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Human-Computer Interaction Methodologies Applied in the Evaluation of Haptic Digital Musical Instruments

by

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Abstract

Recent developments in interactive technologies have seen major changes in the manner in which artists and performers interact with digital music technology; this is partly due to the increasing variety of interactive technologies that are readily available today. Computer music performers are presented with a myriad of interactive technologies and afforded near complete freedom of expression when creating music and sound art. In real-time, artists can manipulate multiple parameters relating to digitally-generated sound, effectively creating gestural interfaces and sound generators that have no real-world acoustic equivalent. When presented with such freedoms of interaction, the challenge of providing performers with a tangible, transparent, and expressive device for sound manipulation becomes apparent.

Digital Musical Instruments (DMIs) present musicians with performance challenges that are unique to this form of computer music. One of the more significant deviations from conventional acoustic musical instruments is the level of physical feedback conveyed by the instrument to the user. Currently, new interfaces for musical expression are not designed to be as physically communicative as acoustic instruments. Specifically, DMIs are often void of haptic feedback and therefore lack the ability to impart important performance information to the user. Moreover, there currently is no standardised way to measure the effect of this lack of physical feedback. Best practice would expect that there should be a set of methods to effectively, repeatedly, and quantifiably evaluate the *functionality*, *usability*, and *user experience* of DMIs.

Earlier theoretical and technological applications of haptics have tried to address device performance issues associated with the lack of feedback in DMI designs. It has been argued that the level of haptic feedback presented to a user can significantly affect the user's overall emotive *feeling* towards a musical device. Previous research has also indicated that Human-Computer Interaction (HCI) analysis techniques can be applied in the development of unique and creative applications of computing technology.

Within this thesis, a number of solutions to these problems were explored. To begin, an experimental tool was constructed to examine the physiological and psychological parameters of vibrotactile feedback. Following this, a combined audio and tactile experiment was conducted to further investigate the effect of multisensory feedback in auditory frequency detection tasks. In addition, this thesis also proposes an analytical framework for DMI evaluation. This framework tackles the multi-parametric nature of

musical interactions whilst also assessing the application of haptic feedback in DMI designs. Although DMI evaluation approaches exist, they do not consistently apply *functionality*, *usability*, and *user experience* aspects of technology in use as is seen applied in many HCI analyses. To validate the evaluation framework, an experiment was formulated that examined two prototype DMIs, each capable of displaying unique aspects of haptic feedback.

An analysis of vibrotactile feedback was successfully conducted with the developed analysis tool and the parameters of vibrotactile feedback were quantified and applied to the design and construction of two prototype digital interfaces. The proposed framework of analysis was then successfully implemented, evaluating the effect of *haptic*, *force*, *tactile*, and *no feedback* in a functional and explorative context. The results of the analysis showed that although haptic feedback had no functional effect upon device performance, it did display a number of significant effects upon the user's perception of usability and their experiences with the device.

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This thesis is dedicated to my friends and family.

Thank you all for everything.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institution of learning.

Signed:

Gareth William Young

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Publications

Book Chapter:

- G. W. Young, A. Kehoe, and D. Murphy, “Usability Testing of Video Game Controllers: A Case Study,” in *Games User Research: A Case Study Approach*, by Dr. M. A. Garcia-Ruiz, Ed., Canada: CRC Press/Taylor & Francis, March 2016. ISBN: 978-1-4987-0640-7

Peer Reviewed Publications:

- G. W. Young, D. Murphy, and J. Weeter, “Vibrotactile Discrimination of Pure and Complex Waveforms,” in the *Sound and Music Computing* Conf., Maynooth, Ireland, 2015.
- G. W. Young and D. Murphy, “HCI Models for Digital Musical Instruments: Methodologies for Rigorous Testing of Digital Musical Instruments,” in the Int. Symp. on *Computer Music Multidisciplinary Research*, Plymouth, UK, 2015.
- G. W. Young and D. Murphy, “Digital Musical Instrument Analysis: The Haptic Bowl,” in the Int. Symp. on *Computer Music Multidisciplinary Research*, Plymouth, UK, 2015.
- G. W. Young, D. Murphy, and J. Weeter, “Audio-Tactile Glove,” in Proc. of the 13th Int. Conf. on *Digital Audio Effects*, Maynooth, Ireland, 2013, pp. 247-251.

Digital Publications:

- G. W. Young, (2013) “Twenty-first Century Music Technology,” in *Digital Arts & Humanities: Scholarly Reflections*, J. C. O’Sullivan Ed. [Online]. Available: https://itunes.apple.com/us/book/digital-arts-humanities-scholarly/id529097990?ls=1

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List of Acronyms

3D	Three-dimensional
ANOVA	Analysis of variance
CAD	Computer-Aided Design
CIT	Critical Incidents Technique
CMJ	Computer Music Journal
CPQ	Consumer Product Questionnaire
DAH	Digital Arts & Humanities
DAW	Digital Audio Workstation
DMI	Digital Musical Instrument
DoF	Degrees of Freedom
HCI	Human-Computer Interaction
HID	Human Interface Device
I/O	In/Out
ICMC	International Computer Music Conference
IQR	Interquartile range
IR	Infrared
IST	Inter-stimulus time
JND	Just Noticeable Difference
LED	Light emitting diode
MIDI	Musical Instrument Digital Interface
MOCAP	Motion capture
NASA-TLX	NASA Task Load Index
NIME	New Interfaces for Musical Expression
OSC	Open Sound Control
PD	Pure Data
PSE	Point of Subjective Equality
RA	Rapidly Adapting
SA	Slow Adapting
SEQ	Single Ease Question
SMEQ	Subjective Mental Effort Questionnaire
SUS	System Usability Scale
TSE	Tactile Simulation Event
UDP	User Datagram Protocol
UEM	Usability Evaluation Method
UEQ	User Experience Questionnaire
VR	Virtual Reality
WIMP	Windows, Icons, Menus, Pointer

Chapter 1: Introduction

When physically interacting with the world around us, deliberate actions are performed with the purpose of achieving some external effect. When connections with external objects are made, the perception of the consequences of these actions upon the senses is processed and the body adjusts its effectors accordingly. The senses applied in the perception of mechanical displacement and stimulation of the skin are not only internally processed, but are used to monitor the behaviour of the body and the response of the world around via haptic feedback. The term ‘haptic’ is also applied to machine feedback techniques that are capable of combining both tactile and kinaesthetic stimulation in response to a user’s input. As a user interacts with this type of technology, input gestures are captured and the device responds in return with feedback that adheres to the predefined biological parameters of the human body. The research contained within this thesis investigates the role of haptic feedback in new technologies for musical expression by examining the physiological parameters of feedback and applying Human-Computer Interaction (HCI) frameworks for the evaluation of haptic feedback devices applied within a digital arts domain.

1.1 Haptic Interactions

Haptic technology conveys information to a user by stimulating tactile and force receptors within the body. Haptic feedback, in its most basic form, is created by transducers that deliver stimulation via tactile and force feedback: tactile feedback excites receptors in the skin and force feedback stimulates kinaesthetic receptors deeper within the muscles and tendons. To further elaborate, tactile stimuli are associated with our sense of touch, such as the perception of different surfaces. Receptors distributed within our skin are sensitive to this stimulation, such as thermal receptors for temperature and mechanoreceptors that are sensitive to mechanical vibration, skin stretching, and compression. Kinaesthetic perception relates to the body’s awareness of its own movement. This includes information on position, velocity, and the forces supplied by our muscles. Receptors sensitive to this type of stimulation are located in the body’s muscles and tendons. Therefore, haptic feedback can be observed in devices that stimulate both tactile and kinaesthetic receptors in combination. Contained within this thesis are research methodologies that focus on the investigation of devices that apply haptic feedback, implemented in the domain of Digital Musical Instruments

(DMIs). The outcome of the investigations contained within will inform new haptic interface designs, update our current understanding of haptic feedback applied in DMI interactions, and assist in devising new methods for the evaluation of music technology.

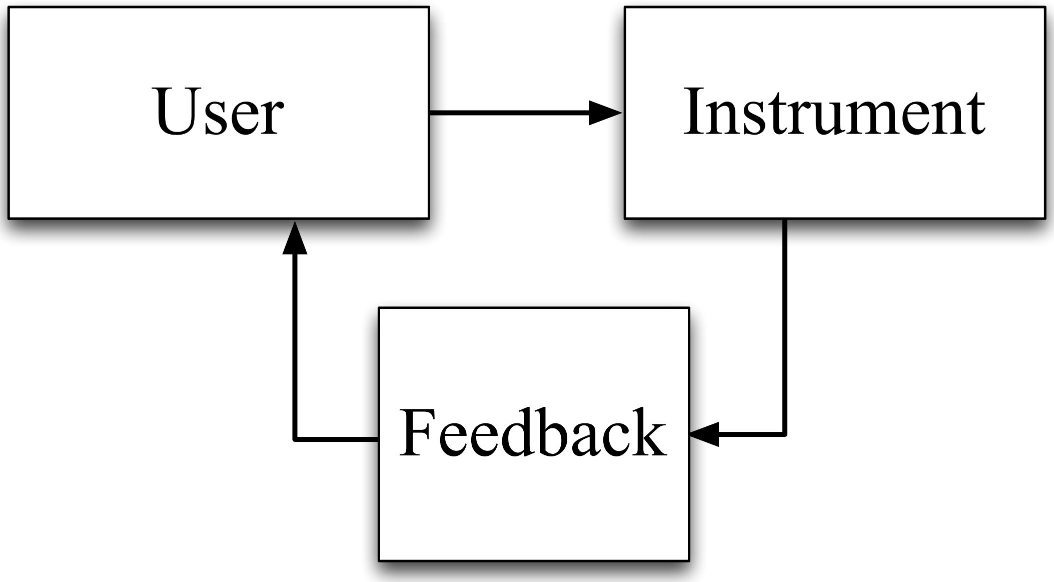


Figure 1.1: Basic control loop for musical instrument interactions.

Haptic feedback in DMI applications delivers performance data that has been identified as missing in genres of music that require the implementation of interfaces for musical expression, as expressed by Castagné et al. [1]. This communicative technique has been acknowledged as embracing an enactive approach to human computer interface design and provides the end user with tactile and kinaesthetic stimulation relating to the operation of the device in a musical context [2]. When musicians interact with musical instruments, they apply their extensive training and experience to execute performance related actions, activities that aim to achieve a musical outcome. Throughout the musical process, the musician embodies the role of system monitor, scrutinising the instrument's behaviour and adjusting performance actions accordingly. This creates a control loop system where the musician directly monitors the output of the instrument and the information feedback is used to control or adjust their input gestures in relation to this information, see Figure 1.1. DMIs designed to incorporate haptic feedback provide the user with continuous information relating to electronic and/or computer-generated sound produced by the instrument and completing the feedback required for a stable closed-loop system.

Digital music controllers that do not incorporate haptic feedback information bring about a divide, or *disconnect*, between musician and the musical devices used in contemporary compositions [3]. The relationship between the performer and the performance medium presents itself lacking in both form and engagement. Specifically, near motionless performances can be observed in some types of laptop music and the relationship between the sounds created and the interactions of the performer appear arbitrary or the connection between both of these elements is unclear. The introduction of haptic DMIs in this context aims to address the divide and devise meaningful multi-path communicative feedback for electronic musical instruments and digital controllers. Areas of interest in this field include performance communications that are a characteristic element of traditional instrument interaction and the application of sensor technologies that are effective for both gesture capture and machine output. The amalgamation of these two areas of study make it possible to map the physical interaction of the musician and create resultant and haptic responses that are intuitive in their application to the operation of the instrument and its feedback system.

1.2 Motivation

Advances in technology have always influenced the field of music technology, facilitating the modern musician's requirement for new devices and encouraging creative expression. Music has a deep-rooted history of performance and a close-knit relationship with human interactions with musical devices. Through the use of natural sound generating objects, such as reeds, bells, pipes, and others, humans have made possible the creation of musical instruments. Traditionally, it was the limitations of the sound-generating device that determined the design of an instrument. However, this fact has never deterred the making of music from most any manmade or naturally resonant object.

An example of how physical sound generation affects form can be observed in many of the instruments found in the classical orchestra. For example, in the collective brass ensemble of the classical symphony orchestra, the individual instruments of the ensemble changes in size determined by the frequency range produced. Examining the first instrument, the trumpet, and down through the pitch range of the horn section, tenor trombones, bass trombone and the tuba, it can be observed that the instruments increase in size as they advance down through the audible frequency range being produced. The scientific theories behind the development of brass ensemble instrumentation incorporate sympathetic vibration of air in tubular resonator principles. This pattern of instrument size augmentation for frequency range and altered timbre can be observed in most orchestral instrumentation groups. However, these relationships are no longer apparent when observed in the field of electronic and digital musical instruments.

With the discovery and widespread application of electricity in the early part of the 20th century, the number of new mediums for sound generation increased. This relationship can also be observed between the increasingly complex progressions made in communication sciences. It is apparent that the relationship between developments in the field of music technology and advances in many other areas of study can be also be mapped, such as materials science and software development. The majority of early electronic musical instruments were keyboard based, drawing upon the universal success of acoustic instruments such as the piano and harpsichord. Notable exceptions that deviated from this design principle are instruments such as the Theremin [4] and other instruments that made use of gesture sensitive inputs to control timbre, pitch, and/or volume. Another example would be the Trautonium [5], which operated via a touch sensitive strip across its length. Of the keyboard-based instruments, advancements in functionality were achieved via increasing the devices sensitivity or manipulation through the development of additional knobs and buttons, for example, the Ondes Martenot [6] and the Electronic Sackbutt [7].

