveness derived from research by Juslin [36]. By asking users to judge the expressiveness of the interfaces based on playing techniques that correspond to cues for expressiveness, the three interfaces were ranked. However, the interfaces used differed more in sound synthesis and mapping than hardware.

In [25], four features are presented that they propose figure largely in controller evaluation. The features can, for example, suggest attributes of musical tasks. The features are as follows:

- *Learnability* concerns itself with the difficulty of performance. How easy is it to play, does it borrow gestures from other musical instruments, i.e. an existing corpus of motor abilities? As it has been shown that it takes less time to learn a second instrument [37], "musical tasks thus should account for the time needed to learn how to replicate simple musical gestures by experienced musicians."

- *Explorability* deals with the controller's ability to capture different performance gestures. This is tied to the sensors and mapping used. By asking subjects to recreate certain sound examples, a controller can be examined for how intuitively it allows users to 'find' the sound.

- *Sound controllability* is based on controllers applicability for a given musical task *as perceived by the user.* This emphasizes the music perception aspects of controller design, such as the integrality vs the separability of musical gestures [38].

- *Timing controllability* is a defining characteristic of music that is absent in classical HCI in that musicians are required to perform tasks at specified times and so "time becomes a constraint rather than a variable to be measured". Musical tasks must therefore take into account this requirement for timing precision together with any latency and mapping issues that may be involved.

The importance of these features lies in that none of them rely solely on the visual appearance or sensing apparatus of the gestural controller as the methods mentioned above generally do, but instead on the usage patterns and opinions of actual users. Issacs [39] subsequently used these features as the basis for an evaluation of a Korg Kaoss Pad and a two dimensional accelerometer for musical applications. This evaluation included user tests of two musical tasks and questionnaires for established gestural controller designers and users.

2.1.3 Percussion in Music Technology

The instruments in the percussion family number in the thousands [40]. In an orchestra setting, these are all played by the same person. A percussionist must therefore use many different playing techniques and are in this sense well suited to using and evaluating new instruments, especially ones that resemble traditional percussion instruments such as the ones in this study [41]. In [42] reflections on percussion playing reinforce the idea that percussionists do not have a single instrument but instead an attitude towards sound and a specific set of techniques that involve ballistic movements. Besides being used to playing in many different contexts, percussionists are especially interesting for movement study because "compared to instruments where individual finger movements are used to larger extent, the playing movements tend to be larger for percussion playing" [41].

Music technology research has briefly dealt with percussion. Tindale et al. [43] and Young and Fujinaga [44] provide informal comparisons of DMIs inspired by percussion in order to present novel percussion controllers. Dahl and Bresin [45] use a Radio Baton to study the interaction between auditory and tactile feedback in percussion playing. They reported a latency between 40ms and 55 ms as being detrimental to keeping a steady rhythm. Maki [46] performed a comparison of interfaces for a virtual drum and found that latency could be dealt with easier with a real stick than only with a virtual stick projected on a screen in front of the user.

Chapter 3

Technical Specifications

This chapter contains a comparison of the Lightning and Radio Baton in terms of their design histories and technical characteristics. By understanding the technical limitations of these controllers, one can better identify the gestural vocabulary that is best adapted to each.

3.1 Brief Histories of the Lightning II and the Radio Baton

The Lightning II

By the late 1980s, over five years after the introduction of the MIDI standard, electronic instrument maker Don Buchla felt commercial controllers still did not deviate far from the organ keyboard paradigm [20] [47]. The standard was supposed to allow novel gestural controllers to communicate with sound generators resulting in customized instruments. To realize this, Buchla began working on a quartet of controller designs named *Lightning*, *Thunder*, *Wind*, and *Rain*. Thunder was a hand drum controller design that went through several prototypes and was eventually sold to Creative[1] but was never mass produced. Wind was a novel breath controller while Rain was conceived as an electronic rainstick, although both did not progress beyond prototype models.

The Lightning, however, was brought to market in 1991 as a spatial controller using the triangulation of infrared signals to provide a large 2D (x and z) area for the user to freely gesticulate within. It provided three different interfaces with which to control sound, including wands, a ring for keyboard players, and drumsticks that were to be used to hit objects [48]. The Lightning II was introduced in 1996; the infrared receivers were detached from the sound engine and only the wand interface was included. Both models included their own sound engine and also output a highly interpreted MIDI stream that contains some higher level information about the captured

[1] www.creative.com. Accessed 30/08/07.

gestures such as strike velocity and direction. It is currently going through its third revision, including software and resolution improvements, and is still marketed through Buchla and Associates[2]. Long time performers include Joel Davel, Mark Goldstein, Forrest Tobey and Pamela Z.

The Radio Baton

While in residence at IRCAM in Paris during the early Eighties, Max Mathews created a novel controller called the Daton that used four pressure sensors in the corners of a plate to sense position and force of a strike by rubber tipped hammers [49] [50]. This was an improvement on an earlier design called the Sequential Drum that used a contact microphone for velocity and a wire grid for position [51]. While neither were used by any composers there at the time, they did (along with GROOVE, Mathew's interactive performance system) inspire Pierre Boulez to ask for "an expressive tape recorder" [50]. This was eventually achieved when Mathew's returned to AT&T Labs in New Jersey during the late Eighties where he collaborated with physicist Bob Boie, using a variant of capacitive sensing to create the first incarnation of the Radio Baton[3]. Using five electrodes over the surface of a square plate, two antennas shaped like batons would increase the capacitance value when near an electrode (see **Figure 3.1**). The differences between electrode capacitive values could be used to deduce the xyz position of each baton [52].

It has gone through several incarnations including an improvement over the poor accuracy and resolution of the original design, a separation of the electronics from the sensing apparatus, and MIDI implementation. It has been used in over 40 pieces [53] and is now marketed by MarMax[4]. Noted performers include composer Richard Boulanger [52] and Andrew Schloss [54].

3.2 Buchla Lightning II Specifications

The Lightning II has been called "a complete electronic instrument" [55] as it contains a gestural controller, extensive mapping capabilities, and a sound engine. The user holds two battery operated wireless wands which each contain five infrared LEDs. The IR signals are captured by the "head" and triangulated to provide x and z coordinates (see **Figure 3.2**). The current sound engine is a Yamaha General MIDI DSP board.

[2] www.buchla.com/lightning. Accessed 30/08/07.
[3] At the time, it was also called the Radio drum.
[4] 223 Precita Ave, San Francisco, California, 94110

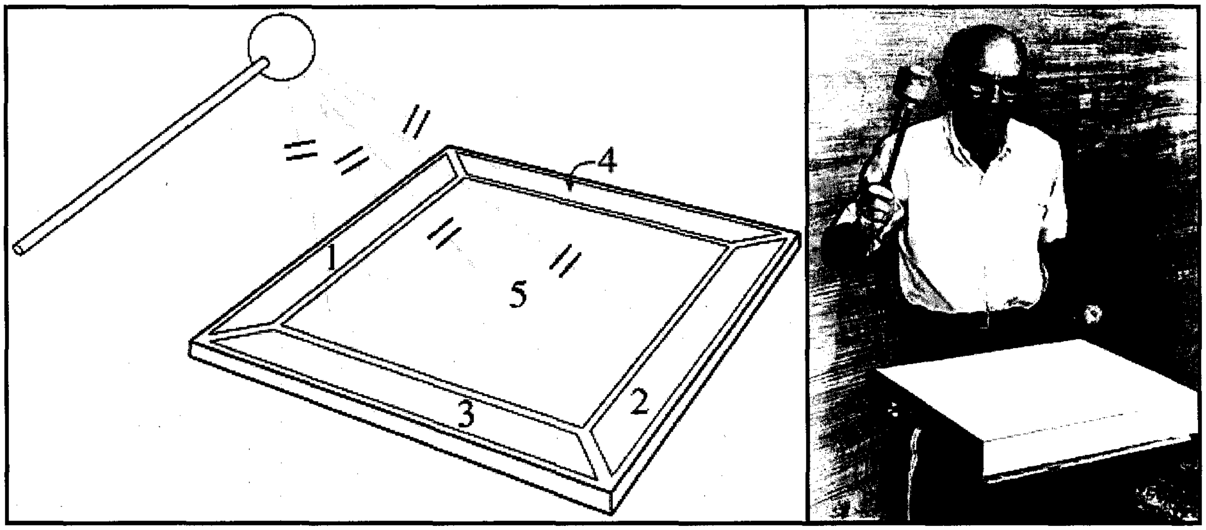

Fig. 3.1 Drawing of early Radio Baton design and M. Mathews playing it
Drawing of early Radio Baton design [52] and a picture of Max Mathews playing this design (copyright Patte Wood 1992). Note that all the electronics are encased with the capacitive sensors. This design suffered from poor accuracy in the center of the board [50].

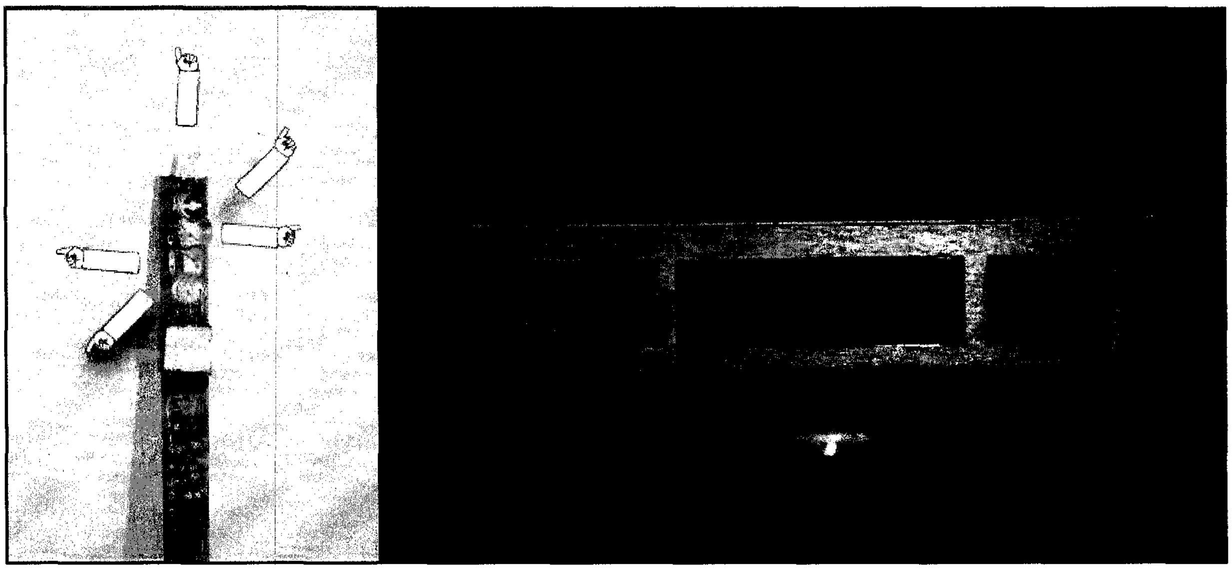

Fig. 3.2 Lighting wand electronics and Lightning head
(a)Electronics of Lighting Wand. Note the arrangement of the IR LEDs in 5 of the six possible directions. (b)The receiving head of the Lightning also provides minimal visual feedback. The LEDs show the scaled position of the wands relative to the sensing area and therefore change depending on the distance of the performer to the head.