It was the designers of early electronic instruments that pioneered the idea of utilising the limitations of the user as a design restriction rather than the limitations of the physics behind sound generation. Instrument designers became part performer, composer, and engineer, creating an interdisciplinary subject embracing many different fields of study. Modern mediums of sound generation and control have given inventors and musicians unlimited freedom in capturing the nuances of performer movement and transforming this into music. For the greater part of the development of electronic music controllers, the keyboard, with a number of control knobs, has dominated the interface market. Despite the ascendance of the Musical Instrument Digital Interface (MIDI) keyboard, many performance tools do not adhere to this model. With the availability of multiple sensors increasing exponentially, there is a wide variety of off-the-shelf gesture sensing devices available.

With the development of increasingly sophisticated sound synthesis techniques, the frequency and timbre of sounds produced by a sound generator are far less clear than in an acoustic instrument; new musical interfaces take the form of most anything imaginable. Acoustic instruments are limited by the physics of sound generation and the interaction required to produce sound. In contrast, the relationship between input gesture and sound generation with contemporary sound synthesis controllers can be ambiguous. The removal of sound generation from gesture interface has created a requirement for new gesture capture devices to control these new sound sources. Since the nineteen fifties, a broad range of sound synthesis techniques have been developed along with ever more elaborate methods of interaction being refined with them. These systems afford composers and performers with the tools required for real-time manipulation of multiple parameters. Modern sound synthesis engines are no longer restricted by the shape, size, or material of the medium of sound generation employed, but are capable of high fidelity sound reproduction and the creation of sounds that would have been near impossible or impractical to produce before.

DMIs have very few limits and the potential design possibilities are vast. Beyond musical performance, in devices that operate on a one-to-one interaction, new musical instruments are also encompassing other jurisdictions of musical composition. Artists may become proficient in the use of a singular instrument or they may choose to become the master of a multi-instrumental controller. Musicians may concentrate all of their efforts into increasing their skill in playing a stand-alone instrument or they may choose to master the control of multiple sound sources through digital manipulation. A performer can have a direct influence on an installation or live recital, becoming a unique and often difficult to control aspect of a performance. Beyond the musician, performance itself has also changed. The musical medium is no longer a static performance, as a single musician or ensemble on stage, it moves beyond this. It can be inclusive of the movements of a dancer, a dance troupe, or even the audience itself. The inclusion of multiple free movements into music production paves the foundations for a more expansive interaction.

1.3 Scope of Thesis

Following in the footsteps of the earlier pioneers, within this thesis, single-player instruments are focussed upon. The concepts of one-musician-one-instrument will be described and thoroughly explored; however, it must also be acknowledged that the effects of haptic feedback may reach further than this. During a musical performance, the performer is communicating to the audience some thought or ideal through their compositions or arrangement. This may also be true for indirect interactions with haptic DMIs. In this circumstance, the audience may be affected in some way when watching someone perform with a haptic DMI as opposed to a non-haptic one. In the research presented herein, it is the effects of feedback upon the performer that will be focussed upon. By understanding the effects of feedback in this context, we can start to gather a greater understanding of the role of haptics in performances that operate on a gesture-to-gesture basis and in future work the effects of instrument physicality may also be explored.

Outside of the context of this study, a gesture is a movement of the body that is used to express an idea or an encoded message that contains some meaning to the recipient. Gestures form part of the non-verbal communication channels that humans construct to compose wordless modes of expression, messaging, and meaning. In the field of HCI, gestures usually originate from the movement of the hands. These intentional movements or gestures are captured and interpreted via hardware and mathematical algorithms; these then create some form of predefined reaction within the system. The application of gesture recognition in HCI requires the operator to perform some task that makes use of natural manipulators, such as the hand, and communicate these movements to a machine that will in turn control some predefined function contained within [8].

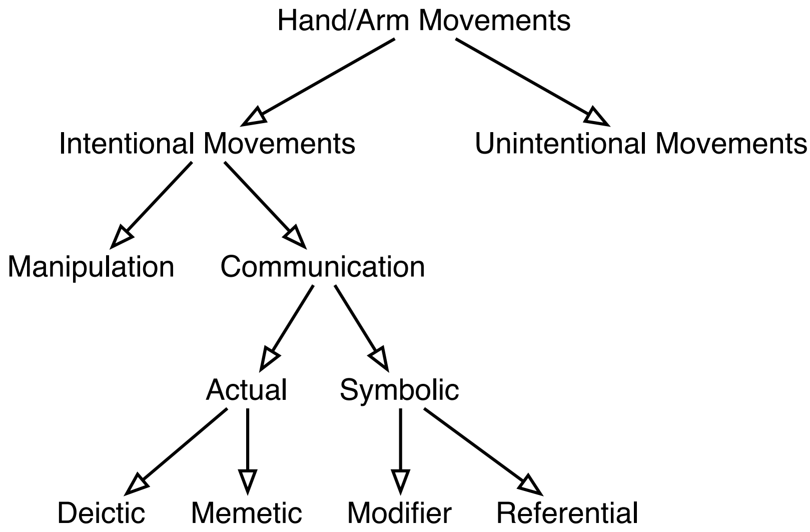


Figure 1.2: Taxonomy of hand gestures in HCI, adapted from Quek (1994) [9].

There are several accepted methods of categorising gestures; however, Quek proposed a modified version of the taxonomy in 1994, see Figure 1.2 [9]. The movements of a hand or arm are first categorisation as unintentional and intentional movements. As unintentional movements convey no further information, they can be ignored. However, intentional hand or arm movements can be interpreted as meaningful gestures, which can display two modalities. Gestures that manipulate refer to intentional movements that are applied to move an object in an environment (such as moving a mouse), and can therefore be ignored in the context of gesture recognition in hands-free applications.

Movements that intend to communicate some form of information are purposeful and can therefore be applied to convey information to an interface device. Communicative movements can be used to send information via movements that relate to the interpretation of the movement as actual or as symbolic movements. Actual movements are either memetic (imitating an action) or deictic (pointing to an object). Symbolic movements are referential (referring to an object or action) or modifiers that accompany speech and the gesture supplies additional information.

In computer music, virtually any gesture can be captured and translated into a control signal. In the application of DMIs, these gestures are often used as a control source for complex sound synthesis modules. With the separation of interface from sound source, new musical devices are afforded near endless freedom of form. However, they are becoming unrecognisable, as the gestures captured by a device do not require

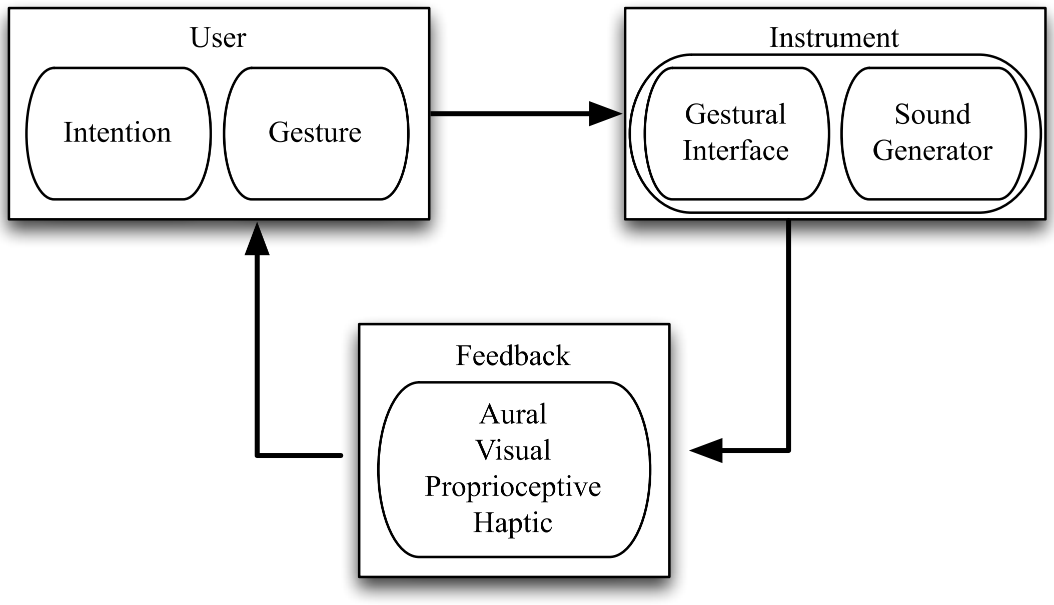


Figure 1.3: Acoustic musical instrument feedback loop.

resemblance of anything ever applied before. Furthermore, the augmentation of existing musical instruments that extend their sound generation beyond recognition can be observed. This is achieved through the addition of sensors to traditional musical instruments that increase the functional abilities of the instrument in some way. The multiple combinations of these styles of interface design have protracted the performance techniques that musicians are afforded in performance. This can be observed in the increased popularity of DMIs in contemporary music, as they have been embraced and accepted as a new means for artistic expression.

A model of a musical interface, based upon the playing principles of an acoustic instrument, can be seen in Figure 1.3. Both artist and instrument can be observed as two separate entities that are independent of each other [10]. The link between user and instrument mediates between the components contained within. The relationship between these two modules is realised through gestures made and gestures captured. The musician or artists are independently providing the intention (attained through training and previous experience) and the gestures for capture by the interface. The instrument captures physical interactions and processes them into control data. The sound generator makes use of the data collected from gestures captured by applying control parameters to a physical sound generating design. The physical separation of these modules is impossible to achieve in acoustic instruments, as the gesture interface is rarely removed from the sound source. DMIs allow us to separate the user from the instrument, permitting us to rethink the relationships formed between the two. For example, a gesture can be made and the sound generated varies in some way; however, the gesture does not necessarily have to relate to a control change in the sound generator, as it may also convey performance information that is not audible.

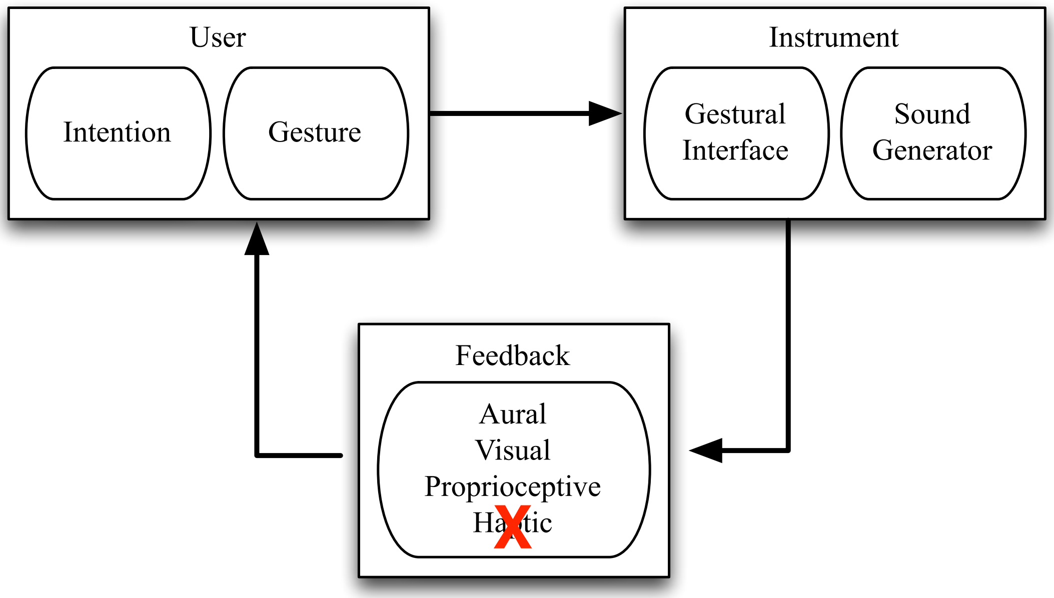


Figure 1.4: Digital musical instrument feedback loop.

What has become apparent from such observations is that whilst performers have been given absolute freedom of movement in gesture capture, they have at the same time eliminated a key feedback channel of information through which they can measure the response of the instrument and the accuracy of their movements, Figure 1.4. In the realm of gesture capture, synthesis algorithms and control rate data have been separated from the sound producing mechanisms along with the performer. The capture of human performance with such devices forces the user to rely heavily on proprioceptive, visual, and aural data cues or more simply put "...*the computer music performer has lost touch*" [1].

Technology provides musicians with a vast array of sound synthesis techniques; which has in itself further increased the distance between sound controller and sound source. It is becoming apparent that designing instruments based upon freedom of movement is removing musician from music. It is suggested within this thesis that the manner in which the human effectors (the hands and lips) control instruments and the information re-conveyed by the instrument being played can address the disconnected physiological and emotive *feel* of DMI interactions.

It is difficult for DMIs to convey comparative tactile feedback to that of acoustic instruments, as these instruments possess a vibrating body or mechanism that provides feedback to the musician. In DMIs, vibrations are not produced unless there is some form of transducing element included in their design, such as a loudspeaker or other actuator. If no such design feature is present, then the feedback a performer receives is reduced to aural, proprioceptive, and/or visual. The removal of control surface from the sound generator has caused a loss in haptic feedback from instrument to musician. The feedback provided by electronic and digital instruments is mainly auditory through the sounds produced and sometimes visual via screens. Tactile and kinaesthetic feedback information relayed from the interface is rarely used, with the touch of a key and the manner in which it is pressed being the same irrespective of the sound produced.