The playing surface is a vertical plane whose size changes according to the proximity between the user and the head. As the user goes farther away, up to about 4 meters, the size of the plane increases. There are several presets included with the sound engine that change the output of the Lightning. These range from x and z coordinates to interpreted output that correspond to higher level gestural data such as circular movements and strikes. According to Joel Davel, strike latency is 40ms (see **Chapter 4**).

Haptic feedback is limited in the Lightning to the weight and feel of the wands. However, this is to be expected with a free movement controller. There is visual feedback from the head that corresponds to the position of each wand within the vertical plane, although this is highly scaled and may be difficult to note when the user is far away from the head.

3.3 Radio Baton Specifications

Originally referred to as an electronic drum controller [56], the Radio Baton consists of two batons which are in essence radio transmitters (**Figure 3.3a**). It employs a near-field capacitive measurement [57]. Each baton is driven by an oscilllator at a different frequency (50 kHz and 55 kHz respectively) so as to allow for independent tracking of both. They are tracked over a rectangular tablet that houses two pairs of shaped radio receiving antennas (**Figure 3.3b**). The first pair is shaped so that the X coordinate of each baton can be determined as close to linearly as possible; similarly, the final pair corresponds to the Y coordinate. These coordinates refer to the horizontal plane in front of the user. The incoming signals are processed by a CPU such that a vertical Z-coordinate up to 15 centimeters above the surface is also output.

It improved upon previous capacitive tablets of the time in that x and y coordinates were captured separately and it also determined the z coordinates [50]. This allowed for accuracy and latencies that were acceptable for a music performance context. In [58], latencies are listed at between 5 and 10 ms with a resolution of 0.5cm. In the current model, position coordinates are given from 0-127 to correspond to traditional MIDI values on a tablet approximately 30 by 50 cm, theoretically limiting the resolution to 0.2 - 0.4 cm per value. In practice, the position values are not linear and also depend on the vertical distance of the baton to the sensing board. It provides two data streams: one contains the continuous xyz values, while the other outputs the results from a trigger algorithm so as to capture drum-like strikes. A threshold can be set to vary the sensitivity of this algorithm.

In terms of feedback, nominal haptic feedback is achieved only if the user comes in contact with the surface. Contact is not necessary, however, to yield output, and so the Radio Baton can also be used as free gesture controller, albeit within a bounded volume. Visual feedback is also provided by the sensing surface since output can only be produced when the batons are over it.

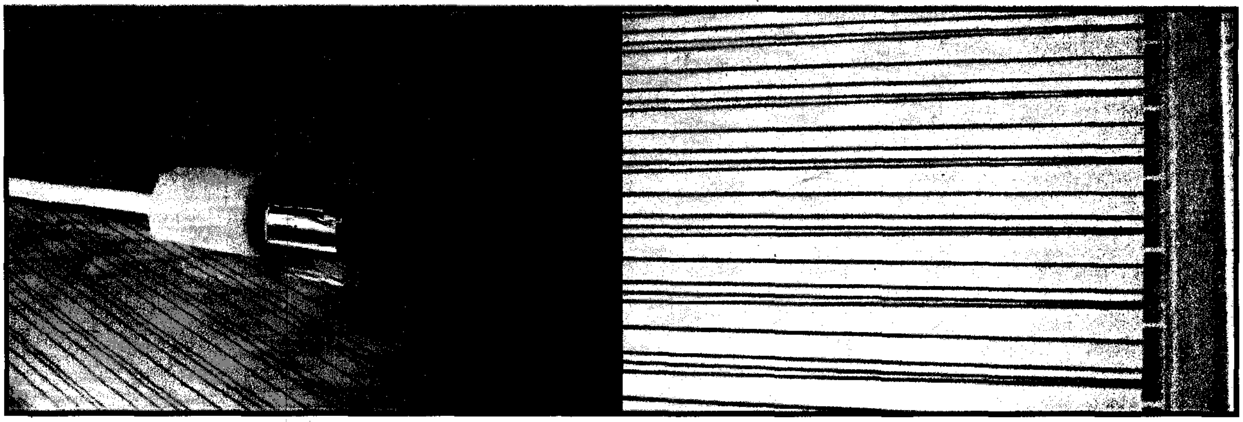

Fig. 3.3 A baton and a close up of the sensing board
A Radio Baton baton resting on the Radio Baton surface. The foam covering has been pulled back to reveal the construction of the baton tip. A wire in each baton carries a frequency around 50 Khz. The end of this wire is visible in the photo, soldered to copper tape, thus creating a transmitter. The close up of the surface reveals the shaped pair receivers. The different sized receivers will measure different capacitance values depending on the proximity and position of the batons. It is this difference that is used to give the baton position.

Table 3.1 gives a summary of the specifications of each controller. A similar comparison of these controllers can also be found in [23]. **Figure 3.4** shows a modified version of the dimension space analysis. With the inclusion of the technical specifications listed in this chapter, the differences between the controllers are more easily visible when compared to **Figure 2.3**. For instance, if a controller is needed that provides a large sensing space wirelessly and the need for low latency is less important, than the modified dimension space suggests the Lightning as the best option. If instead low latency, a certain amount of feedback, and the ability to be used in areas with considerable infrared interference is important for the performance, the Radio Baton is clearly the best choice.

Table 3.1 Summary of Lightning II and Radio Baton Characteristics

	Lightning II	**Radio Baton**
Designers	Don Buchla	Max Mathews and Bob Boie
Version	2 (1996)	2 (1997)
Sensors	infrared	capacitive
Controller Style	wireless wands	wired batons
Output Type	individual discrete tracking of two wands in x and z 10 Hz with a trigger algorithm for strikes	individual continuous tracking of two batons in 3 dimensions (z less accurate above 5cm) at 10Hz and discrete according to trigger algorithm
Output Protocol	MIDI	MIDI
Output Parameters	position and strike velocity evenly discretized 0–127 in each dimension	position unevenly discretized 0–127 in each dimension
Range	1–4 m from sensing head	15 cm above sensing board
Feedback	minimal visual feedback by sensing head	minimal haptic feedback for strikes
Reported Strike Latency	40 ms	5–10 ms

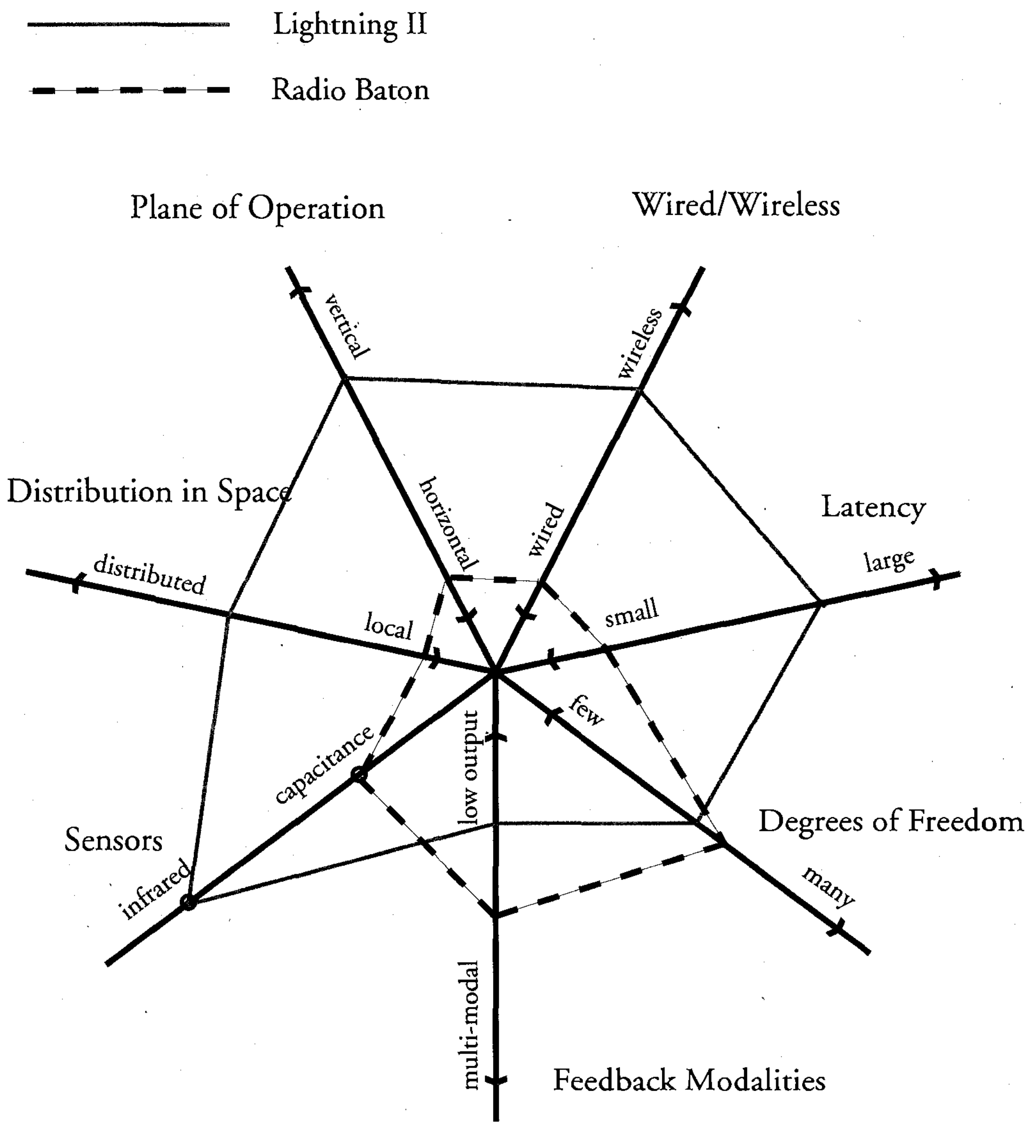

Fig. 3.4 Modified dimension space analysis of Lightning and Radio Baton
Dimension space analysis of Lightning using modified criteria from [32].

Chapter 4

Long-time User Insights

4.1 Overview

Among the many reasons why the Lightning and Radio Baton are unique is their continued availability. It is rare for MIDI controllers being marketed relatively unchanged over 15 years after they were introduced, especially ones as unorthodox as these[1]. This longevity has allowed for expert users, some with over 10 years of performance experience on these devices.

In order to get a sense of usage over time, informal questionnaires were sent out to the known professional users of both controllers, which totaled under ten. Five questionnaires were received, three from Lightning users (Joel Davel, Mark Goldstein,and Forrest Tobey) and two from Radio Baton users (Richard Boulanger and Andrew Schloss). This small set of responses is to be expected when so few are known to play the instruments under study. The questions and resulting answers were informal in nature thus contributing an important qualitative aspect to the present study. Each question and response is reported in the following tables. Answers have been paraphrased for presentation. Performers 1-5 correspond respectively to the respondents mentioned above.

4.2 Comments

The amount of experience amongst the respondents is noteworthy (see **Table 4.1**). It has been proposed that over 10 years of formal training on a particular acoustic instrument qualifies a musician as an expert [59]. While there is no formal pedagogy for gestural controllers, the ability to become an expert user of these devices should be assumed, in the same way as race car drivers

[1] "...an instrument has to exist long before performance techniques can be developed and a repertoire arises. Because of this, the market for the instrument doesn't exist for many years after the R&D that goes into developing a truly new instrument. With short term profits a primary motive, the big corporations are simply not interested [in novel designs]." [20]

Table 4.1 Experience
How long have you been using the Lightning/Radio Baton?

Performer	Lightning	Radio Baton
1 (JD)	14 years	
2 (MG)	15 years	
3 (FT)	15 years	
4 (RB)		20 years
5 (AS)		20 years

are assumed to be more skilled drivers than the average.

Table 4.2 Usage
What were some of your favorite uses of the Lightning/Radio Baton?

	Lightning	Radio Baton
1	solo performance, accompaniment of dancers	
2	performance of compositions for Lightning, accompaniment of silent films, children's theatre, medical rehabilitation	
3	solo performance, as part of jazz ensemble, score-following/conducting, spatialization	
4		performance of compositions for Radio Baton w/ voice, orchestra, manipulation of video, spatialization
5		performance of compositions for Radio Baton, improvisation with acoustic instrument musicians, as part of world music ensemble

The responses in **Table 4.2** seem to indicate that the controllers are extremely adaptable to as many different music performance settings as established acoustic instruments are (as well as some that acoustic instruments cannot be used in, such as the manipulation of video). Also evident in the answers is that many opportunities to perform arose almost solely from the novelty of the controllers, the "shiny new gadget" phenomenon. For example, Performer 3 was approached to perform for millenium celebrations in Times Square, New York for what he supposes was this reason. The novelty aspect also had drawbacks: Performer 1 recalls a dance accompaniment performance where the program notes did not specify his usage of the Lightning. As a result, the audience perceived the movements as dance-oriented rather than those of a music instrument performance.

Table 4.3 Musical Education
Do you play any other instruments, acoustic or electric? How has this informed your performance/compositional technique regarding the Lightning/Radio Baton?

1	acoustic mallet percussion, movement training in theatre/circus skills
2	piano, percussion
3	piano, conducting
4	guitar, trumpet, piano, voice, data-glove, theremin, laptop
5	percussion

According to the responses in **Table 4.3**, almost all respondents are either percussionists, pianists, and/or conductors and admit their respective approaches to these percussion-like interfaces owe a great deal to their acoustic instrument training. Performer 2 finds that "realizing when (and when NOT) the gestural repertoire of the Lightning fits percussive technique and sounds sent me off on a path of exploration that continues today". Performer 5's percussion training has raised his expectations of the performance behaviour of the Radio Baton in terms of strike latencies. Performer 1 recognizes that the emphasis in mallet percussion on proper mallet placement in space has influenced his approach to the Lighting. He also mentions the theatrical nature of playing the Lightning. Finally, Performer 4 notes that musicality can be transferred: "the more musical you are, the more musical your music and your performance of ANY instrument". Contrasting these answers with those from **Table 4.2** suggests acoustic musicians can take these controllers beyond their usual performance settings, all the while drawing on their acoustic instrument training.

Regarding the answers in **Table 4.4**, although only Performer 1 explicitly worked on the development of these interfaces, all respondents had close relationships with the controller designers. Performer 2 eventually collaborated with the Don Buchla to build other controllers and Performer 3 had several conversations with Buchla about possible design improvements to the Lightning. Performer 4 has worked closely with Max Matthews; his "musical use of the system influenced the design of the hardware and the features of the software." It is interesting to ask whether being in close contact with the designer kept the musicians motivated to continue using the interfaces.

The answers in **Table 4.5** can be viewed from two perspectives. The first revolves around the nature of a gestural controller in the schema of a DMI (see **Figure 1.1**). In Performer 2's own words:

Table 4.4 Role

What role have you played in the development of the Lightning/Radio Baton?

	Lightning	Radio Baton
1	Lightning I repairs, primary technician for beta-testing, preset development, soldering and assembly of Lightning II, circuit board layout for Lightning III	
2	none	
3	none	
4		composer/collaborator
5		none

Table 4.5 Approach

Do you approach the Lightning/Radio Baton as an instrument or a controller?

	Lightning	Radio Baton
1	both	
2	instrument	
3	gestural controller	
4		instrument
5		both

> "A controller is a device that transduces a physical gesture to a defined control signal. The signal is then sent to some sound-producing apparatus. A musical instrument is...a device or system...for real time musical performance...concerned with expressive and reliably repeatable control of...musical parameters."

In this sense, Performers 2 and 3 utilize the sound engine of the Lightning with its mapping abilities in many of their performances and therefore use it as an instrument. It is impossible to do so with the Radio Baton as it does not have it's own sound engine, thereby rendering it a gestural controller by default. Performer 4 substantiates this by mentioning "the Radio Baton is what turns my laptop into a musical instrument."

The second perspective is more philosophical in nature involving the question of when does a gestural controller become a musical instrument. Performer 1 feels the Lightning is "a controller that only becomes an instrument after a lot of practice". This is echoed by Performer 2's remark that "almost anything can be an instrument in the hands of an accomplished player". This would seem to support the claims regarding expertise [59] in which time spent practicing is essential.

However, Performer 5 approaches these terms as states of operation which can be intermingled in a performance: "I use it in both modes, sometimes simultaneously and always jumping from one mode to the other. To me it would not be worth playing if it couldn't occupy both roles."

Table 4.6 Mapping

What have been some of the more successful mapping strategies you have employed with the Lightning/Radio Baton? Do you find certain paradigms or mapping strategies more easily 'fit', for example as a percussion controller or "an expressive tape player"?

	Lightning	**Radio Baton**
1	virtual conductor, mallet keyboard, large drums, diatonic scales played with horizontal movement and button switch, use and tuning of sound engine presets	
2	percussion controller, control of continous parameters spatially, piano controller, layers, use and tuning of sound engine presets	
3	virtual conductor, max patches and external synths	
4		conductor, soloist, improvisor, timbre sculpting, note-based, remixing, spatialization, triggering
5		flying over surface to trigger events, image/video controller

For Performer 2, each different mapping scheme creates a new instrument (see **Table 4.6**. As evidenced in the responses, these controllers can take the (conceptual) form of many existing and novel control paradigms which do indeed resemble completely different musical instrument contexts. From Performer 4:"It is NOT a percussion controller - that limits its function, subtlety, and role to something too primitive and simple. The construction does influence its perception, but not it's use or potential."

The changes proposed by the Lightning users run the gamut between performance, usability, and ergonomic improvements (see **Table 4.7**). Performer 5 has improved the Radio Baton [60] physical interface such that he is now satisfied with the latency and feel of it. His main problem now is no longer the technical limits of the instrument, but just to "create sounds that are vivid and malleable". Performer 2 has invented his own notation for scoring his Lightning performances,

Table 4.7 Modifications
Is there anything you would change (or have changed) about the Lightning/Radio Baton in terms of ergonomics, technical performance, etc.?

	Lightning	Radio Baton
1	**Would change**: strike latency time of 40 ms	
2	**Would change**: software for editing presets, wireless connection between head and sound engine, haptic feedback in wands	
3	**Would change**: sensing of wand position in all 3 dimensions, more ergonomic wand grip, change wand to one resembling conductor baton	
4		**Have changed**: software has allowed for all necessary changes
5		**Have changed**: foam moved to surface, batons changed to modified drum sticks, computer interface through audio interface

as well as a symbolic notation for modifying and creating presets on paper.

4.3 Conclusions

Several interesting points seem to emerge from the responses. It is apparent that these interfaces have been designed well enough to sustain the interest of these particular musicians. Given access to the designer, the musician will suggest design changes or even undertake the changes themselves, thereby prolonging the life of the interface and improving its technical specifications.

Also, there seems to be a correlation between the physical interface of these controllers and the acoustic musicians it attracted. As the sample for this questionnaire is much too small to make any large generalizations, it is still interesting to note that percussionists and conductors were drawn to these gestural controllers that use sticks /batons. Whatever the connection between user acoustic instrument training and the physical interface, this did not limit the performance contexts in which the controllers were used. Respondents included many different types of music instrument performance contexts as well as other contexts such as video and spatialization control.

Mapping is at at least as important to musicians as the physical interface, and even more so over the long term. Using a different mapping strategy results in a new control paradigm to explore. This ability to easily change such an elemental part of the instrument seems to be part of the appeal of these controllers. Conversely, the challenge of finding a good mapping scheme also seems to be part of that appeal.

Chapter 5

Motion Capture of Percussion Exercises

Thus far, the Lightning and the Radio Baton have been considered in light of their technical characteristics and the opinions of long time users. To further develop this comparison, motion capture of percussionists on the controllers in question was performed.

This part of the study places the controllers within a music instrument performance context, specifically that of percussion instruments. The controllers resemble percussion instruments insofar as they have sticks as part of their physical interface. This context allows us to explore to what extent traditional acoustic instrument playing techniques may be used with digital instruments that resemble them.

5.1 Experiment Setup

Over the course of one year, the experiment setup took shape. The goal, as stated above, was to create conditions where acoustic instruments and digital instruments could be quantitatively compared in terms of playing technique. The fact that both controllers under study employ sticks or wands as the physical interface led to percussion as the acoustic instrument context. All experiments took place in the Input Devices and Music Interaction Lab at McGill University.

The first version of this experiment took place in July 2006 and focused on the hardwired capabilities of each controller. Preset 67 of the Lightning sound engine is a mock drum set, with a kick drum, a snare drum, and a high-hat sample horizontally mapped left to right, equally spaced within the sensed area. Strike velocity is automatically mapped to sample loudness in this preset. Using a MaxMSP patch, the Radio Baton board was divided into three equal parts and mapped similarly to the Lightning preset (see **Figure 5.1**). The hardwired Radio Baton strike and strike velocity information output as poly key pressure values was also routed via MaxMSP to the MIDI port of the Lightning sound engine in order to compare both instruments using the same sound set.

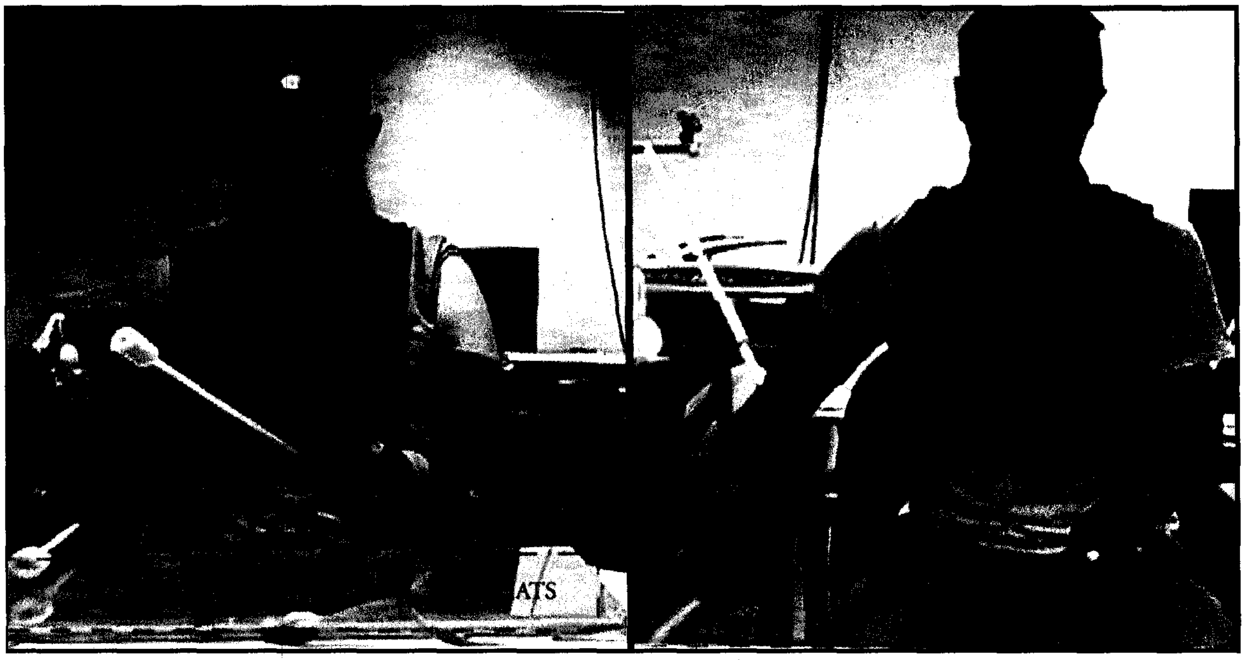

Fig. 5.1 Experiment 1 setup
The overlaid squares show the mapping of the first set of experiments.