To quantify the importance of this feedback, it is suggested that existing research from the field of HCI can be adopted to apply evaluation techniques that can measure and quantify the various aspects of musical interactions. Addressing the element of touch has helped to restore the relationship between feeling and synthesis in other areas of technology, such as in Virtual Reality (VR). Therefore, it is proposed that HCI evaluation techniques that have been applied to measure interactions in these fields can be used to observe and quantify the same or similar elements in a DMI evaluation context. In doing so, a validated framework of evaluation between different interface technologies can be built. For example, if a device or product is attributed a System Usability Scale (SUS) score of 80 or a Throughput measured at 3.2 bits per second it is understood in HCI what these figures represent and how they are applied to compare the design of different devices. Other techniques, such as the Subjective Mental Effort Questionnaire (SMEQ), have comparative structures prebuilt into their scale. In summary, acquiring data from *known* products or prototype devices can be useful in identifying and understanding relationships that may exist between them. Additionally, they may effectively identify any distinguishable or measurable differences between devices.

1.4 Original Research Contributions

The primary contributions of this thesis to the field of Computer Music research are outlined below:

- The design and construction of an analytical tool for the investigation of physiological and psychophysiological parameters of vibrotactile feedback.
- Validated vibrotactile feedback in signal detection tasks, in terms of vibrotactile amplitude, frequency, and timbre
- Established the significance of concurrent auditory and tactile signals in pitch/frequency detection tasks.
- The development of an analysis framework for the evaluation of interaction with DMIs.
- The design, construction, and analysis of two new DMIs that incorporate derivatives of haptic feedback.
- Developed a set of recommendations for the role of previous user experience in DMI design.

The first contribution of this thesis was the design and construction of a vibrotactile research tool, one that was capable of providing continuous vibration feedback in isolation to the hands of a participant. The Audio-Tactile Glove was constructed and applied to a reductive physiological and psychophysical analysis of vibrotactile feedback, specifically, its role in the detection of waveform dynamics, pitch, and timbre data. Further to this, an investigation into the combined application of both audio and tactile feedback was carried out. This investigation was conducted to examine if multimodal stimulation can have some effect upon auditory Just Noticeable Difference (JND) measures.

After exploring the effects of vibrotactile feedback, further research was carried out to develop evaluation techniques that could be applied to measure and quantify the performance of a DMI displaying derivatives of haptic feedback. This approach differed from previous research in its application of HCI analysis techniques that include consideration of *functionality*, *usability*, and the overall *user experience* when assessing haptically enabled DMIs. Two prototype devices were developed that were capable of addressing the communicative divide that exists between musicians and digital interfaces. These devices, named "*Bowls*", were then analysed by applying this newly formulated framework of DMI analysis, specifically highlighting the role therein of haptics in DMI design. Furthermore, the study applied this analysis to compare the Bowl devices' feedback effect, incorporating specific derivatives of haptic feedback and no feedback at all. This allowed for the comparison of functionality, usability, and user experience data relating specifically to the individual feedback devices and the design techniques applied. Moreover, the context of analysis was performed in both functional and explorative conditions, allowing for the comparison of these two different approaches to evaluation.

1.5 Outline of Thesis

Within Chapter 2 of this thesis, the history of haptics was explored and a review of its application to computer music interfaces was conducted. Following this, the findings of existing research literature and its relation to the current work were presented. Chapter 3 drew upon existing physiological studies that highlighted the parameters of the human body responsible for processing such information and its role in a musical context. In order to explore these concepts, a prototype research tool was developed and applied in three experiments. These experiments were conducted to investigate the role of vibrotactile feedback in a physiological context. This was then followed by a discussion of the potential role of vibrotactile feedback in musical interactions. In Chapter 4, a framework of analysis was formulated and discussed. Here, previous HCI evaluation techniques were examined to create a formal structure for a flexible rigorous structure of analysis. In Chapter 5, the newly formulated framework of analysis was applied to prototype DMIs ("*The Bowls*"), each capable of presenting derivatives of haptic feedback. Chapter 6 discussed the implications of these findings in providing musicians, composers, and musical interface designers with the methodologies that are necessary to accurately evaluate their DMIs and highlighted the role of previous user experience and haptic feedback in computer music instrumentation.

Chapter 2: Discussion of Related Work

This chapter contains a review of literature and previous research findings relating to the history and application of haptics in technology. These topics are discussed to provide a broader understanding of haptic interfaces and their application to instrument design theories. Familiarity with the subject was attained through the appraisal of existing theories and practices in industrial application and digital instrument design modelling. The studies focus on the design and use of electronic devices that can be applied to technology to convey haptic information to the user. The studies analysed relate to the history of haptics and the role haptics has played in industrial applications, which have ultimately lead to its inclusion in DMIs. Others highlight the importance of haptics in the control of gesture nuances, such as tonality, in a musical context. Additionally, studies that analyse the importance of haptic information in the control of alternative interfaces are included. Finally, musical device studies that include a variety of analysis techniques are discussed.

2.1 Defining Haptics

The term *haptic* refers to our ability to touch and manipulate an object. A haptic interaction is bidirectional in nature, enabling the exchange of information between the body and the object being explored. In haptic simulations, a user is engaged in an explorative interaction with a virtual object. To facilitate the body's requirement for physical stimulation in these simulations, the user manipulates a mechanical device; this is known as a haptic display. The term *display* is applied here to affirm the unidirectional transfer of information between the user and the simulation. Haptic displays are required to contain two main elements of feedback, *tactile* and *kinaesthetic*. Tactile and kinaesthetic feedback techniques differ in the manner in which they can be applied in both the context of the stimulation of a physical response and the reactive capabilities of the virtual system manipulated.

Tactile stimulation is received via receptors in the skin, with the highest density being in the hands and lips. The skin is the only organ responsible for communicating the parameters of an external physical interaction, via the stimulation of the receptors within. This includes information about an object's geometry, corrugation, temperature, and slippage among others. This is discussed in more detail in Chapter 3. Force feedback receptors are found much deeper in the body, typically in muscles and tendons. These receptors present information relating to the forces associated with contact and movement of an object: such as weight, mass, and contact force. The terminology for discussing such interface parameters is intermixed and can lead to confusion when not clearly defined. Therefore, the definitions in Table 2.1 will be closely adhered to in this thesis.

Table 2.1: Definition of key terminology.

Title	Description
Haptic	Relating to the sense of touch, in particular relating to the perception and manipulation of objects using the senses of touch and kinaesthesia [11].
Feedback	When the output of a process is routed and returned back into the input stage of the same system.
Tactile Feedback	Sensation applied to the skin, typically in response to contact or other actions in a virtual world [12].
Force Feedback	A technique deployed in flight simulation, telepresence, and virtual reality systems whereby the controlling device provides a form of physical response to the user that corresponds with the physical mass of the real or virtual object being manipulated [13].
Kinaesthetic Feedback (kinaesthesia)	Awareness of the position and movement of the parts of the body by means of sensory organs (proprioceptors) in the muscles and joints [14].
Proprioceptive Feedback	Relating to the stimuli arising within an organism. It provides information relating to body posture and is based on receptors located at the skeletal joints, in the inner ear, and on impulses from the central nervous system [15].

The level of feedback a device is capable of displaying, as derived from the tactile and kinaesthetic information feedback, generates five distinct modes of feedback.

1. Tactile perception via cutaneous stimulation only.
2. Passive kinaesthetic perception via kinesthesis only.
3. Passive haptic perception via cutaneous stimulation and kinesthesis.
4. Active kinaesthetic perception via two-way kinesthesis feedback.
5. Active haptic perception via cutaneous stimulation and two-way kinesthesis.

2.2 Historical Overview of Haptics

To provide some historical context to the topic of haptic feedback, the earliest references to haptics as an academic subject will be discussed. Further information about these specific topics can be found in Brent Gillespie's discussions on haptics found in "Music, Cognition, and Computerized Sound: An Introduction to Psychoacoustics" by P. R. Cook [16].

2.2.1 Aristotle

Arguably, Aristotle first conceptualised the field of haptics as an academic discipline in his treatise *De Anima* (On the Soul) in 350 BC. As discussed by Polansky in "Aristotle's De Anima: A Critical Commentary" [17], Aristotle is credited as the first person to observe and document the sense of touch as a distinguishing feature of animals. That is to say, a definition that could be applied and accepted as a functional definition of what it is to be an animal; to have the ability to move of one's own volition. These initial suppositions highlighted an important link between movement and the gathering of tactile information, such as is observed when a musician exerts control over a musical instrument. Further to this, in *De sensu et sensibilibus* (Sense and Sensibilia), Aristotle reported on early definitions of how the individual senses of the body perceive the world around it. Here, he defined only four senses: *sight*, *sound*, *smell*, and *touch*, as Aristotle viewed the sense of *taste* as a specialised sense of touch. These philosophical discussions were applied later as the foundation for contemporary research in touch; describing the five exteroceptive senses in more detail and separating the sense of *taste* from touch.

2.2.2 Diderot

In 1749, Diderot published an essay titled *Letter on the Blind for the Use of Those Who Can See*. As discussed by Jourdain in "Diderot's Early Philosophical Works" [18], Diderot observed the sensory perception of congenitally blind men and controversially dismissed the assumption that visual imagery was fundamental for the formulation of abstract thoughts. This early work was fundamental to the modern theory of *sensory substitution*. This particular theory supports the idea that the brain exhibits plasticity when one sense is lost and the other senses have to compensate for this loss. This is seen in many contemporary DMI designs that do not incorporate haptic feedback. In addition to this theory, Diderot was also engaged in the development of the role of touch processes in information retention. He noted that the memory of a form was contingent with the sensation memory created in manipulating the original object. This theory also places some emphasis on the previous experiences of the musician when performing musically with a new instrument.

2.2.3 Weber

In 1834, Weber introduced systematic experimental procedures that were to be applied in the study of the haptic senses; procedures that are now considered fundamental to modern psychophysical experimentation. Weber's experiments on cutaneous sensation, later used to define *Weber's Law*, state that the ability to discriminate differences between two stimuli is a function of the magnitude of the first stimuli received [19]. This can be observed in the discrimination of weight, where the difference between two weights is required to be greater for a large weight than it is for a smaller weight. For example, if you add 0.005 kg to a 2 kg weight, there will be little or no perception of weight increase. If you keep adding weight to the original 2 kg, the perception of extra weight is only realised when it is equal to 0.2 kg. Therefore, from Weber's Law it can be observed that the increment threshold for determining difference in 2 kg weights is 0.2 kg. This is commonly referred to as Just Noticeable Difference or JND and will be applied in the psychophysiological studies presented in later chapters. Weber also predicted future developments in the study of haptics, such as the role of intentional movement in the perception of hardness and the distance between objects.

2.2.4 Katz

In 1925, David Katz published his seminal work *Der Aufbau der Tastwelt* (The World of Touch) [20]. At the time, many psychological studies were being conducted in the area of audition and vision, but very few in the field of haptics. Specifically, Katz focussed on the correspondence of the internal response to an external stimulus. He also maintained the popular theory that the invariants of an object are obtained by specific movements over time. In addition, he proposed that an internal impression of an object is formed in isolation from the sensory input. These ideas relate back to the movement suppositions made by Aristotle many years earlier, as Katz was also interested in the role of movement in haptic perception. For example, he postulated that the texture of a surface was almost impossible to distinguish if the hand was placed upon it with no lateral movement. It is only when movement is introduced that an analysis of textural information can be undertaken.

Katz also expanded further the findings of Frey, who, in 1894, proposed that touch was comprised of four sensory components: pressure, warmth, cold, and pain [21]. Katz added to this list by including the sensation of vibration. He observed that the sensation of pressure adapted over time, regardless of stability or changes in the stimulus applied. For example, the reader does not perceive the weight of glasses upon the bridge of the nose nor the weight of clothes upon the back. However, when a hand is passed over a surface it is capable of perceiving the texture of the surface, theoretically, indefinitely. In his later studies, he concluded that vibration was separated from pressure. Vibration is not simply perceived as an oscillation in pressure, but can be treated as a dynamic sense similar to that of hearing. Katz performed many experiments that supported the function of the skin as a means of extending the reach of the body via tools such as styli and other mechanisms. These theories are seen later applied in understanding how haptics have important implications in the design and construction of tools that extend the natural abilities of the body, such as in the manipulation of musical instruments.

Katz was also responsible for distinguishing between the operation of active and passive touch in haptic interactions. He reported heightened accuracy and detail in independent active explorations of texture than when the material being assessed was passively passed over or under the fingertip. In modern tactile systems, passive feedback is delivered through the physical characteristics of the system, such as switch click, and active feedback is produced by the system in response to user actions, such as the vibrations produced by a musical instrument. These concepts were further developed in the work of Gibson, who explored the concept of active and passive exploration of various objects with the hands. Gibson demonstrated how passive haptic stimulus resulted in subjective descriptions of an object [22]. However, when subjects were allowed to actively explore an object, they were able to identify actual properties of the object being held and accurately identify the object. Specifically, when an object is explored actively, the object is externalised and prescribed with external real-world qualities. An example of this would be the report of weight, texture, pressure, and other descriptive sensations when an object is passed over the palm of the hand versus the ability to definitively identify an object through the explorative handling of the object.

2.2.5 Effects on Technology Today

In modern technology, the application of haptics has many supporters, in both research and industrial-backed applications. The proponents discussed so far have endeavoured to bring this subject to the forefront of perceptual psychology. From these studies, the function of haptics in static or fixed interactions and the role of active/passive exploration have facilitated the development of haptic display metaphors applied to interactive technology. It is through these haptic interfaces that users are enabled to explore virtual objects. In addition, not all aspects of touch have been suitably addressed and certain aspects of this research are still actively explored. For the research contained within this thesis these aspects are worthy of exploration in the application of haptic feedback, for example, the notion that haptic sensation cannot be removed from an assumption of manipulation in activities that involve touch. The designers of DMIs that are enabled to convey information through a haptic display are required to acknowledge these active/passive feedback principles, and other sensory equivalences, for effective devices to be developed. This highlights that the manipulation of a musical device is not the result of a sensory process, but a manipulation task undertaken in motion.