Two subjects from the jazz performance program in the Faculty of Music at McGill University were asked to improvise in three different styles, each at a different tempo, for a total of 3 performances per subject. The tempos were provided with an audible click track. The performances were captured using 8 Polhemus markers on the upper torso, the hardwired MIDI output that was recorded in Max, and two DV video streams at 180 and 90 degrees. Each performance lasted roughly two and a half minutes. The difficulty in quantitatively analyzing and comparing improvised musical material led to a redesign of the experiment.

In February 2007, the second version of the experiment was carried out. This time, the Lightning and Radio Baton were mapped, through a MaxMSP patch, to a single tom drum sound instead of multiple instruments. Through consultation with McGill University percussion professor Fabrice Marandola, 20 single drum technique exercises were isolated, along with three exercises from [61]. Two subjects from the graduate classical percussion program from the Faculty of Music at McGill University were invited to perform the material on an acoustic tom drum, a Roland V-Drum, the Radio Baton, and the Lightning, in that order. The test instruments were chosen so as to provide a spectrum from an acoustic instrument to an instrument-like controller (the Roland V-Drum) that emulates the acoustic instrument, to the controllers in this study, which straddle the line between instrument-inspired and alternate controllers [23]. It was assumed this progression would reveal performance differences of the same material. The gestural controllers were all mapped to a physical model of a tom drum using the Tassman modelling software. Performances were captured using 8 Polhemus markers on the upper torso and one DV video stream, all of which was routed to and recorded in MaxMSP. The volume of data, along with data syncing and truncation issues in Max and the poor quality of the video stream, led to the final revision of the experiment.

The final version of the experiment was carried out in May-July 2007 and retained several aspects of the previous version. The progression from acoustic drum, to V-Drum (which, despite being a digital input device, is clearly designed to mimic an acoustic drum), to the Radio Baton and Lightning was kept. Instead of using the Tassman physical model all three digital controllers were mapped to a tom drum sample controlled by the V-Drum sound engine. Preset 67 in the Lightning and the hardwired trigger algorithm in the Radio Baton were used to map strike velocity to loudness.

The original set of 23 exercises was shortened to the following subset, all performed at 120 beats per minute:

- single strokes, forte (SSF)
- single strokes, piano (SSP)
- double stroke rolls, forte (DSRF)
- double stroke rolls, piano (DSRP)

It was thought that this subset of exercises was the smallest that would clearly show differences in playing technique concerning bodily control and timing. Timing is obviously paramount in percussion performance, and percussion pedagogy often advocates "letting the stick do all the work" while suppressing upper body movement as much as possible [61]. Each subject played the entire set of exercises on the tom drum, followed by the V-Drum, the Radio Baton, and the Lightning. In the following analysis, only the forte loudness conditions of the single stroke and double stroke roll exercises are considered.

The DV video stream, with a resolution of 720 pixels wide by 480 pixels high was changed to a High Definition video stream. A JVC GR-HD1, with a resolution of 1280 pixels wide by 720 pixels high, was turned 90 degrees so as to capture the entire subject from the knees on up at a distance of roughly one and a half metres. Furthermore, a high speed shutter setting was used to minimize the temporal skewing of stick motion. The reduced aperture time of this setting required three 750 watt lights to be centered on the subject to provide adequate color contrast. Finally, the subject was placed in front of a green screen to allow for easier video analysis. In order to

Fig. 5.2 Frame from Subject 1 SSF video
Videos of each session were made such that each exercise on each instrument was synced and placed side by side to facilitate movement comparisons and the parsing of the motion capture files. Syncing was performed in Final Cut Pro using the click track on the audio channels. Note the positions of the Polhemus markers on the upper torso.

sync the various data streams, a 120 bpm click track was played throughout each experiment. This allowed the video examples of each exercise on each instrument to be synced across each performer (see **Figure 5.2**) by manually aligning the associated video and sound files in the video authoring software Final Cut Pro. These videos were pivotal in the manual parsing of the motion capture files. The 8 Polhemus markers were positioned on the upper torso, their output of 3D position and orientation data streamed to text files and timestamped using the CPU system time of the host Linux computer for an average sample rate of 30Hz per marker, although this rate was found to irregularly vary (see **Figure 5.3**). Nonetheless, this system was sufficient in capturing the necessary data to observe movement, speed and timing differences across each instrument for a particular subject. This research was conducted under the ethics certificate "Analysis of Expressive Performer Movements", REB File 186-0306.

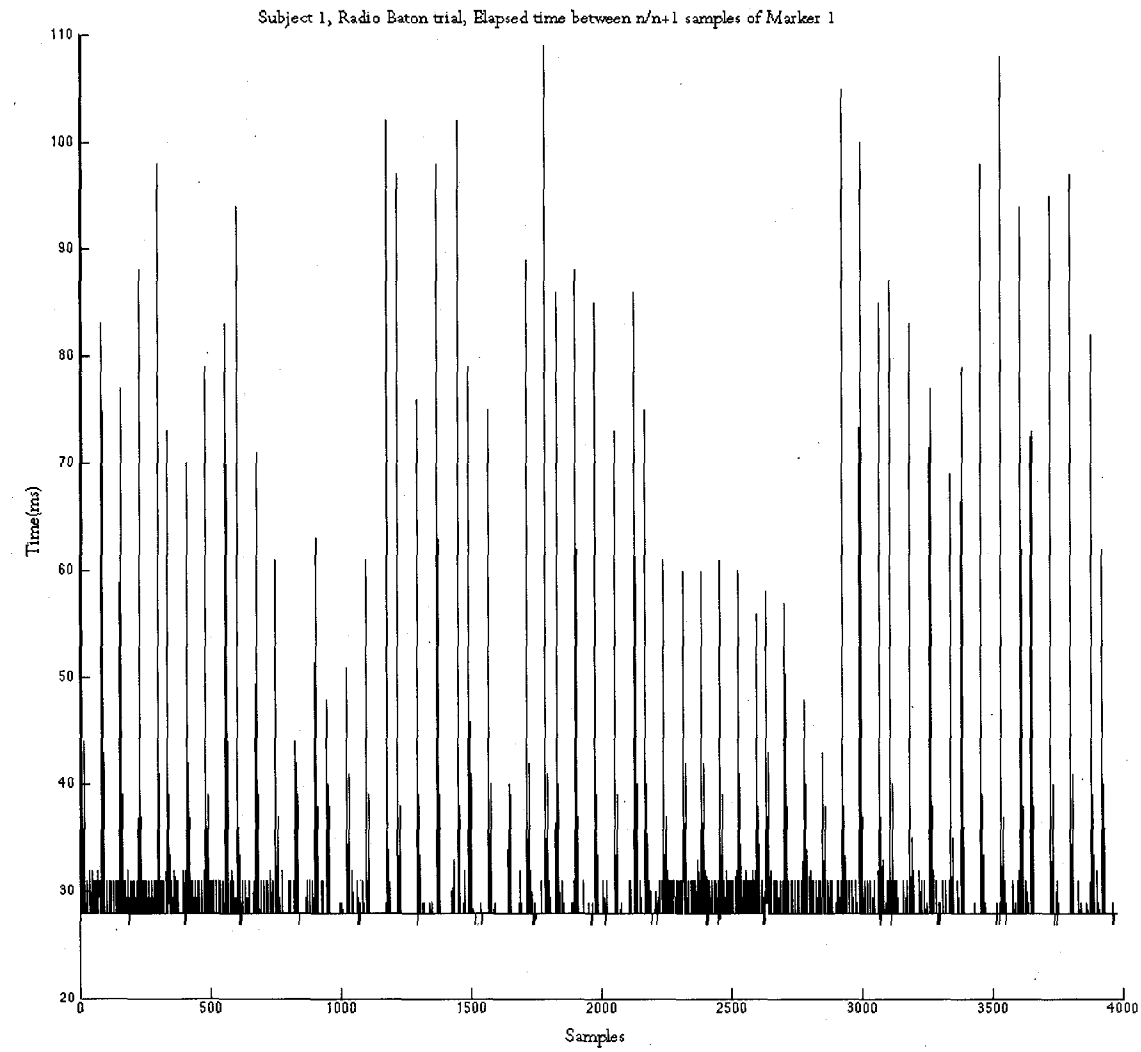

Fig. 5.3 Graph of typical variation in Polhemus marker sample times
This graph shows the time differences between n and n+1 samples of the Polhemus data from Subject 1's Radio Baton trial. Although most samples are taken every 27 or 33 milliseconds, there are many that are captured after longer values giving only an average sample rate of approximately 30Hz.

5.2 Experiment Results

5.2.1 Subjects

All three subjects were from the classical percussion program in the Schulich School of Music, with at least 9 years of playing experience. Subjects were asked to fill out a questionnaire prior to performing regarding their percussion backgrounds, the results of which are summarized in

Table 5.1.

Table 5.1 Subject Background

Subjects	1	2	3
Sex	male	male	female
Handedness	left	right	right
Experience (years)	9	20	9
Level	advanced	advanced	advanced
Sight-Reading Proficiency	very good	excellent	excellent
Experience with Controllers	no	yes	no

Subjects played the entire set of exercises on one instrument before passing to the next in the following order: tom drum, V-Drum, Radio Baton, and Lightning. A click track of 120 bpm was played throughout the entire session. The only performance limits subjects were asked to respect was to allow least 4 beats between exercise and to limit their movement as much as possible when not performing.

The wired Polhemus markers were placed over the upper body of each subject, namely on the head, the back, each biceps, each forearm, and the back of each hand for a total of 8 (see **Figure 5.2**). The video data suggested that the subjects move very little of their torso during performances beyond inertial effects: the majority of the movement appeared in the forearms and consequentially the hands, and much of this is in variations of the height of the hands (z values). The sensing technology of each controller, especially the infrared wands of the Lightning, makes it impossible to track the wands using the Vicon wireless infrared-optical tracker in the IDMIL. It was considered a major performance hindrance to attach the wired Polhemus markers to the wands[1], so the motion of the wands was not captured. As a result, the following analysis is based on the movement characterized by the hand height variations along with the timing information present in the sound files. Audio onset intervals for the single stroke exercises was performed in Matlab using peak threshold values (see **Figure 5.4**). To provide the comments of the subjects themselves, this analysis is followed by the results of post-performance subject comments.

5.2.2 Alternating Single Strokes, Forte Loudness

The first exercise on each instrument was single strokes of alternating hands accompanying a click track at 120 bpm. Subjects played 8 to 32 strokes at a forte loudness until they were comfortable with the quality of their performance, paused for at least 4 beats, and followed with 8 to 32 strokes

[1] Attaching the active-sensing Polhemus markers to the wands could not only adversely affect wand movement but potentially break the markers themselves.