2.3 Early Adaptation and the Application of Haptics in Technology

Following the development of haptics theories in physiological and psychological studies, haptic displays have been developed for industrial and academic research purposes. Precursors of the widespread application of these theories were seen in simulation technologies as early as the 1920s, specifically, as a safer practice method for training pilots to fly instrumentally [23]. Later examples of haptic feedback can also be observed applied to telerobotic operations. Industrial research and development teams have been engaged in the development of haptic telerobotic systems from as early as the 1950s. These systems were developed for master-slave arrangements, which incorporated the following principles:

- Master Device: An anthropomorphic mechanical device with Degrees of Freedom (DoF) comparable to that of the human arm.
- Slave Device: Often isomorphic to the master device, but equipped with an effecter to perform a specific task.

In this arrangement, the slave device follows the movements of the master input device and interacts remotely within a separate environment, usually in a harmful or hazardous space. Early teleoperation devices saw the master-slave mechanisms directly linked, but later systems were developed to operate via electrical servomechanisms. These mechanisms are able to control the positioning of a device via position sensing and error-correction feedback. The development and inclusion of servomechanisms allowed the teleoperator to receive feedback relating to the applied forces of their actions, thus allowing the user to virtually feel the manipulative movements of the slave mechanism in the master device.

In 1965, Sutherland theorised that a graphical interface could be directly manipulated via a system that included haptic feedback [24]. The *ultimate display* speculated that a virtual environment could be manipulated through simulations. Additionally, Sutherland highlighted that the virtual simulations created by a computer need not follow the expected rules of the real world, but could be applied in simulating scenarios that are physically impossible or difficult to recreate. This idea inspired many researchers to investigate the inclusion of haptics in computing.

Most notable of the early pioneers was Frederick Brooks, one of the founders of the GROPE project at the University of North Carolina in 1967. This research group aimed to graphically simulate three-dimensional molecular docking forces whilst generating haptic feedback for the user. The first GROPE-I system was developed in 1973 and was successfully able to replicate two-dimensional force simulations. The second GROPE-II device that was constructed used a remote manipulator arm from the Argonne National Laboratory for effecting simple wireframe models of construction blocks. The GROPE researchers expressed a preference in the application of a finger-hand display rather than a hand-arm system, highlighting that the relative manipulation resolution of the finger-hand was as good as that of the hand-arm system. The final form of this device took many years to complete due to speed restrictions in computer hardware. The original concept of a three-dimensional docking simulation was not fully realised until 1990 [25].

In 1966, the first glove-based controllers with feedback were developed. Previously, with the Argonne Arm and other such devices, the feedback had only been provided to the operator's wrist. In these new designs, a sensing glove was used to capture the dexterous movements of the user, information that was then transmitted to a slave device. The first of these devices pioneered the application of pneumatic bladders to simulate independent forces directly to the fingers of the operator. Errors in position between the master-slave were presented to the operator as proportional pressures in the pneumatic bladders placed on the back of each finger. The actuators inflated and deflated, replicating the forces applied at the slave device. This design concept can be seen applied in devices such as the Teletact I and II developed at the Advanced

Robotics Research Ltd. [26]. A similar, multi-dexterous design was also patented in 1981 [27]. This device was housed in a rigid external shell that was connected to an inner glove via several actuators.

2.3.1 Adaptations for Computing

The devices listed so far were developed for or from telerobotic operations and not specifically as In/Out (I/O) control devices explicitly for computer applications. However, researchers expanding upon these advances created special purpose tactile and force feedback technologies that could be adapted for more imaginative computing applications. Early tactile prototypes were customised to present graphic simulations to the user. Most notable of these early systems was the *Sandpaper* system created at MIT's Media Laboratory [28]. This 2-DOF joystick incorporated large electrical actuators that created a high bandwidth of tactile and force feedback system (500-1000 Hz). The Sandpaper interface haptically displayed textural information based upon the movements of a cursor over different virtual surfaces, with inertia and damping modelled on a two dimensional plane.

Later developments in desktop systems provided the user with the same high bandwidth haptic feedback without the unwieldy actuators that had come before them. However, these desktop feedback devices were unable to offer the same DOF found in industrial applications. To provide equitable freedom of movement, master devices were required to be both lighter and portable for prolonged simulation use. The Rutgers Master was one of the first lightweight computer I/O devices to incorporate pneumatic actuators to simulate virtual object hardness [29]. This lightweight device contained four pneumatic actuators, similar to those seen in the Teletact systems, which could be independently controlled to represent the hardness qualities of a virtual object.

Haptically enabled devices, such as the SAFIRE Master and the Touch Master from EXOS Inc. became commercially available in 1993. The PHANToM Arm and the Impulse Engine later followed these two devices. Developers were enabled by these new devices to create haptically enabled I/O frameworks that harmonized with their audio-visual interfaces. The incorporation of these commercial haptic systems has become more prevalent as these systems develop more interactive methodologies.

The application of haptics in computing has in recent years gained momentum in the public domain as computers have become ubiquitous. Computers are capable of communicating via increasingly sophisticated interfaces, which enable multimodal human-computer interactions. Examples include textual interfaces, auditory displays, graphical animations and live video displays. The bimodal communication modes that are implemented strive to create a more Aristotelian mode of interactions in artificial or virtual environments.

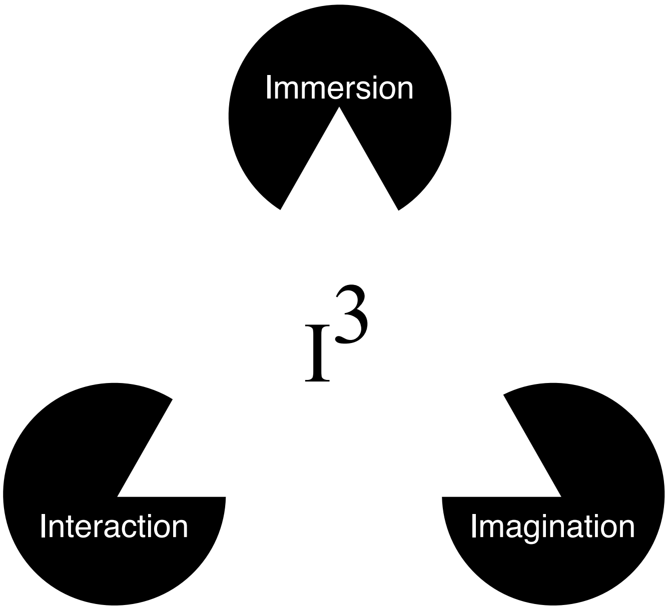


Figure 2.1: The *Virtual Reality Triangle* as seen in [12]

Indeed, virtual reality is built upon the premise of complete immersion of the user by stimulating as many of the senses as possible, as suggested in Figure 2.1. Techniques used to achieve this include binocular vision, three-dimensional imaging, binaural surround sound, haptic feedback, and even gustatory and olfactory stimulation in a small number of applications. By addressing all Aristotelian senses in real-time, VR creates an immersive and interactive environment that is manipulable and modifiable from within.

The creation of interfaces that seek to naturalise human-computer interaction are influenced by many sociological and anthropological factors that aim to increase productivity and the motivation to apply this technology. The application of such technology has benefited many fields of academic research as well as commercial markets. VR simulations have led to advances in military and surgical training, teleoperation, home entertainment, education, and the arts. Consequently, it has generally become more readily accepted. However, VR has yet to reach its full potential due to two major drawbacks.

The first of these problems is the requirement for optical realism in the presentation of visual data. The perceived reality of visual information is dependent upon the capabilities of the device being operated, often resulting in a sacrifice of visual realism for higher frame rates. For ideal visual representations of interactive environments, to achieve flicker fusion frame rates are required to be above 15 frames-per-seconds (fps), for film 24 fps, TV up to 30 fps, for 3D computer graphics and movies 60 fps, and for VR 120 fps. This can present a less than perfect trade-off between scene complexity and real-time operation. Currently, a few commercial devices that are being developed will address these shortcomings. Most notable are: Sony's Project Morpheus, HTC's Vive, Samsung's Gear VR, Oculus' Rift, Microsoft's HoloLens, and Carl Zeiss' VR One.

The second factor that is negatively affecting VR is that of the lack of physical interaction with the virtual environment and objects. In real-world interactions, the importance of touch and force processing is paramount to the success of any physical interaction. Tactile stimulation is received in all actions of exploration that require physical contact, such as the identification of an object's location and its orientation. Secondly, tactile information is applied to manipulate or move objects, such as tools. The lack of adequate feedback in computing highlights a major deficiency in information that can be presented to the user. Current trends in computer interface design favour a more AV interaction style over a tactile one when displaying information to the user. However, the application of haptics is becoming more commonplace as researchers endeavour to address the physical-digital divide.

Examples of these failings in the field of music technology can be observed in the proliferation of AV software interfaces. In application, AV software interfaces are adequate for the majority of musical applications where physical characteristics can be neglected, as in Digital Audio Workstations (DAWs). However, tactile information is critical for applications that require the user to actively manipulate a digital instrument. To create adequate realism within a virtual environment, physical semblance is required to represent the real world constraints of the system being manipulated, such as stiffness, mass, material, resistance dynamics, and other surface properties. The reproduction of these characteristics requires high processor speeds and specialist apparatus that a user is required to wear or manipulate. Unfortunately, specialised I/O devices are expensive and are often only available in certain application areas.

2.4 Haptic Technology in Digital Musical Instruments

Through the amalgamation of digital music technology and electronic musical instruments, digital musical instruments have emerged. A digital musical instrument is a musical instrument that is capable of producing sound via digital means. They are specifically constructed with a separable control interface and sound generator; however, these are not always separate, see Figure 1.4. The mapping of a gestural interface to a sound generator translates the input gestures into sound control signals that are applied to a sound generator. The separation of these two elements enables musicians to approach the creation of music differently from how they would with an acoustic instrument, as the physical constraints of sound generation and input gesture are no longer inseparable. This approach allows for the sonification of gestures or the creation of a sound-generating algorithm that is controlled via an unknown or undefined input gesture.

DMI designs, such as the *Rhythm'n'Shoes* [30], *The Sound Flinger* [31], the *Haptic Carillon* [32], *The Vibrobyte* [33], *StickMusic* [34], and *The Plank* [35] have demonstrated the successful application of haptics in musical devices. However, the majority of commercial interfaces in the field of digital synthesis have focussed on simulating the effects of acoustic keyboard instruments (such as the piano, harpsichord, or organ) and bowed instruments (such as the violin, viola or cello) [36]. Furthermore, previous research has highlighted that many of these DMIs fail to balance complexity with usability and that they lose transparency due to the separation of sound generator and gestural interface [37]. In the research outlined from here, haptic information that can be used to address these issues will be focused on and attempts to resolve problematic issues of interaction are also included.

In the book, *New Digital Musical Instruments: Control and Interaction Beyond the Keyboard*, Miranda and Wanderley discuss musical instruments that utilise computers for sound generation [38]. Computer sound synthesisers have historically incorporated a piano keyboard as the main controller. Although, in recent years, interfaces have been bestowed a near complete freedom of form, the commercial market continues to be dominated by this style of interaction. Additionally, as digital sound generation makes use of elaborate software packages, the application of the keyboard interface loses transparency. Miranda and Wanderley discuss the multitude of new musical controllers that are available and specifically examine control and interaction in emerging interface designs. With reference to haptics, the authors discuss the use of tactile and force feedback information in music. Based upon the materials contained within this subsection, the definition of haptics is reinforced as an amalgamation of both force and tactile feedback. Moreover, the tactile element of sensing through skin is defined as skin touching against an object's surface. The authors go on to explain that our skin is sensitive in this way due to the various receptors distributed within. This array of receptors includes mechanoreceptors, which are used to sense mechanical vibration, skin stretching, and compression; discussed in more detail in Chapter 3. Therefore, tactile sensation can be further elaborated upon to comprise sensations of vibration, pressure, texture, thermal properties, softness/hardness, and friction-induced experiences. Also discussed is the definition of kinaesthetic sensations and how these can be identified as our body's awareness of its own state, including information relating to our muscles position, velocity, and the forces applied to an object through them. It is explained that this information is gathered through receptors in our muscles and tendons. This further supports our definitions expressed earlier.

Miranda and Wanderley continue to highlight the importance of this information through the comparison of acoustic instruments to digital interfaces. They observe that when interacted with, acoustic musical instruments have both aural and mechanical responses that are directly related to each other, this is further substantiated by the findings of Gillespie [16]. Therefore, the mechanical information conveyed by an acoustic instrument to the user is directly related to the instrument's mechanical sound generator, such as vibrating surfaces, resonant bodies, reeds or pipes. Also included here is an examination of the forces produced by the mechanical action of the piano. This mechanical production of sound, that is inherent in all acoustic instruments, contributes to how a musician *feels* their performance both physiologically and psychologically. Of particular interest to Miranda and Wanderley are the force-feedback features provided by the weighted mechanisms of the keyboard and the tactile stimulation of receptors. With respect to the piano keyboard, other researchers have also modelled keyboard-based instruments.

Hans-Joachim Braum and the contributing authors of *Music Technology in the Twentieth Century* cover many of the important technological advances in music technology for this period [39]. Specifically, within this piece of research, they discuss developments made in the design and construction of keyboard based instruments. Braum et al. emphasises the socio-economic factors that led and directed individuals to develop new musical instruments. Within this study of music technology, contributor Hugh Davies outlines the historical journey of voltage-controlled synthesisers and their role in removing sound generator from sound controller [40]. He indicates that the piano keyboard, as a musical interface, features some degree of remote control in its acoustic form as the player does not strike or pluck the sound generator directly, but mechanically agitates the strings through hammers. This may be evidence of why users readily accepted the keyboard as a controller of artificial sound generators. Discussed further is research that questions why the keyboard is used in modern music when it restricts the user to a twelve-note structure.

In the same Edition, Pinch and Trocco discuss the pioneer of early synthesizers, Robert Moog [41]. Apparently, he saw the keyboard as the only commercially viable option for a synthesis controller. This is not to say that the keyboard is the only interface that has had commercial success, as many novel interfaces have surfaced over the years. However, these interfaces are often the product of composers who perceive the keyboard as a restrictive interface. For example, they discuss designers such as Don Buchla, who see the keyboard as a repressive interface. That is to say, those who wish to escape the twelve-tone structure of traditional musical styles are given very few options. Only a minority of non-traditional interfaces have been commercially viable or mass produced in comparison to the keyboard. Pinch and Trocco put forward the following question to try to explain this phenomenon: “If a new instrument does come along, how do people recognise that instrument and its sound, and how does it get incorporated into the wider corpus of musical culture?” [41]. In answer to this question, they simply highlight that certain *social groups* of musicians have voiced their preference through sales and the personal adaptation of these synthesisers by instrument manufacturers.

In *The Cambridge Companion to the Piano* are practical and informative essays about the world’s most popular instrument: the piano [42]. The authors discuss the history of the piano, performance styles, and the vast repertoire of compositions that are available. In the first part of this book, the authors discuss the mechanisms and acoustics of the piano. In the early nineteenth century, many experiments were conducted on the hammer and action mechanisms of the piano. In summary, the overall design of these components has been modified over time, but the general concept has remained the same. The action of a piano keyboard is the mechanism that converts the musician’s keystroke into a hammer blow onto a string. The action is a system of levers used to amplify the velocity of the keystroke so that the hammer travels five times faster than the initial keystroke. The key components of an acoustic piano are modelled and replicated in weighted electronic keyboards. This allows the musician to play a much smaller instrument whilst duplicating the action of the original acoustic instrument. The weighted system of an electronic keyboard is designed to give the musician the same kinaesthetic feedback as the original without incorporating the complicated hammer mechanism. This follows the remote control concept as described by Hugh Davies [40] where the musician indirectly controls the sound generator. This is also a good example of how the user of a digital interface can be afforded with the physical feedback characteristics and interface modelling of an acoustic instrument.

2.4.1 Haptic Theories in DMI Research

In 2011, Marshall and Wanderley explored the effects of vibrotactile feedback on the *feel* of a DMI [43]. Their research highlighted the importance of inherent tactile feedback in support of AV information conveyed to a performer through traditional musical instruments. They found that in the acoustic form, tactile information is used to pass performance information to the musician and it creates a bond between instrument and performer. Following this principle, an analysis was conducted to measure the relationship between tactile feedback and how a performer *feels* an instrument. Systematically providing sound related vibrational feedback into a DMI and measuring how this affected a performer's rating of the instrument quantified this concept. Marshall and Wanderley emphasised that DMIs are devoid of this information and as a result, lack the popularity of traditional instruments and that vibrotactile information allows for the near instantaneous conveyance of an instrument's state to the performer, allowing for increased control of articulation. It is suggested within this research that one possible use of a vibrotactile mechanism in a DMI is to model vibrations of the sound produced by the sound-generating module. This mode of conveying information is exhibited in acoustic instruments and how they communicate tactile information to the user, through the direct linking of sound generator to the interface used to control the sound.

Marshall and Wanderley identified four characteristics of vibrotactile actuators for the development of a successful tactile interface:

1. Capable of producing the full frequency range of human tactile sensation.
2. Offer independent control of frequency, amplitude, and waveform.
3. Offer a large range of amplitude control (to allow for instrument dynamics).
4. Be driven by an audio signal, or a control signal easily derived from an audio signal.

Further to this, the most applicable devices capable of addressing these requirements are piezoelectric elements and voice-coil actuators. The voice-coil design is very similar to that of a standard speaker unit with the cone removed. Therefore, if a speaker were to be included in a DMI's design, vibrotactile information relating to the sound synthesis system can easily be included.

This design concept can also be applied to address the *divide* that occurs when sound is reproduced externally at some distance away from the DMI. Sound reproduction conveys aural information to a performer and the internalised sound generator can also be applied in providing tactile substance to a device. With a voice-coil actuator, a full audio frequency spectrum is produced. However, a significant point to note is that the range of frequencies that the skin is sensitive to is confined to a much narrower frequency range than our hearing system. A filtering device may be applied to a signal prior to its delivery to an actuator to limit the bandwidth of frequencies produced; however, there is no conclusive evidence that indicates that frequencies above this range are not detected and processed by the body. In addition, the measurable frequency response of the skin sensitivity bandwidth is not flat across its width. Therefore, a dynamic model of a tactile feedback system should also be considered. The findings of Marshall and Wanderley highlighted an increase in performer engagement and entertainment, but also a decrease in performance controllability. Therefore, a balance should be found in the level of vibrotactile information allowing for increased *feel* without surrendering controllability.

Hayes also parallels the idea of vibrotactile feedback in assisted DMI performance, highlighting the importance of sensitivity in control that is comparable to that of an acoustic instrument [44]. Hayes illustrates how a vibrotactile-enabled interface can be applied to address the limitations of current DMI designs in the mediation of a performer's control of sound synthesis and musical information. She argues the necessity of incorporating haptic enabled controllers in the development of DMIs to convey important performance related data back to the operator. Specifically, it is stated that although musicians are capable of receiving feedback in the form of resistive forces and vibrations, provided by the physics of sound generation in acoustic instruments, they are neglected in many DMI designs. It is concluded that tactile feedback can be used to support audio and visual cues, so long as the user receives them in near unison. Interestingly, Hayes concludes her research stating that she wishes to include nonperformers in the design of haptic interfaces, allowing for the audience to hear and feel the performance they are experiencing.

2.4.2 New Interfaces for Musical Expression

The New Interfaces for Musical Expression (NIME) is an interdisciplinary conference covering topics in DMI design, research, and applied practice [45]. The proceedings of NIME cover topics relating to new and novel controllers for musical systems, ranging from new musical devices to theoretical practices. The vast range of disciplines covered here include such topics as Computer Science, Electrical Engineering, Human-Computer Interaction, Musicology, Electro-Acoustic Music, Dance, Composition, and Electronic Music. In recent years, the topic of haptics has received attention from both designers and researchers. Discussed here are a few unique and interesting applications that have been presented.

The *Rhythm 'n' Shoes* design of Stefano Papetti et al. is a musical interface that allows the user to capture foot gestures and rhythms [30]. What is particularly noteworthy of this interface is that the user is provided with audio frequency tactile feedback through actuators embedded in the sole of the shoe. Voice-coil actuators are applied in providing a wide bandwidth for full audio frequency feedback, creating a tactile display of the audio generated by a computer. This device offers spontaneity and expressivity, whilst enabling an embodied experience of the interaction for the user. The inclusion of audio related tactile feedback in the design closes the interaction loop and achieves an embodied interaction.

Another noteworthy design presented to the NIME conference of 2011 was the *Sound Flinger* [31]. This musical interface was an interactive spatialization instrument that allowed the user to touch and move sound in two dimensions. The user manipulated motorised faders controlling the location of two virtual sound objects in a quadraphonic sound field. The designers made use of a Texas Instruments Beagleboard to enable the interface to operate without the use of a portable computer. This created a fully stand-alone interface that was free from excessive outboard equipment and accessible to novices with only a basic understanding of the system.

Another device discussed at NIME was the *Haptic Carillon* of Mark Havryliv et al. [32]. The authors proposed that as haptic information in acoustic instruments is used to physically inform a performer of events occurring during a performance, so too can the inclusion of haptics in the design of DMIs for training traditional performers. Havryliv et al. highlight what they consider the two most important justifications for haptic feedback in this context:

1. To replicate and augment the capabilities of conventional instruments.

2. To assist in the exploration of musical gestures and engage musicians with new technology.

Further to this, Havryliv et al. address the difficulties of gathering information from traditional musical instruments. In conclusion, they state that however difficult this may be, the dynamic performance of an instrument that is built with the purpose of developing musical skill must perform in the same manner as its acoustic form. That is to say, the technology applied to accomplish this task should be modelled as closely to the original instrument as possible.

McDonald et al. explored the use of haptic information to assist in the performance of remotely located ensembles via *The Vibrobyte*, a device that conveys haptic information using telematics [33]. Telematic performances heavily rely on AV communications and generally disregard the use of haptics due to latencies introduced by heavy processing requirements. The Vibrobyte addresses these issues and facilitates remote performers with the ability to communicate haptic information. This research highlighted the computationally complex aspects of haptic feedback and the importance of including haptic feedback in multi-musician performances, enabling musicians to interact with each other via remotely communicated haptic feedback.

The application of haptic feedback can also be seen in the design of *Stick Music* [34]. This device applied haptic feedback to a joystick and a mouse. These two familiar interfaces were used to control a computer generated synthesis algorithm, which generated sounds that the authors describe as being "unidentifiable through traditional musical analogies." The author discussed findings that highlighted how musical instrumentation had been freed from the physical constraints of generating sound through the application of digital synthesis techniques. From this, any arbitrary interface could be mapped to a complex synthesis algorithm. Furthermore, Steiner highlighted how feedback applied to an interface closes the information feedback loop that is fundamental in acoustic musical instrument interactions, supporting previous research in the application of haptic feedback in DMI design.

Finally, Verplank et al. developed a simple haptic controller (*The Plank)* made from disused computer hard drives [35]. *The Plank* was designed to evaluate the theory of active force feedback and test its potential for precise and rapid control of synthesis software. This DMI took advantage of several tactile communicative factors that allowed the device to remain simple while maintaining haptic semblance. The interface measured forces applied perpendicular to the device's motion, permitting for the measurement of surface force. The Plank was capable of simulating terrain, friction, and dynamics for the control of a scanned synthesis program, that is, a computer based synthesiser. It was also capable of replicating the feel of traditional instruments. The Plank is an excellent example of a bidirectional interface that incorporates haptic feedback into DMI design.

To summarise, haptically enabled DMIs can incorporate elements of tactile feedback through actuators and mechanical means, allowing the user to experience tactile sensations in active and passive applications. In reference to the piano examples given earlier, it is proposed that although an electronic keyboard may be weighted, addressing the kinaesthetic playing feel of an acoustic piano, it cannot reveal any other information about the sounds produced that are comparable to that of the acoustic form without the inclusion of tactile feedback. Furthermore, researchers have found that the inclusion of haptics in instrument design can increase the speed at which an instrument is mastered [43]. The performance signals are received by the user's senses at the same time, reinforcing the user's understanding of the cause and effect of their actions.

2.4.3 Vibrotactile Feedback in DMI Design

The International Computer Music Conference (ICMC) is a prominent annual conference that discusses current research in the field of computer music [46]. Of particular interest to this thesis is the work of Chafe [47] and Birnbaum and Wanderly [48]. In 1993, Chafe presented experiments relating to vibrotactile feedback and proposed that future designs for new music controllers should incorporate vibrotactile feedback profiles that are based upon physical modelling. In Chafe's studies, it was found that the constraints within which instrument vibration are found relate directly to timing, amplitude, and spectral weighting and that certain frequencies can be neglected due to poor tactile frequency discrimination.

Chafe highlighted four primary characteristics of tactile feedback [47].

1. The fingers and lips are our most sensitive appendages.
2. Frequency response range is from near 0 to approximately 1000 Hz.

3. Frequency discrimination is very poor.
4. Subjective sensation changes occur across separate frequency bands.

From Chafe's studies, it can be concluded that the audible output of an acoustic instrument is always going to be the most important mode of communication; however, other information feedback loops are also present and convey meaningful information to the user. Early in a musician's training, they learn that *feel* is an essential supporting sense for a successful interaction with their instrument. Pressure and resistance are communicated through our kinaesthetic receptors and vibrations are applied to our tactile receptors. Together, they address the need for haptic feedback.

Chafe states that the sensitivity of our bodies to sinusoidal stimulus varies with location on the body and that the heightened or increased sensitivity around our hands is relative to the area of our brain that processes touch (the somatosensory cortex). In the somatosensory region, two of the four known physiological information paths relating to the perception of vibration and its overlap with the tactile frequency range. The ability to separate the distinctly different modes of instrument communication is integral to deciphering the importance of this information. Chafe emphasises that cutaneously detectable frequencies fall into a range of 0.3 Hz to 1000 Hz, where the region of 100 to 500 Hz is the most sensitive. This frequency range is much narrower than that of the audible range, with threshold detection being of the order of 20 - 30% higher than the reference. Consequently, only certain information can be represented: "*Specifically, timing, amplitude and spectral weighting, but not precise pitch*" [47]. Further to this, it has also been shown that humans are able to discriminate between tactile signals with the same fundamental, but with different spectral contents [49]. Tactile DMI devices are free from the constraints of *intrinsic modelling,* which is associated with conventional instrument design. Physical modelling approaches that have been developed for DMI instruments have resulted in *unforeseen* instrument designs [47]. From these findings, Chafe suggests that vibrotactile feedback can assist in directing the use of an instrument, enabling the musician to establish a perceptual reference frame of how instruments of this type should behave.