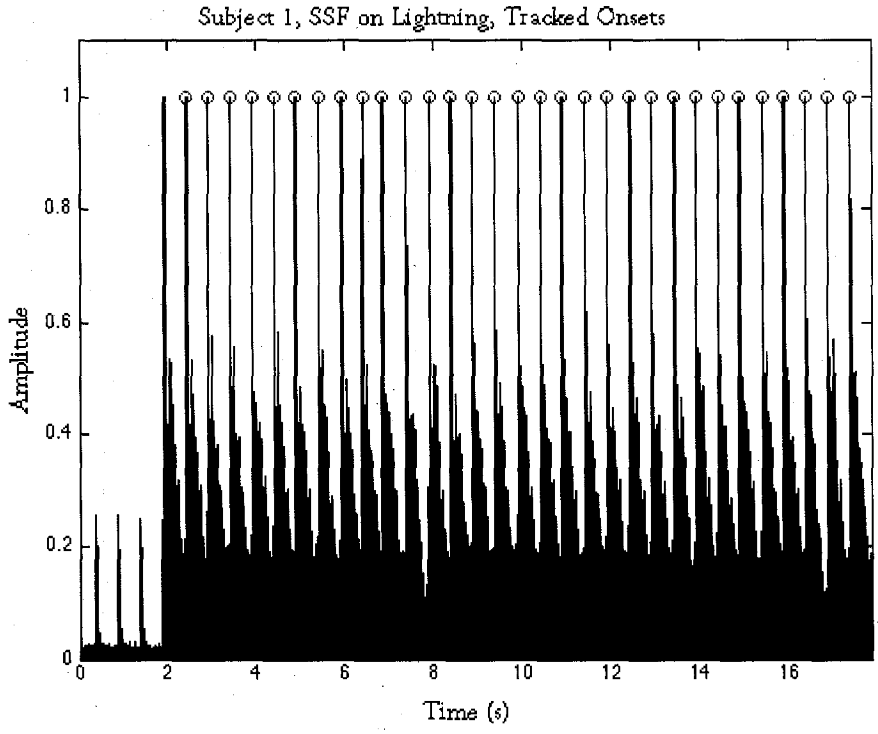

Fig. 5.4 An example of tracked inter-onset intervals in SSF trials
This graph shows the found inter-onset intervals from the audio of the Subject 1's performance of alternating single strokes at a forte loudness on the Lightning. The left channel of the 44.1 kHz audio signal is fullwave rectified and analyzed for peaks above a manually set threshold. Since each peak in the audio shown here contains several values over the threshold, only the first value to go over the threshold is kept. The first major peak is considered to be time zero and therefore not recorded, while the three initial smaller peaks are also discarded as they arise from the click track.

at a piano loudness.

Figure 5.5 shows the hand height variations of Subject 1's single strokes forte condition. The tom and V-Drum conditions show very similar periodic peaks, with the Radio Baton condition periodic within a smaller range and the Lightning condition performance slightly less periodic. The timing information, however suggests that the Lightning condition comes closest to the ideal condition of one strike every 0.5 s (see **Figure5.6**).

Figure 5.7 shows the hand height variations of Subject 2's SSF performance. While all four graphs show periodic motion, Subject 2 uses much larger (and therefore faster) strokes on the Lightning to compensate for the lack of membrane rebound. In an actual performance setting in which single strokes frequently occur at a fast tempo, this extra effort might dissuade the use of the Lightning so as to limit performer fatigue. During the Radio Baton condition, the trigger

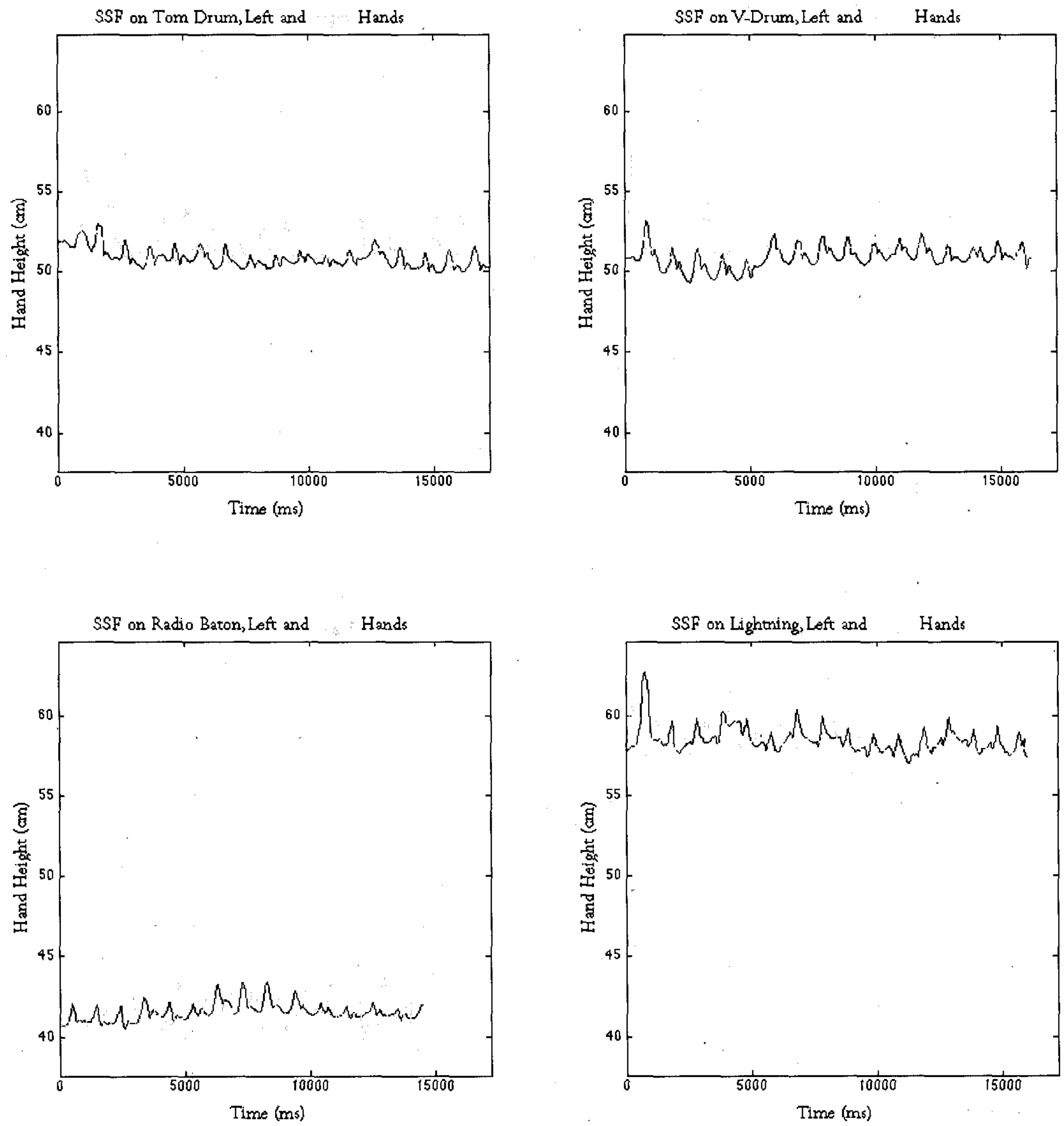

Fig. 5.5 Subject 1 - Alternating Single Strokes, Forte Loudness

algorithm failed to capture three strokes (see **Figure 5.8**), another factor which would favor against real performance usage. The IOI averages once again reveal the Lightning condition as being the most accurate, followed by the V-Drum (see **Figure 5.9**).

Figure 5.10 shows the third subject's hand height variations during the SSF performance. The video shows that Subject 3 begins each exercise by an ancillary gesture [62], i.e. the raising of the right hand before the first strike. The graphs show that after this initial spike, the range of the strike gestures lowers over time. This is especially evident in the graphs of the three

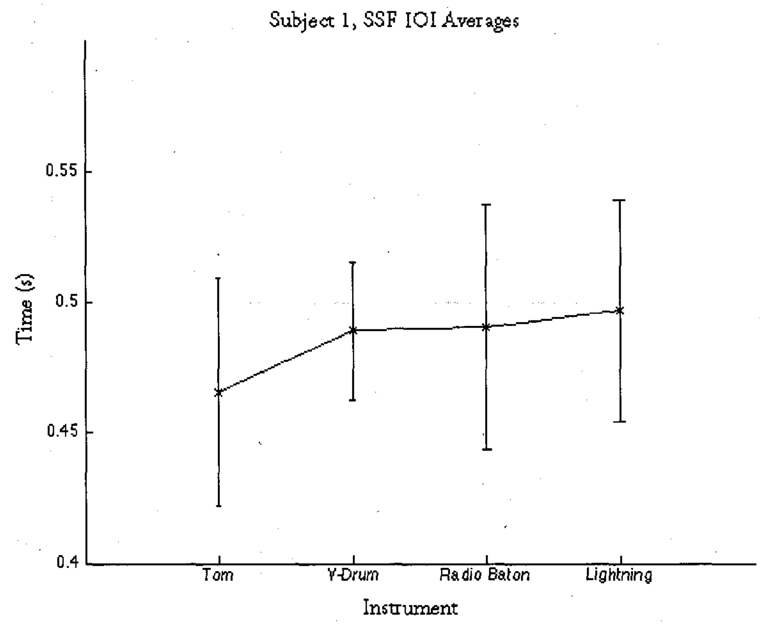

Fig. 5.6 Subject 1 - Alternating Single Strokes, IOI averages
The inter-onset interval averages for each instrument for Subject 1's alternating single stroke exercise at forte loudness. Also shown are the minimum and maximum IOIs in each condition.

gestural controllers. Once again, the IOI averages reveal the Lightning performance to be the most accurate followed by the V-Drum performance (see **Figure 5.11**).

5.2.3 Double Stroke Rolls, Forte Loudness

Subjects were asked to play double stroke rolls on each instrument at a forte loudness at a 120 bpm. The hand height variations for each participant is summarized in **Figures 5.12-14**. After this part of the experiment, Subject 3 commented that musically speaking, a percussionist would not play a double stroke roll at 120 bpm to achieve the 'roll' sound, but would instead play a press roll, where the stick is made to bounce on the membrane several times before lifting the hand. As a result, different strategies were used during this exercise. The graphs show that Subject 2 and 3 used 6 strokes (3 per hand, alternating) per quarter note. Subject 1 instead chooses to ignore the click track or a set number of strokes per quarter note. In the Lighting condition for Subject 2, once again larger strokes are needed to play the exercise. The Lightning condition for Subject 3 also shows more erratic height variations than the other three conditions. The audio of the each participant's Radio Baton and Lightning trials consistently contained the same missed triggers that showed up in only some single stroke results. It would seem that the trigger algorithms for each controller were unable to deal with the stroke density required to perform this exercise.