Furthermore, Birnbaum and Wanderly conducted a study to investigate systematic approaches to vibrotactile feedback design [48]. Their system also involved the application of vibrations in response to sounds generated by a synthesis model. This feedback was applied directly through a prototype DMI that incorporated a vibration transducer. This transducer was used to relay performance data to the user via a vibration-based cutaneous display. Interestingly, the less integrated the sound generator and the interface, the greater the perceived distance between instrument and musician. The *disembodiment* of sound from the musical instrument is in opposition to the expected vibrations associated with the performance of an acoustic instrument. Removing embodiment essentially ignores the potential of an instrument to incorporate touch generation in its design. This information was seen as essential for increased control in musical activities. In the case of active haptic devices, these vibrations may compliment and strengthen interactions when producing sounds. Many new DMI designs do not have the benefit of teletaction or virtual touch communication with performers. Therefore, the inclusion of tactile feedback can be applied to include embodiment and improve transparency in the use of these devices.

Birnbaum and Wanderly expand upon this idea by directly comparing vibrotaction to audition; concentrating on frequency discrimination within the critical ranges outlined earlier [48]. They developed their earlier findings by referencing psychophysical discoveries, such as frequency perception being dependant on duration, amplitude of skin displacement, and body loci; all of which should be considered as variables of vibrational feedback design. Many of the findings they investigated concluded that due to the interdependence of frequency and amplitude in vibrotactile feedback, they should be considered as a complementary pair. Birnbaum and Wanderly argue that "*Pitch perception is such a central aspect of musical experience that it naturally tends to play a dominant role in feedback, in both auditory and vibrotactile modes*" [48].

The frequency range of cutaneous detection can be divided further. Earlier, it was stated that the range of this cutaneous detection ranges from 0.3 Hz to 1000 Hz, with increased sensitivity between 100 to 500 Hz [43]. When incorporating more recent studies, this range is further divided to include the following: within the range of 20 Hz to 40 Hz, the perception of vibration shows an inability to distinguish between individual vibrational frequencies; however, in the range of 40 Hz to 700 Hz our perception is sensitive to individual frequencies, with peak sensitivity at 250 Hz.

With acoustic instruments, this information is tied directly to the sound-generating device. The vibrotactile information passed to performers from acoustic instruments has an intrinsic relationship with the sound produced. The sound generator, typically a device vibrating in response to the performer's actions, is tightly coupled with the acoustic properties and affordances of the instrument's design. However, with respect to

DMIs, the addition of active haptic feedback can increase the usefulness of vibrations beyond that of the acoustic experience. It can evoke memories of touch (known as virtual touch) by building upon the musician's pre-existing tactile experience. Active feedback models can also be applied beyond this, as the content of vibrotactile information can be anything that the instrument designer wants it to be, such as score data or performance cues. The usefulness of vibration information is dependent upon the musician's ability to process this information whilst performing with the instrument. Therefore, it can be said that sound related vibrotaction has a wide range of (perceptual) variation to consider when incorporated into new DMI designs.

Studies published in *Music Perception* (journal) have investigated vibration perception in musical interactions [50] [51] [52]. Some of the multiple disciplines covered in past issues have included psychology, computer science, and music theory. Articles that are more recent have focused on tone evaluation, voice, memory, empirical studies relating to perception, and the conceptualisation of music [50]. In the spring issue of 1992, Ronald T. Verrillo published an article, titled *Vibration Sensation in Humans*, which proposed that performing musicians incorporate vibrotactile signals to increase tonal control of instruments [51]. Specifically, research findings were presented relating to the sensory capacities of skin and how these enable tactile cues to be used by performers to control the tone of their instrument. The fundamental characteristics of human vibrotactile processing were presented, including the measurement of thresholds of detection and subject specific variables that can affect this processing. Human physiological characteristics were discussed with regard to the receptor systems associated with the cutaneous detection of vibration at different frequencies. Moreover, experiments relating to the application of vibrotactile contacts placed upon the right hand found that sensitivity increased with frequency, with 40 to 250 Hz being the most sensitive range. Verrilo showed that although sensitivity drops considerably outside of this range, being near undetectable above 1 kHz, there is no empirical evidence that suggests that harmonics above this threshold are not processed. Verrilo concluded that the skin's ability to detect frequency changes was poor when compared to the sensitivity of the hearing system. Moreover, he stated that humans can distinguish frequency differences of only 20 to 30% cutaneously, whereas the hearing system can detect difference changes of as little as 0.3%. This indicates that vibrotactile feedback above this sensitivity range (40 to 250 Hz) is of no use to the cutaneous system in support of audio interactions. However, vibrotactile feedback outside this range may be important for other forms of communication, such as timing with kinaesthetic cues.

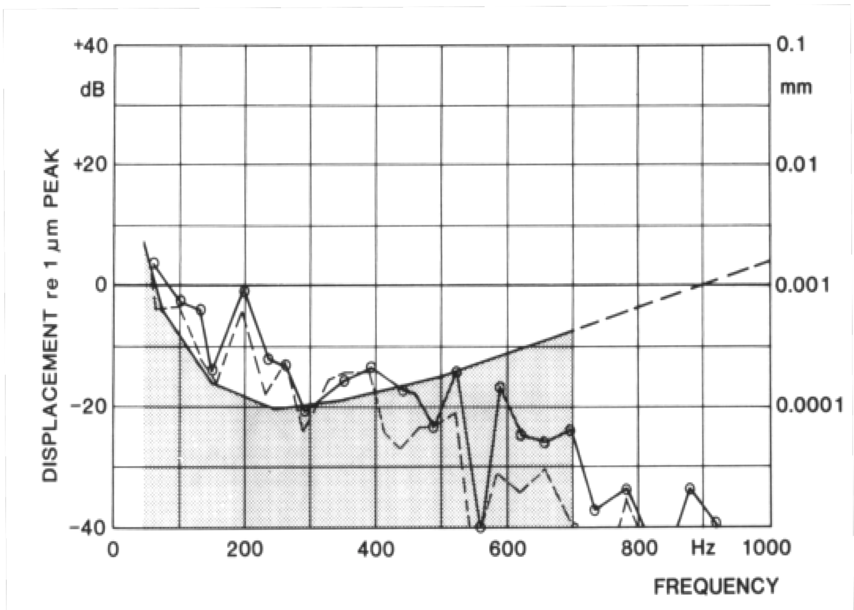


Figure 2.2: Vibration levels in a depressed piano key (solid line) and pedal (dashed line), from Askenfelt & Janson (1992) [52].

In the same edition of *Music Perception*, Anders Askenfelt and Erik V. Janson published their findings on vibration sensation and finger touch in stringed instruments [52]. They investigated the vibration levels in four traditional stringed instruments including the piano. They found that the vibration levels produced by each instrument were within the range of tactile detection. They discussed the importance of vibrotactile information and its use in the identification of ensemble instruments and the pitches they produce. With reference to the piano, Askenfelt and Janson concluded that in addition to touch, the kinaesthetic forces perceived in playing the instrument assisted in the timing of a performance. They highlighted that the resulting vibrations within an acoustic piano are the product of the sound radiating surfaces vibrating in sympathy with the sound generating strings. The musician's contact points detect these vibrations at the keyboard and foot pedals. The pianist, via the fingertips and feet, is therefore capable of perceiving these vibrations. While the pianist has disjointed contact with the instrument, it can be seen that the musician is still able to interact with the sound generating strings within the instrument, albeit indirectly. When compared to other instruments, these vibration levels are lower. The vibrations at the two points of contact of the piano can be seen in Figure 2.2.

In the 2002 autumn edition of the Computer Music Journal (CMJ) [53], Wessel and Write discussed the problems associated with the intimate control of computer music [54]. They covered the prerequisites for computer based musical instruments, metaphors applicable for musical control, and the tools developed for implementing and exploring these theories. They proposed that the relationship between a gesture and a musical event falls into a "*one gesture to one acoustic event*" paradigm. Wessel and Write recommend that latency between a gesture and a musical event should be reduced to 1 ms, which includes feedback returned to the musician from a sound generator. From these findings, relationships that have developed between the intimate placements of a performer in relation to their acoustic instrument can be observed. This allows performers to smoothly convert musical intention and gestures into musical events. Additionally, it was observed how traditional acoustic instruments offer a low entry fee with no ceiling on virtuosity. They are difficult to play at first, but not so much as to detract from the overall playing experience. The novice is afforded the opportunity to develop a higher degree of musicality given time and practice. In comparison to DMI interactions, flaws in an interaction's characteristics are perceived by the user early on and the user is often unable to elicit a continuous musical evolution of education in their application.

2.4.4 Haptics in New Music

In NIME 2011, Verplank and Georg discussed the use of haptics in new music [55]. They considered the application of haptic interfaces, which were specifically constructed to replicate traditional musical instruments in the making of music. They argued that these types of devices could be used to make new sounds and therefore new music. Specifically, Verplank and Georg suggested that with inexpensive actuators, computer hardware and open-source software, the creation of "*high-performance haptics*" was within the reach of many interface designers. They elaborated upon this topic by discussing current devices that could be used to explore new modes of expression potentially leading to original music.

Berdahl et al. explored haptic interfaces with active controllability of force-feedback features and found that the best type of haptic assistance is dependent upon the task being completed [2]. The authors found that after they had accounted for the finite reaction time of the psychomotor system, they could design assistive haptic interfaces that were deterministic and easy to implement. From these findings, it was observed how an interface that contains sensors for capturing the response of a musician could also incorporate actuators capable of exerting force to the user, completing the feedback loop required for a responsive and meaningful interaction. They suggested that haptic technology could be used to assist performers in making musical gestures through their instruments. To be considered an active haptic interface, controllers need to be programmable in such a way that allows the system to determine the appropriate feedback to apply to the musician. In conclusion, they state that haptics are innate factors of acoustic instrument design, and these design features can be included to incorporate kinaesthetic affordances in a digital musical instrument. On a haptics-level, a DMI has the potential to mimic any number of conventional acoustic instruments, if the haptic feedback of the interface is appropriately programmed.

2.5 Evaluating Digital Musical Instruments

A review of existing DMI studies that include HCI evaluation techniques is presented here. This appraisal explores the various practises applied in the assessment of DMIs in both functional and musical contexts. In HCI, the formal evaluation of a device comprises of a rigorous and structured analyses and often involves the use of specific analysis methods to ensure the repeatability of a trial. The formality of the process guarantees that the findings of one researcher can be applied and developed by other researchers. In the field of Computer Music, the testing of DMIs has been highlighted as being unstructured and idiosyncratic [56] [57]. However, it is challenging to accurately measure and appraise the creative and affective application of technology in creative contexts. These aspects of a DMI's evaluation cannot effectively be represented by quantitative techniques alone. In response to these shortcomings, DMI researchers seek to gather data using both quantitative and qualitative studies [58] [57]. Another factor that has been raised as being problematic for crossover HCI analyses is that of the central role of timing in musical interactions. Additionally, the emphasis of an analysis may change depending on who is the focus of the study, for instance the performer, composer, audience, designer, or even the device manufacturer [59]. Therefore, finding an appropriate analysis technique that is formally structured and that incorporates the various interaction factors of a musical device is difficult. The requirement for an established, rigorous, and flexible technique is highlighted in the studies presented here.

In 2002, Wanderley and Orio investigated and suggested appropriate device analysis tasks in a *musical context* [60]. The suggested musical tasks focused on examining a device's effectiveness as an instrument in simple exercises, even when these tasks appeared to be non-musical or overly simple. These shortcomings are alleviated by the application of simple tasks as a formative phase of a more complete device evaluation, that these tasks are not considered as an analysis of musicality or as a completely standalone examination. It can therefore be concluded that the individual tasks applied by Wanderley and Orio, although basic, non-compositional, and non-centric to musical performance in their design, can be used to accurately measure and compare the performance capability of a DMI. Further to this, if the evaluation techniques applied in a musical device's analysis are simple enough, they make allowances for the inclusion of novice DMI users and early prototype devices in an experiment. Simple tasks are complex enough to present meaningful data and an understanding of the device's performance in a musical context can be deduced. Therefore, to present a complete study of a DMI, an extra stage of device analysis is required to evaluate the performance of a device in an explorative and creative context. Previously, other researchers have attempted to analyse devices in musical tasks. However, the majority of these evaluation techniques focus on only one aspect of a device and fail to include the individual elements that constitute an in-depth and all-inclusive analysis, discussed further in Chapter 4.

Examples of previous DMI Studies that include single elements of *functionality*, *usability*, and *user experience* will now be discussed. Investigations that include these individual elements have been reviewed, outlined, and executed in many other studies of musical devices. The techniques applied and fundamental aspects of device examination that these analyses focus on are influential to the framework presented later in Chapter 4 and should therefore be discussed. Specifically, they highlight the importance of the individual elements in accepted DMI studies and how the data is collected and applied.

2.5.1 Functionality Testing

The most basic form of device analysis is the testing of its function. Functionality testing is used to determine if the device's features afforded to the user are practical, as well as evaluating the performance, consistency, and the sturdiness of the designs used [58]. Many examples of this type of analysis applied to DMIs are available; some of the most notable are discussed in the following work.

Many new musical interfaces that are presented for academic analysis incorporate some basic form of performance analysis, an important subcategory of functionality, as observed in [61]. A recent example of a quantitative study can be seen in the implementation and evaluation research of Skogstad et al. in 2011 [62]. In this thorough functionality description of the Xsens MVN, Skogstad et al. incorporate operational characteristics, latency measurements, and other performance data relating to the functional features of their device. They conclude from their collected performance data that the Xsens MVN was capable of presenting useful data for musical applications, outlining its potential function in a DMI context. Another good example of performance analysis can be found in the development and evaluation research of Torresen et al. in 2012 [63]. Here, a ZigFlea-based wireless transceiver board for use with a CUI32 USB sensor interface was investigated and important performance data was analysed and compared. In their analysis, Torresen et al. deduced that the ZigFlea board applied in this configuration was not optimal for musical interactions due to latency issues. The outcome of these two examples signify the potential application these devices in musical contexts, but do not explicitly measure this aspect. That is to say, the functionality of the devices are quantified, but not applied in a musical context.

The application of HCI informed functionality testing has been highlighted in a number of previous research investigations, most notably Wanderley and Orio [60]. From this, a number of HCI style functionality tests have been described. Most noteworthy are the findings of Pedrosa and MacLean from 2009 [64]. The evaluation of three-dimensional (3D) haptic rendering in the support of musical timing was interesting because of the design and implementation of a target acquisition experiment. The augmentation of a common HCI task to focus on a musical undertaking was achieved though the requirement of temporal synchrony of movements with a metronome device, addressing the requirement of timing controllability, a major characteristic of most musical tasks. The participants of this study were required to target and acquire spatial targets in sequence, presenting quantitative functional data for analysis. Specifically, the data captured represented the precision of targeted movements and the maintenance of rhythm whilst transitioning between targets. The acquisition data was then used in conjunction with cognitive task-load measurements to conclude that a fixed-reference force feedback environment was the most preferable for their participants. Whilst these findings in themselves are interesting, the most intriguing part was the augmented experimental procedure for the gathering of functionality data.

2.5.2 Usability Studies

Usability assessment is used to raise issues of *efficiency*, *effectiveness*, and *user satisfaction* in the application of technology. Further descriptions of device *transparency*, *learnability*, and *feedback mechanisms* can be drawn from analysing this data. The measure of usability is defined in ISO 9241-11 as "quality in use" [65]. Known areas of concern for DMI evaluation include the requirements of *Learnability*, *Explorability*, *Feature Controllability*, and *Timing Controllability* [2]. Many examples of usability testing of DMIs can be found; in the following subsection, a few notable examples are discussed.

In their most basic form, DMIs can be described as a combination of the constituent components that create a complete musical device. In 2009, Gelineck and Serafin undertook an investigation of the basic workings of common DMIs, applying HCI usability evaluation techniques in their experiment procedures [66]. Their study applied a user centred methodology that evaluated DMI components in creative and exploratory tasks. The framework that they applied attempted to analyse the work process of the end user and evaluate the interfaces being used to facilitate this procedure. Their research did not deal with the expressivity of the interfaces, but focused on their application in the composition of computer music. The methodology of this study was conducted through a formal questionnaire that established the musical background of the participants and through a usability test that was followed by a quantitative questionnaire. The usability test was structured in two parts: through a free-play and explore session, and through a subsequent series of musical tasks. The musical tasks section involved participants listening to reference sounds and then reproducing each reference sound through imitation. The reproductions were then evaluated on a Likert scale by the authors and by an impartial sound engineer. The post-task questionnaire elicited the perceived difficulty of the task by the participants and their overall impressions of the instruments. The difference-rating criteria of these questions were chosen from traditional HCI evaluations as well as incorporating features associated with the framework of creativity and exploration mentioned earlier. The most concerning shortcoming of this experiment, as highlighted by the authors, was the relatively short time the participants were afforded during the usability test. Additionally, the authors acknowledged that self-evaluation of performance by the participant would have also presented some interesting data, but this too was lacking.

Other researchers have also attempted to devise structured design and evaluation models for DMI constituent component analysis. Most notable was the 2006 presentation of Marshall and Wanderley's research into the design and creation of interfaces for computer music [67]. In this paper, they investigated the suitability of appropriate sensors for specific tasks in computer music. In the experimental section of their work, they investigated the usability of particular sensors for specific musical tasks. Participants were required to manipulate a computer based synthesis system using sensors in combination with a button. Data from these experiments was gathered via ease-of-use questioning, time taken for task completion (which was later applied to ease of learning, accuracy, and quality of sound analyses), and a final verbal debriefing. Quantitative data was presented from the study that indicated that the users displayed a preference interfaces for specific musical tasks based upon their usability. The study of the fundamental components of a DMI in a usability testing presents data that evaluated the constituent interface components, data that can also be applied in a more comprehensive interface evaluation.

2.5.3 User Experience

Assessing a user's experience whilst performing musical tasks is a relatively new and innovative area of investigation. To surmise, a number of appraisal methodologies exist, along with examples of their application in DMI evaluation. However, these techniques remain underdeveloped and underused as they are still in the early stages of creation and adaptation. In addition, the nature of the relationship between a musician and certain types of musical instruments can be idiosyncratic, especially in experiments that have only brief introductory and exploratory stages. Moreover, the data collected from user experience questioning is ultimately subjective and difficult to objectively process. These measurements are difficult to quantify and can be dependent upon a number of contributing influences, such as psychological or sociological factors [68]. Here a number of studies that have sought to evaluate musical devices via user experience data are discussed.

In 2008, Geiger et al. [69] apply the AttrakDiff system [70] to evaluate their users' opinion of a Theremin-based interface in musical tasks. The AttrackDiff questionnaire addresses both the hedonic and pragmatic dimensions of a user's experience, providing quantitative and comparative data for analysis. The experiments of Geiger et al. allowed for a brief introduction to the device, followed by two musical tasks. The first task consisted of simple scales and the second a free improvisation of a played back drumbeat. These methodologies were successfully applied and data was presented to analyse the performance of Theremin stylised input devices. Another interesting example of the same technique applied in DMI testing can also be seen in the personal usability and design testing performed by Poepel et al. in 2014 [71]. Here, the HCI AttrackDiff tool was applied to analyse their participants' experiences whilst interacting with a singing voice synthesis system. However, in this case, the data captured was used to identify potential device usability improvements. One shortcoming of this system is its lengthy post-task delivery, providing only a reflective assessment of experience, not the actual in-task experience.

Another example of a user experience focussed analysis is that of Overholt and Gelineck in 2014 [72]. Their research focussed on user experiences when playing hybrid DMIs and explored the application of such devices in interactive performances. Their prototypes were qualitatively evaluated in an exploratory focus group session with experienced string players. The group session was semi-structured and led by the researchers to cover topics that were pre-determined as important. The methodologies adhered to throughout this study raised several questions about the participants' experience with the prototype devices. In addition, usability studies were highlighted as being imperative for future research in accessible platforms for stringed instrument performers. Vandevelde et al. applied group analysis in their co-discovery methodologies in 2014 [73]. Here, constructive interaction methods were applied to understand the experiences and initial impressions of new products of potential users. This study addressed the shortcomings of post-task analysis by focussing on explorative sessions with a novel device. Co-discovery research is comparable to think-aloud protocols but is less verbose and disruptive to flow. From this data, the researchers concluded that tangible musical interfaces are advantageous in comparison to standard desktop interactions.

The most common form of user experience data gathering is via post-task interviews and questionnaires. Several examples of data collection in this style can be seen. For example, in 2010 Beilharz et al. studied user and audience experience by conducting a study that applied data gathering techniques orientated towards experience [74]. Their participants were interviewed one-to-one on a daily basis, and finally asked to complete a device-orientated questionnaire. Zappi et al. applied a similar technique in 2011 [75], where the focus was the evaluation of an audience's experience whilst observing a hybrid reality performance.

Finally, formally structured user experience experiments can also be observed in the studies of Barbosa et al. [56] and Johnston [76]. These studies highlighted the lack of formality in previously conducted device evaluations in the field of DMIs and suggested that a structured device analysis would address many of the shortcomings of current device comparison studies. Specifically, Barbosa et al. concentrated their study on audience experiences, stating that traditional HCI models have no comparative for this mode of focus in their designs, leading to a direct user or performer-centred evaluation

[56]. Their study applied previous research techniques that focused on the human-human communicative aspects of musical interactions and audience perception of cause and effect. Important distinctions were made between perceived understanding and actual understanding. The authors of this study aimed to create a complete and generic evaluation methodology that could be repeated by other researchers. In a similar vein, Johnson presented a structured methodology, but acknowledged that the measure of user experience is of equal importance to the description of functionality. Johnson's methods of data collection included online diaries, interviews with artists and designers, and the examination of software control logs. This methodology was executed in a user study that recorded professional musicians playing an instrument, capturing their performance and comments on film, and interviewing them with predefined questions. These sessions were also observed and noted upon by attendees, adding the audience's perspective to the identification of instrument design criteria failings. Finally, a questionnaire was administered to elicit the personal opinion of the instrument's design criteria. The findings of this analysis highlighted the requirements for a much broader view of evaluation in musical interface design, effectively bridging practice and theory in performance and research.

2.5.4 Combined Functionality, Usability, and User Experience

As can be seen from existing literature, the individual analysis of these three factors, although unique, should not operate independently of each other if a complete device analysis is to be formulated. For example, usability is not a defining device characteristic. However, the function of a device and how its functionality is delivered to a user has a significant influence on its usability. Additionally, how a device is aesthetically presented to a user can influence the *perception* of usability by a user. Also of importance is how a device's usability can directly influence a user's experience, as poor usability will produce a negative user experience. Therefore, in the assessment of each of these areas, it is best to apply multiple techniques and not focus on one alone [58].

2.6 Chapter Conclusion

This review of literature has highlighted that although haptic feedback is an integral part of acoustic instruments, it is often overlooked in the design of DMIs. A large body of research has been conducted in the field of haptics and DMI design and it is hoped that all aspects have been addressed. The inclusion of haptics in new musical instrument design has been a topic of interest for many years. However, our most common interaction with these devices has taken the form of simulations in VR applications and vibration alerts applied in mobile technology. Furthermore, commercial haptic devices have also been brought into the home; introduced as video game controllers equipped with rumble packs. The acceptance of these haptically enabled devices serves to highlight the importance of tactile information in a passive form. The most recognisable form of passive feedback is, again, the weighted keyboard. Springs and weights are applied to replicate the feel of the action mechanism of a traditional piano, but these components do not engage the performer directly or look beyond traditional music interfaces. The research goals of this thesis intend to expand upon the passive haptic model and give reason to include haptics for improvements in device performance.

To quantify the effects of feedback in DMI interactions, we must first fully understand the physiological and psychophysiological effects and parameters that it must adhere. In the following chapter, an analysis of vibrotactile feedback will be presented. These experiments incorporated validated and well-practiced methodologies of physiological and psychophysiological measurement. An evaluation of pure and complex waveforms and their effect upon the tactile system were conducted, founded upon the research methodologies discussed earlier. The analyses incorporated measures in simple audio-related vibrotactile feedback across the frequency ranges discussed. Following this, an analysis of combined audio and tactile stimulation was used to support the inclusion of tactile feedback in DMI design.

Chapter 3: Physiological and Psychophysiological Studies

It has been outlined thus far that the human body receives and processes information about its immediate surroundings via the sense of touch; however, this is achieved through both physical and perceptual means. By applying the historical and philosophical understandings of the nature of touch to science and technology, it has been made possible to design interactive devices that display enhanced tactile feedback. The following chapter describes the variety of ways in which tactile interactions are sensed by the body. Herein, parameters of tactile feedback are discussed and an exploration of how the perception of this type of stimuli occurs is presented. The interpretation of physical stimuli forms the perceptual aspect of touch. The physiological workings of the peripheral nervous system are used to gather physical information via nerve endings that are sensitive to specific stimuli. This information is then passed through the central nervous system to the brain. Within the brain, the received information is processed and interpreted. For this chapter, the results of previous human-factors experiments were investigated to determine the most favourable characteristics for this type of feedback. Thereafter, validated perception measurements were explored and applied in terms of amplitude sub-thresholds, bandwidth perception, and the acuity of simple and complex waveform detection.

3.1 Physiology of Touch

A definition and history of tactile feedback was given in Chapter 2; this will be further expanded upon to define the function of *touch* in a physiological and psychophysiological context. As was first presented by Aristotle, the sensation of touch is evoked when our skin is subjected upon by some external stimulus. This can be described in modern terms as different forms of mechanical displacement, thermal changes, chemical reactions, and electrical stimuli [77]. Further to the early history of touch presented in the previous chapter, there have been many studies conducted to quantify the various elements of touch; however, there still exists some contention around certain areas of this research. Despite these concerns, physiological experiments were carried out to measure sensory parameters that are pertinent to this thesis. The discussion of these topics presents' parameters of measurement that can be applied to DMI interfaces that wish to relay tactile feedback to the user.

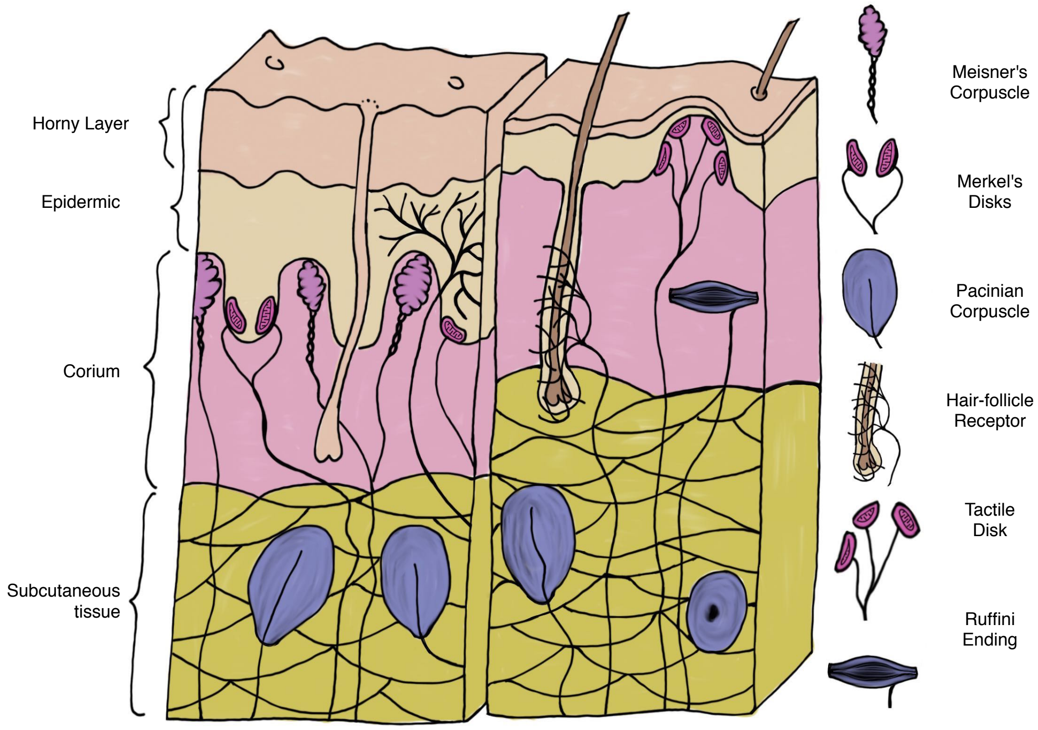


Figure 3.1: The tactile receptors of the skin, adapted from "Force and Touch Feedback for Virtual Reality" (1996) [15].