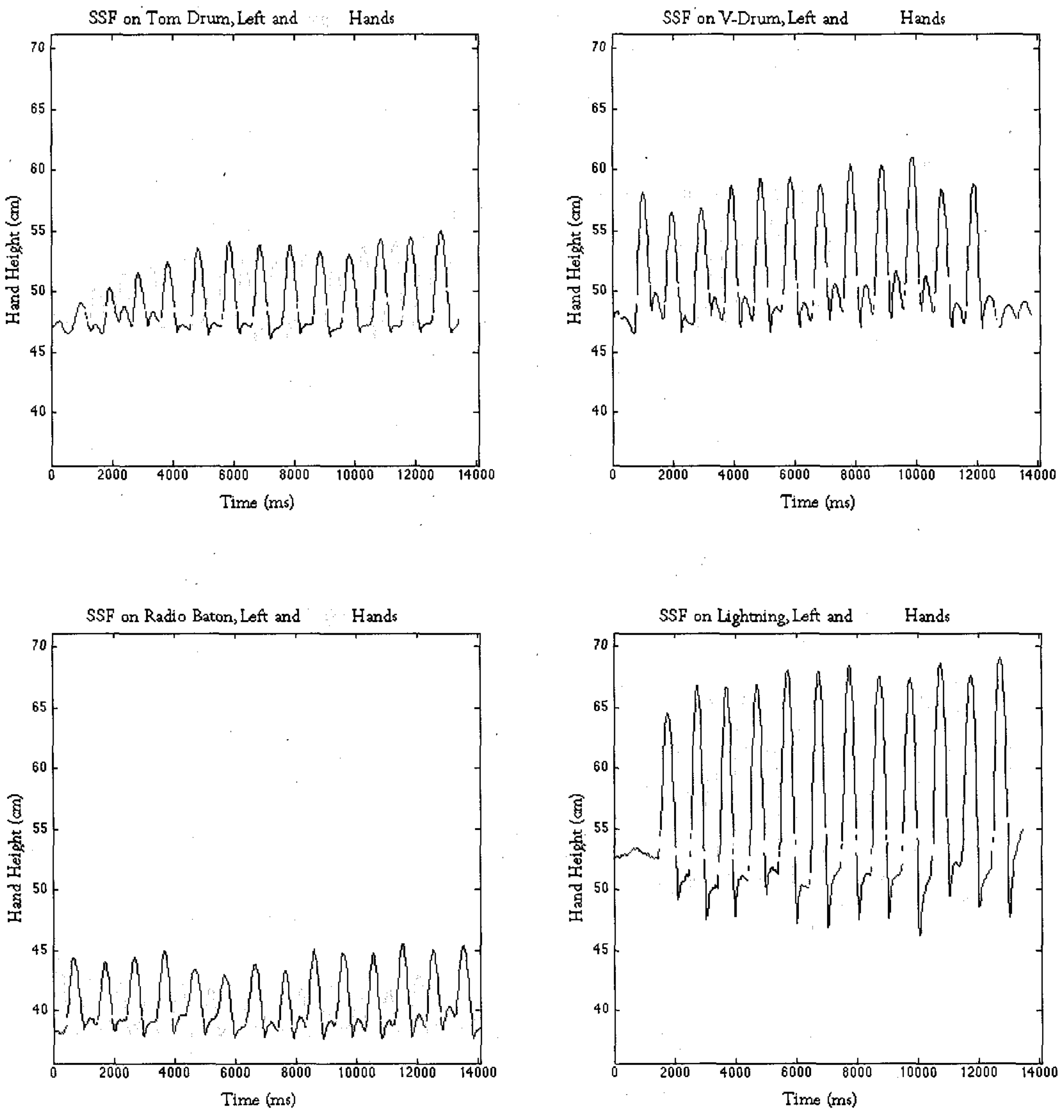

Fig. 5.7 Subject 2 - Alternating Single Strokes, Forte Loudness

This exercise, largely dependent on stick-membrane interaction and rebound, was expected to be difficult using the Radio Baton and the Lighting. The former's batons have rebound-inhibiting foam at the tips while the latter lacks a surface.

5.2.4 Post-Experiment Subject Comments

After the participants had concluded the experiment, they were asked to rate the the gestural controllers they had performed with in terms of a set of features. The ratings is reproduced in its

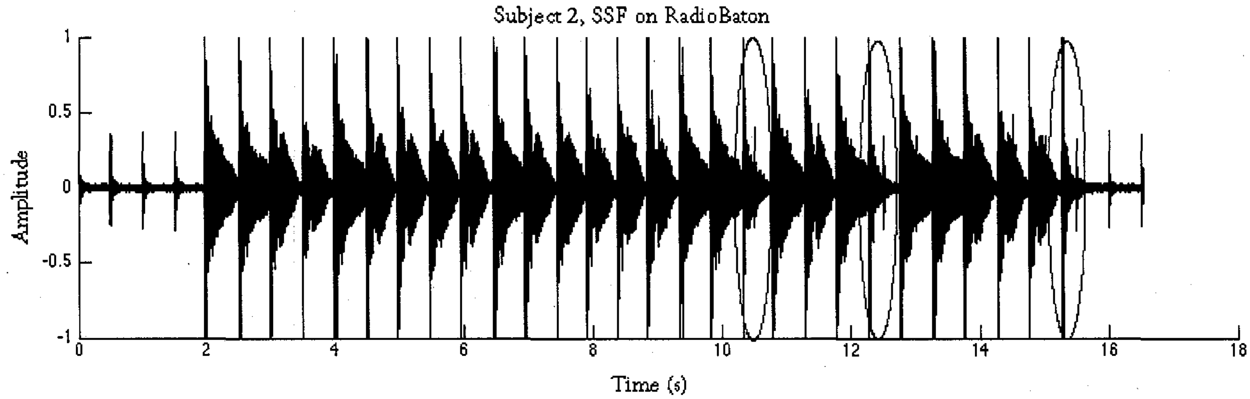

Fig. 5.8 Subject 2 - Alternating Single Strokes, Forte Loudness Waveform
The three ellipses show where the Radio Baton trigger algorithm did not capture a strike. The peaks that are seen arise from the sound of the baton hitting the sensing board.

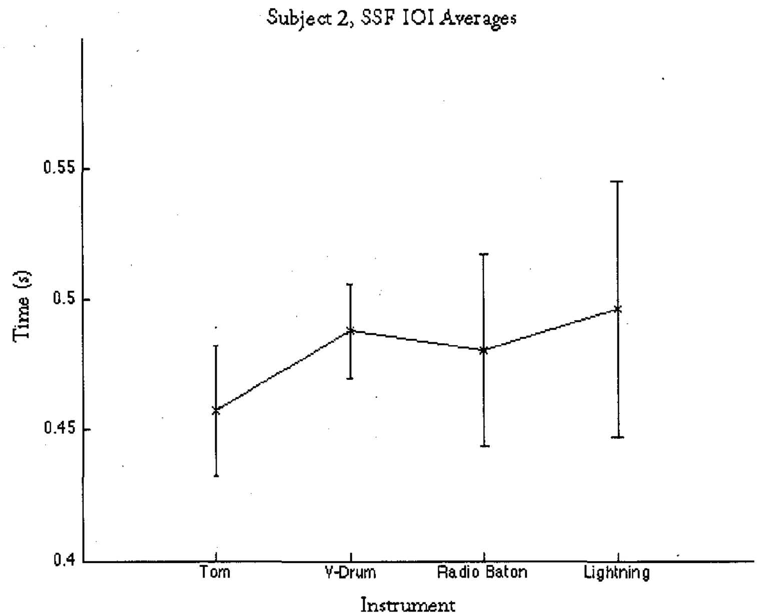

Fig. 5.9 Subject 2 - Alternating Single Strokes, IOI averages
The inter-onset interval averages for each instrument for Subject 1's alternating single stroke exercise at forte loudness. Also shown are the minimum and maximum IOIs in each condition.

entirety in **Figure 5.15**; the results of the questionnaire are reported in **Table 5.2**.

Overall, the V-Drum was considered by far the best facsimile of an acoustic drum, followed by the Radio Baton and the Lightning, as seen in the Acoustic Likeness rating. In fact, the

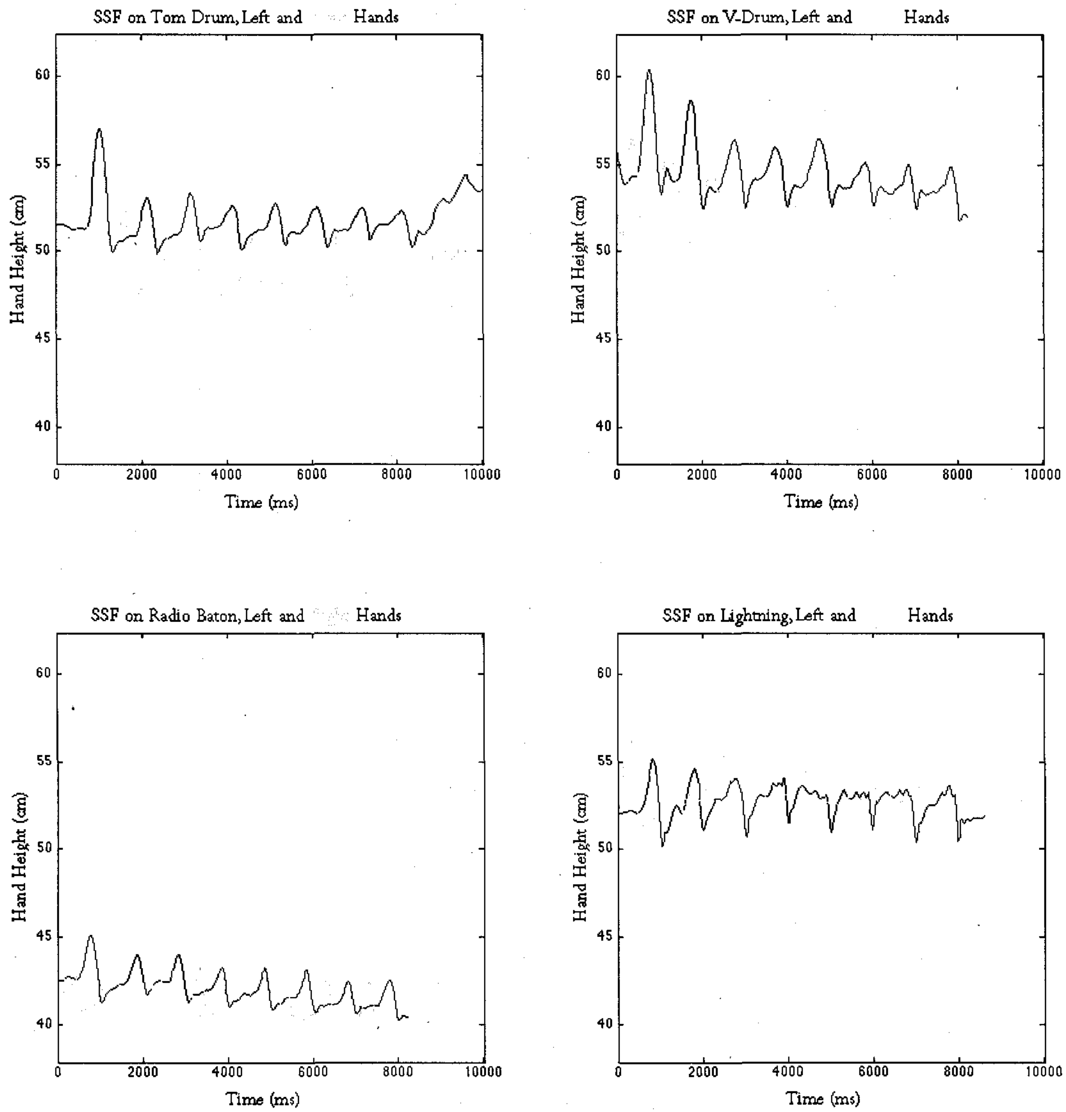

Fig. 5.10 Subject 3 - Alternating Single Strokes, Forte Loudness

instrument-like V-Drum scored highest in all areas. The Radio Baton, considered the instrument-inspired controller, scored higher than the Lightning in all ratings except for timbre expressivity and expressivity. This is interesting in light of the fact all gestural controllers in the trials were only controlling the loudness of a tom drum sample. The impressions about timing accuracy are also interesting as they contradict the results of the single stroke condition. The Lightning was seen as the least accurate, yet scored highest in the single stroke condition.

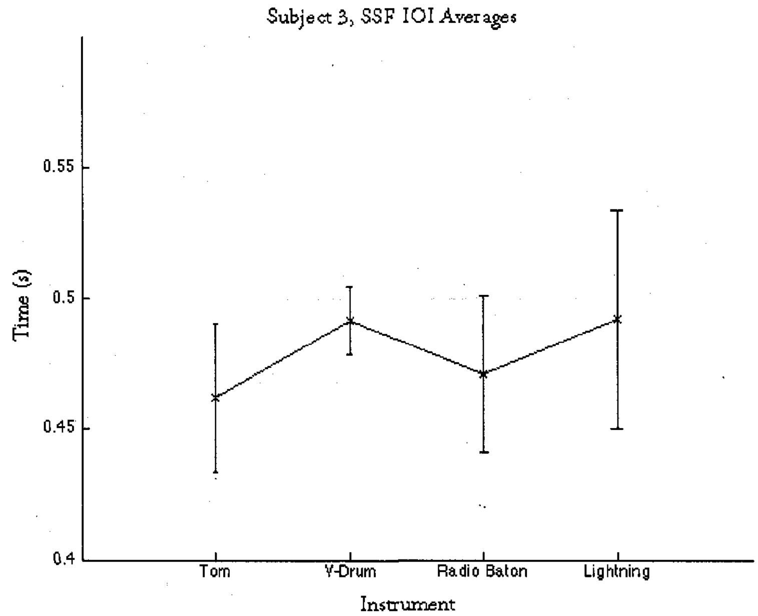

Fig. 5.11 Subject 3 - Alternating Single Strokes, IOI averages
The inter-onset interval averages for each instrument for Subject 1's alternating single stroke exercise at forte loudness. Also shown are the minimum and maximum IOIs in each condition.

5.3 Conclusion

This part of the study was conducted to observe the relationship between acoustic instruments and the gestural controllers that resemble them. The experiment required 3 percussionists to perform two elementary percussion techniques, alternating single strokes and drum rolls, on an acoustic drum, a V-drum, a Radio Baton, and a Lightning. The three gestural controllers were mapped such that the hardwired strike recognition algorithms of each controller were used.

The double stroke roll condition seemed to confirm the participants' opinion that the V-Drum was the superior of the three gestural controllers in terms of accurately translating percussion technique. The strike velocity recognition algorithms of both the Radio Baton and the Lightning seemed to break down during this condition resulting in missed strikes and inaccurate strike velocities.

The single stroke condition had some interesting results in that the Lightning, the one controller without a membrane, was the most accurate in terms of average strike timing accuracy among all four instruments. This may be accountable to each subject playing the Lightning last in each experiment session, therefore acclimatizing themselves to the tempo. This would not explain, however, why the the V-Drum, which was always played second, scored higher in terms

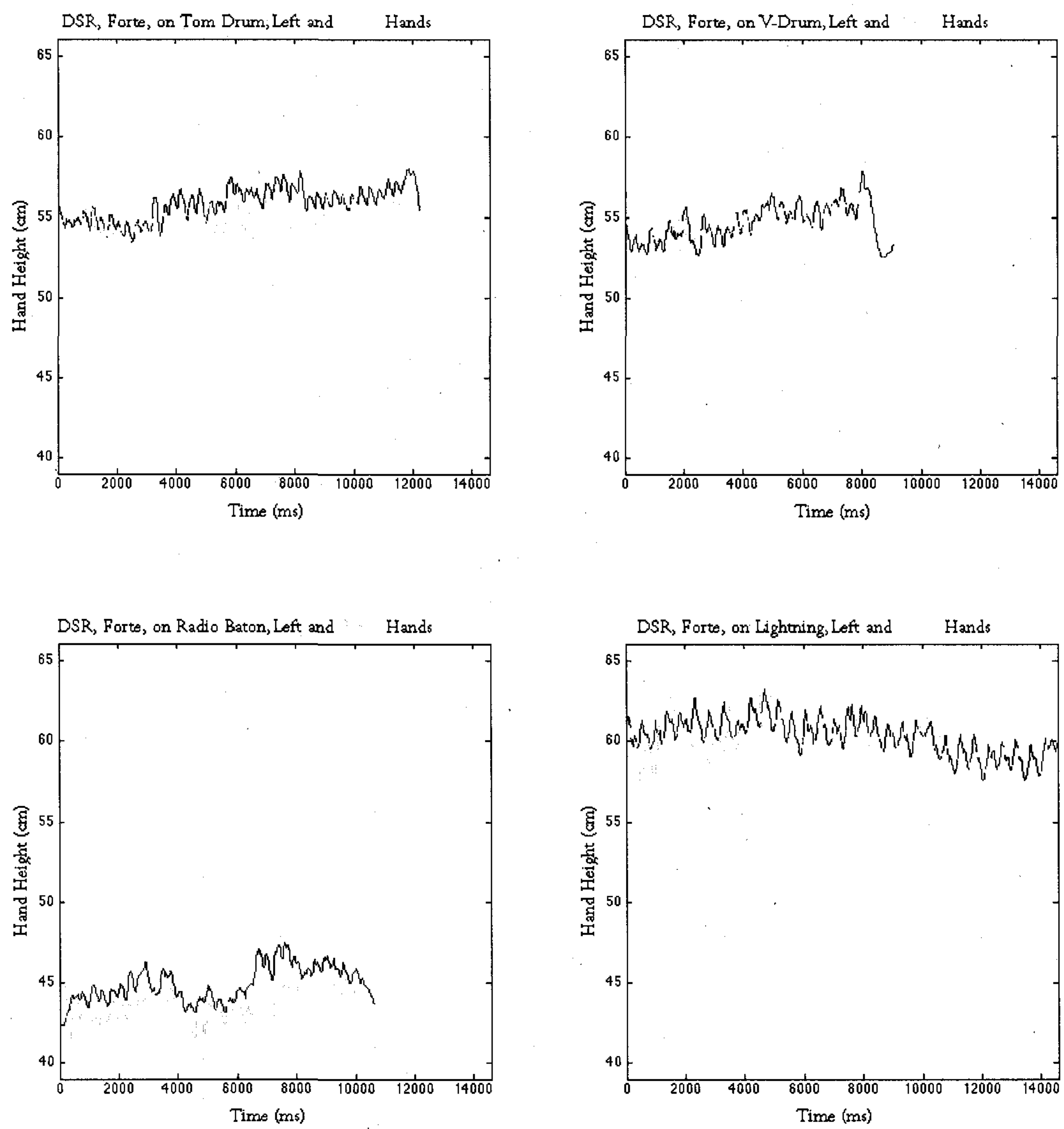

Fig. 5.12 Subject 1 - Double Stroke Rolls, Forte Loudness

of timing accuracy than the Radio Baton, which was always played third.

Altogether, the preliminary conclusion is that the Radio Baton and Lightning could be considered adequate drum controllers depending on the task involved. The mapping layer is as important as the physical interface in this respect. It would seem to suggest that gestural controllers need to be studied in a variety of actual acoustic instrument musical tasks as they might be better at some rather than others, regardless of what their physical interface might imply.

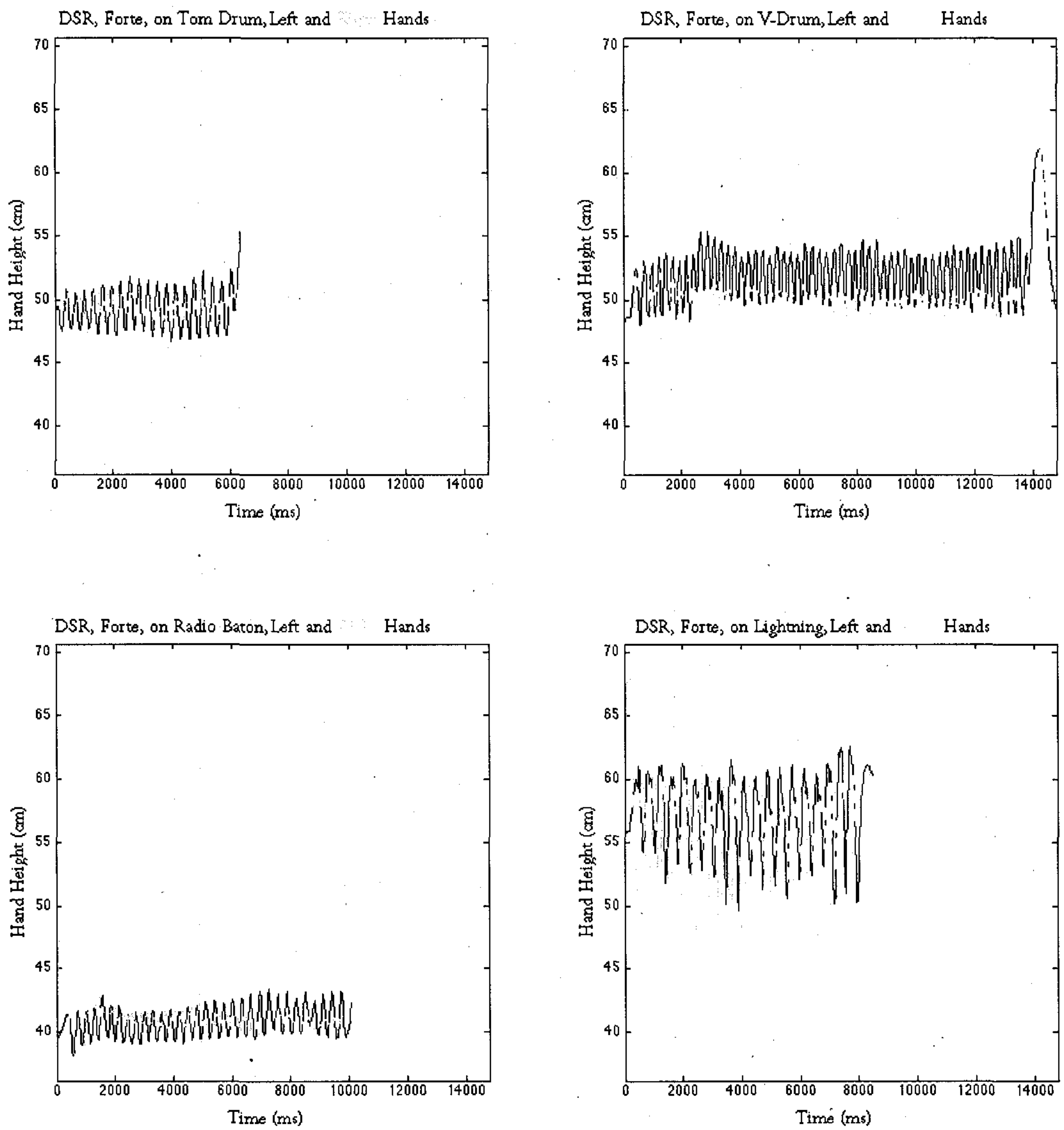

Fig. 5.13 Subject 2 - Double Stroke Rolls, Forte Loudness

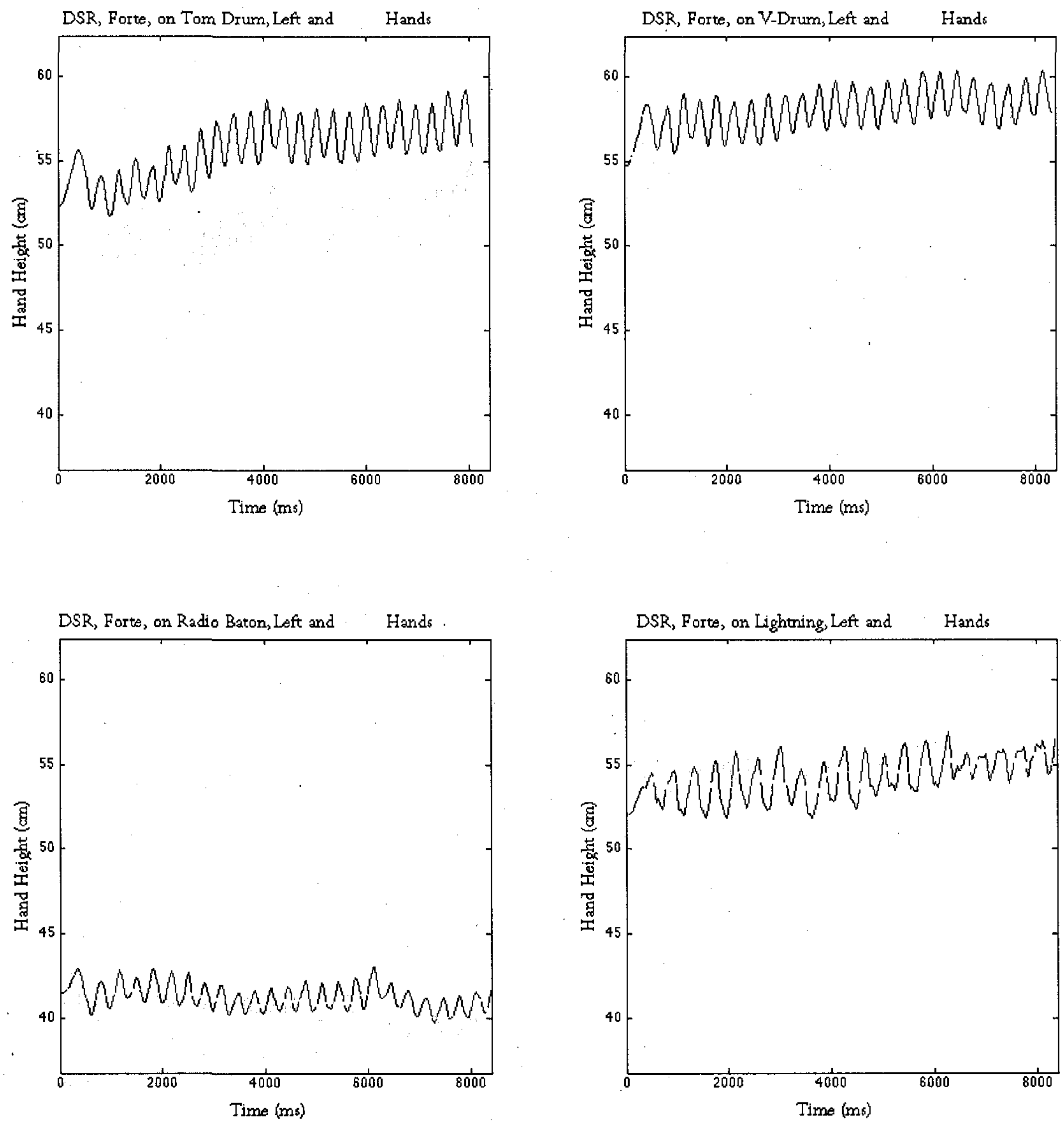

Fig. 5.14 Subject 3 - Double Stroke Rolls, Forte Loudness

Percussion Post-Study Comments

Rate the three controllers on a scale of 1 to 5 in terms of timing accuracy where 1 is poor and 5 is excellent.

Vdrum	1	2	3	4	5
Radio Baton	1	2	3	4	5
Lightning	1	2	3	4	5

Rate the three controllers on a scale of 1 to 5 in terms of timbre controllability where 1 is poor and 5 is excellent.

Vdrum	1	2	3	4	5
Radio Baton	1	2	3	4	5
Lightning	1	2	3	4	5

Rate the three controllers on a scale of 1 to 5 in terms of responsiveness where 1 is poor and 5 is excellent.

Vdrum	1	2	3	4	5
Radio Baton	1	2	3	4	5
Lightning	1	2	3	4	5

Rate the three controllers on a scale of 1 to 5 in terms of expressivity where 1 is poor and 5 is excellent.

Vdrum	1	2	3	4	5
Radio Baton	1	2	3	4	5
Lightning	1	2	3	4	5

Rate the three controllers on a scale of 1 to 5 where 1 is considered a completely different instrument and 5 is considered the closest reproduction to an acoustic drum.

Vdrum	1	2	3	4	5
Radio Baton	1	2	3	4	5
Lightning	1	2	3	4	5

Rate the three controllers on a scale of 1 to 5 where 1 is considered most difficult to play with drum technique considered and 5 easiest to play with acoustic drum technique.

Vdrum	1	2	3	4	5
Radio Baton	1	2	3	4	5
Lightning	1	2	3	4	5

Fig. 5.15 Post-Experiment Comment Sheet

Following the experiment, subjects were asked to rate their impressions of the instruments in terms of a set of music instrument context features [25].

Table 5.2 Post-Experiment Comments Results

Subjects	1	2	3	Average
Timing Expressivity				
V-Drum	4	5	5	4.67
Radio Baton	3	4	3	3.33
Lightning	2	3	1	2
Timbre Control				
V-Drum	4	4	5	4.33
Radio Baton	2	3	1	2
Lightning	3	3	2	2.67
Responsiveness				
V-Drum	4	4	5	4.33
Radio Baton	2	3	3	2.67
Lightning	2	2	1	1.67
Expressivity				
V-Drum	4	3	5	4
Radio Baton	2	3	2	2.33
Lightning	2	3	2	2.33
Acoustic Likeness				
V-Drum	4	5	4	4.33
Radio Baton	3	3	2	2.67
Lightning	2	1	2	1.67
Playability				
V-Drum	5	5	5	5
Radio Baton	3	3	3	3
Lightning	2	1	1	1.33

Chapter 6

Conclusions and Future Work

6.1 Results Overview

This thesis has tackled the problem of gestural controller evaluation for musical applications by considering the comparison of two such devices as a case study. The case study entailed considering the Lightning II and the Radio Baton within two main perspectives. The first perspective sought to describe how the controllers have been or could be used in different musical contexts. This involved the compilation of the design history, technical specifications, and long term usage patterns of each controller. The second perspective involved the motion capture and audio analysis of performances using both controllers within a specific musical context, namely that of an acoustic percussion instrument performance. This context was chosen because the physical user interfaces of both the Lightning II and the Radio Baton resemble drum sticks/batons. This part of the case study examined the relationship between digital and acoustic instruments in terms of playing technique. Three percussionists performed two basic drum techniques on the controllers in question as well as on an acoustic tom drum and a drum-like gestural controller, the Roland V-Drum. All three digital controllers were mapped to the same drum sound controlled by the V-Drum engine. The performances and the subject's impressions of the gestural controllers were then evaluated and compared.

The design history of both the Lightning and the Radio Baton reveal that neither was explicitly inspired by percussion instrumentation despite their use of sticks and batons as the physical interface. The Lighting was part of a quartet of MIDI controller prototypes that Don Buchla hoped would provide an alternative to the acoustic instrument-like controllers of the late 1980s. It is the only prototype that remains in production today and is undergoing it's third revision. Max Mathews' Radio Baton, designed during the same period, was inspired by the idea of "an expressive tape recorder" and an implementation of capacitive sensing available at the time. It also remains in production after several revisions. The designers' willingness to continue improving their unorthodox controllers and keeping them in the commercial market may be the most important reason why these two devices remain available today while scores of other worthy controllers have faded away.

The Lighting II and the Radio Baton both provide continuous control signal output that corresponds to the individual position of each wand/baton; the former does so within a vertical plane, the latter within a horizontal sensing space. Both also output a control signal corresponding to vertical strikes and their velocity. These two modes allow both controllers to be used in a variety of musical contexts, including but certainly not limited to the simulation of percussion instruments. The main technical differences lie in the sensing range, strike latency times, and the use of wired or wireless physical interfaces. These differences, amongst others, were plotted in a dimension space to allow prospective users a visual method of determining the technical differences and limitations of the Lightning II and the Radio Baton.

Long-time users insights reveal the wide variety of actual musical performance settings in which the Lightning II and the Radio Baton have been used in. This has been achieved over the many years each user devoted to exploring the devices using different movement-to-sound mappings. Users reported that different mappings changed the entire nature of the instrument and that creating mappings was the most important and hardest skill to master in gestural controller use. Interestingly, the five users, who are thought to represent nearly 50% of the world's professional Lightning and Radio Baton performers, all have percussion or conducting backgrounds which they use in their gestural controller performances.

Some of the results from the percussion exercise motion capture trials were to be expected. The strike trigger algorithms of both the Lightning II and the Radio Baton performed poorly in the double stroke roll conditions resulting in poor strike timing and volume control when compared to the V-Drum, which was specifically designed to mimic an acoustic drum. Also, when the tom drum movement data was considered as a benchmark, subjects were found to deviate more when playing the two controllers in this case study than the V-Drum. With little rebound between the Radio Baton surface and its long foam-tipped wired batons, and the complete lack of a surface when playing the Lightning, it was expected that the subjects would have to adapt their movements. What was unexpected was the timing results from the single strokes condition. According to the onset detection method used, each subject played very accurate single strokes on each controller. This suggests that some acoustic playing techniques can be transfered over to gestural controller performance. While the range of onset intervals was largest on the Lightning, interval averages showed it had the highest timing accuracy across all instruments, including the tom drum, for all subjects. Despite this result, each subject rated the Lighting far behind both the V-Drum and the Radio Baton in terms of timing accuracy. Furthermore, even though subjects could only essentially control the volume of a drum sample with the three gestural controllers, the Lightning was rated slightly higher than the Radio Baton in terms of timbre expressivity, yet equally in terms of expressivity alone. Further research needs to be done to properly explain the validity and meaning of these results in terms of the relationship between acoustic and digital instruments.

This case study reveals that the Lightning II and the Radio Baton, and by extension all gestural controllers, can be evaluated objectively for many different musical applications. Technical specifications are one way to quantify the possibilities. Long-term actual use still remains one of strongest methods to afterwards assess the quality of the gestural controller for a particular application. This case study also revealed relationships between acoustic instruments and gestural controllers that physically resemble them, but more research needs to be done to quantify these relationships.

6.2 Future Work

The results of this case study seem to confirm that the evaluation of gestural controllers for musical applications requires the consideration of multiple research techniques before an objective understanding of controller capabilities can be determined. In light of this, this section details certain areas where this analysis could be strengthened through improved or different research methods and data.

The technical specifications relied on approximate latencies reported by long term users. It would have been interesting, especially in regards to the timing results in the motion capture trials, to determine accurate latency figures. The motion capture trials would also benefit by including more percussion techniques and longer varied percussion exercises. This should reveal other acoustic instrument techniques that transfer over to the Lightning II and the Radio Baton. Also, multi-session trials would allow for the observation of practice both acoustic and gestural controllers. This observation, along with interviewing a larger number of long term users of different gestural controllers, may shed light on how strong the relationship is between acoustic instrument training and gestural control use. Understanding this relationship could help create pedagogical tools that increase digital music instrument use.

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