The cutaneous sense is engaged in providing an awareness of external effects upon the body, that is, the stimulation of receptors located in our exterior organ, the skin. Tactile perception is achieved when variations in cutaneous stimulation occur. This type of perception occurs only when the individual is stationary. If the subject is in motion, then the kinaesthetic and proprioceptive senses are incorporated and the interaction changes. Therefore, tactile perception is achieved through processing cutaneous information alone. Several types of receptor in the skin and subcutaneous tissue act as transducers for tactile information and the biophysical nature of these receptors vary with their location. For the purpose of our application, the receptor systems that lie in or are proximal to the hand are of most interest. The receptors found here respond differently depending upon their classification. The tactile system dominates the afferent peripheral and central nervous system pathways, culminating in the overall somatic sensory system. Previous psychophysical experiments have highlighted the role of mechanoreceptors in the perception of tactile stimulation. Receptors that are responsive to mechanical displacement can be seen in Figure 3.1.

The sensation of touch presents itself within the human body as a hierarchical system. When an external effector comes into contact with the skin this system is stimulated, such as with heat, pressure, or a vibration source. The skin reacts to contact depending upon the magnitude and location of the stimulus. Within the internal structure of the skin, there are a number of specialised receptors that respond to these varieties of change. For example, thermoreceptors respond to changes in temperature, mechanoreceptors to mechanical displacement, and nocioreceptors to pain. Each of these receptors has a threshold, that when breached, the receptor exudes an electrical discharge. The *action potential* of this charge is then passed into the connecting afferent nerve fibre. Second-order neurons then transmit this signal through the spine and on into the thalamus of the forebrain. Finally, third-order neurons deliver the perceived sensation to the somesthetic area of the cortex for processing [78]. Further explanations of these terms and processes can be found in anatomical bibliographies.

The most sensitive areas of our skin to tactile stimulus are the hairless regions of the body known as glabrous skin (Figure 3.1 – left). The glabrous skin of the lips, palms, and fingertips contain the highest density of tactile responsive receptors. This in turn also corresponds to a larger area of the sensory cortex required for processing this information. Approximately one quarter of the total somatosensory association cortex is dedicated to the mapping of receptors in the hands, resulting in an increased sensitivity to external stimuli in the fingers. Glabrous skin contains five major types of receptor; these include free-nerve endings (which are polymodal), Meissner's corpuscles, Merkel's disks, Pacinian corpuscles, and Ruffini corpuscles. In comparison to glabrous skin, hairy skin also incorporates a hair-root plexus for the detection of hair movement around the surface of the skin (Figure 3.1 – right).

Our free-nerve endings are the closest to the surface of the skin, where they are responsible for registering pain and injury. Unlike the other receptors, which respond only to mechanical stimuli, free-nerve endings are not encapsulated and appear like tree roots in the epidermis of the skin. The Meissner's corpuscles lie just below the epidermis and follow the contours of the skin. These corpuscles are located in the upper regions of the skin and are capable of registering light touch stimulation, stretching, and texture perception. Over forty percent of the hand's receptors are made up of these receptors. They are also sensitive to movement across the surface of the skin and can operate as velocity detectors. Merkel disks constitute twenty-five percent of the total number of receptors in glabrous skin. These receptors detect the presence of sustained pressure and low frequency vibrations. Ruffini's corpuscles lie deeper within our skin and are capable of detecting sustained external pressure. Ruffini corpuscles are spindle-shaped and make up approximately nineteen percent of receptors in the hands. They are capable of detecting skin pressure and shear. These receptors are also capable of detecting changes in temperature. The Pacinian corpuscles are the largest of the mechanoreceptors and are located deep within the subcutaneous tissues. Pacinian corpuscles represent thirteen percent of receptors in the hand. These corpuscles fire in response to high-speed displacements of the skin, but not sustained pressure. They are used to detect deep pressure, high frequency vibrations of approximately 250 Hz in frequency, and are capable of responding to light touch.

Each of the receptors used in tactile detection are constructed around a single sensory nerve fibre that is surrounded by a specialised organ. The constituent factors of the organ determine the sensitivity and frequency range of the neural channel. As can be seen in Figure 3.1, the Pacinian corpuscles are much larger than the other receptors and are constructed from multiple layers of tissue that are encapsulated by fluid. This layered fluid structure is capable of greatly attenuating vibrations applied externally to the skin. The construction of the encapsulating structures serves to protect the nerve ending contained within from overstimulation. Each of the encapsulated receptors found in our skin are similar in construction, as they all contain a nerve ending that is encapsulated. The specialised organ is constructed around the nerve ending in some unique manner that serves the function of protecting it and augmenting its stimulation pattern.

Each of the receptors mentioned display temporal adaptation properties that quantify the number of potential discharges in response to stimulation over time. Receptors that have slow discharge rates are called slow adapting (SA) receptors and receptors that respond quickly are known as rapidly adapting receptors (RA). The unit of measurement is the number of impulses within a second. With SA receptors, the discharge rate decreases logarithmically over a period of 40 seconds. However, RA receptors have such a fast response causing the impulse responses to decay in a very short time. A common example of this is that of people who wear glasses. The tactile receptors quickly adapt and the glasses are no longer felt upon the bridge of the nose or the top of the ears.

For encapsulated touch receptors, we can further categorise them based upon their adaptation rates. The Merkel disks are a SA type I receptor, producing a long and irregular discharge when an external force is applied to the skin. Ruffini corpuscles are

SA-II receptors that produce a regular discharge for steadily applied forces. The discharge rate of the Ruffini corpuscles increases linearly with the logarithm of the force applied. Meissner's corpuscles are RA-I receptors that discharge mainly on the onset of the initial stimulus, making them well suited for velocity detection. The Pacinian corpuscles discharge only once when stimulated, making them insensitive to constant pressure. This property makes them best suited for the detection of acceleration and vibration.

It is in the stimulation of these receptors that tactile feedback is applied. In order to attain a better understanding of the parameters required for meaningful interactions, information must be communicated in a manner that the human body can understand. For example, for all audio interactions, sound must be relayed within a bandwidth of 20 Hz to 20000 Hz. To allow for a meaningful tactile interaction, feedback designs must apply feedback within predefined parameters that our mechanoreceptors are receptive to.

3.2 Threshold of Detection: Pure and Complex Waveforms

The study of relationships between stimulus and sensation is known as psychophysics, a long established and documented field of modern psychology. A fundamental of psychophysics is the concept of a sensory threshold. In addition to this, theories of signal detection and the measurement of sensory magnitudes are pertinent to understanding and quantifying the essential requirements of effective haptic feedback and its role in human-computer interactions.

The *absolute threshold* or *stimulus threshold* is the smallest amount of stimulus energy required to produce sensation. A number of psychophysiological studies have been undertaken to quantify the intensity of touch sensation. That is to say, the point at which minimum touch energy is detected by the hand and the absolute threshold of detection that is derived from this. It has been found that although the absolute threshold of detection varies from person to person, it can be averaged at around 80 mg on the fingertips and 150 mg of force on the palm [78]. The intensity at which vibrotactile stimuli are detected is normally five to ten times greater than the absolute threshold and is dependent on frequency.

As was discussed earlier, the tactile information processing system operates as a multi-channel sensory system, one that is capable of cognitive operation through the qualitative and quantitative dimensions of sensory activity via experience. The tuning of tactile sensation is finite, yet is still capable of receiving information via unevenly distributed mechanoreceptors. As outlined earlier, frequencies that are cutaneously detectable fall within a range from 0.3 Hz to 1000 Hz, with a region of 100 to 500 Hz being the most sensitive [47]. Further studies have divided this range [79]. Within the range of 20 Hz to 40 Hz, the perception of vibration is independent from the vibration's frequency. However, between the frequencies of 40 Hz to 700 Hz our sensitivity can be dependent on frequency, with peak sensitivity at around 250 Hz [48]. An outline of this can be seen in Figure 3.2.

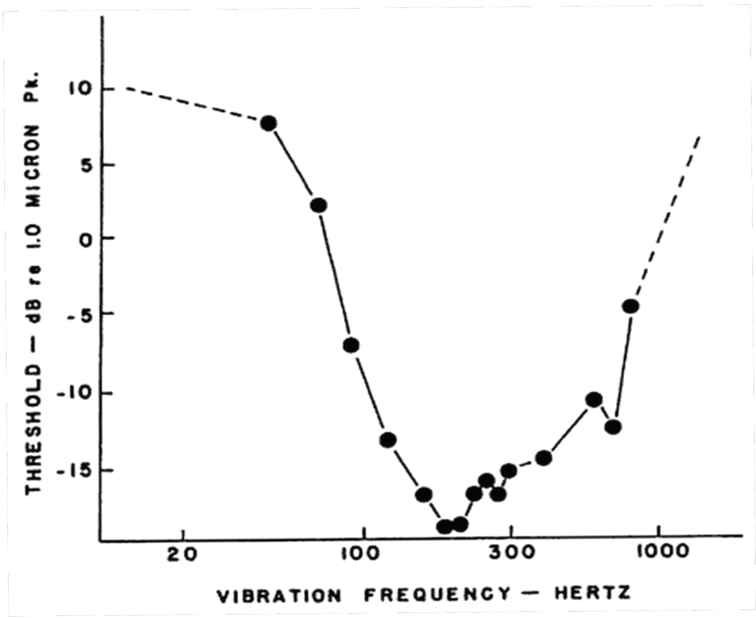


Figure 3.2: The absolute threshold of perception for mechanical vibration of the fingertip as a function of frequency, taken from Bolanowski et al. [88].

3.3 The Audio-Tactile Glove

It is suggested in this thesis that vibrotactile feedback is capable of providing essential information in the operation of DMIs. Before applying these principles to DMI designs, an experimental tool for the analysis of vibrotactile feedback was developed. The Audio-Tactile glove was designed and constructed as a research tool for investigating the various techniques used to apply vibrotactile theory to digital interfaces. When wearing the glove, the user receives vibrations via actuators distributed throughout. These are located so as not to interrupt the physical contact required between user and interface. Using this actuator array, vibrotactile information was independently applied to six stimulation points across each hand, exploiting the broad frequency range of the transducers contained within. The actuators operate with specific sensitivity within the tactile frequency range of the hand. It is proposed that within research areas that consider the inclusion of vibrotactile feedback in existing devices, it can be implemented and explored without altering initial interface or existing design.

Figure 3.3: The Audio-Tactile glove
[93].

The Audio-Tactile glove is equipped with six independent audio haptic exciters that are strategically placed upon the glove, see Figure 3.3. The device presents tactile information to the user through the stimulation of the receptors of the skin discussed earlier. The exciters are 9 mm miniature transducers capable of delivering a significant resonant output at frequencies most sensitive to haptic information. The transducers produce a nominally flat frequency response across their audio frequency bandwidth [80]. Although the underside of the hand is most sensitive to tactile perception [81], the actuators have been distributed on the back of each finger and the palm. This allows for direct contact between user and interface device, uninterrupted by the vibrating mechanisms. The user is able to freely grasp any master device comfortably whilst the glove maintains a consistent pressure against the skin surface. Flexible sub-surfaces run from the actuators to deliver tactile information as close as possible to the areas of the hand most sensitive to vibrational stimulus. These flexible surfaces produce internal structural bending waves, delivering both audio and vibrotactile frequency stimulation to the hand.

The logical linking of tactile feedback with vibrotactile transducers allows the user to sense vibrations through the skin. Tactile localization is achieved through the application of audio signals to the glove, correlating aural feedback with tactile feedback, reducing latency through computer processing of the feedback channels separately, and closing the interaction loop. The transducer array is also capable of producing simple vibration sensations such as pulses or more sustained stimulus supplied from any audio signal source. The combination of these two methods can be used to create complex, virtual tactile patterns, allowing for freedom in designing actuation profiles for a variety of applications.

With the Audio-Tactile Glove it is possible to modify the frequency input so as to create differences between vibrotactile feedback and instrument sound production. When using similar or atypical signals for sound generation and vibrotactile feedback it should be possible to achieve a multitude of special digital audio effects, such as:

- Filtering of audible frequencies to within the tactile range of human skin detection.
- Simulation of vibrations relating to other instruments within an ensemble.
- Amplitude compensation between audio and tactile receptors.

Tactile information is an important factor in VR and Computer-Aided Design (CAD) [76]. In these immersive environments, feedback is usually applied through audio or visual channels. However, the inclusion of haptic feedback here has been shown to improve virtual task efficiency [82]. The Audio-Tactile Glove can easily be integrated into such design processes, allowing vibrotactile stimulation to be an issue for consideration when doing so. This is especially important when virtual devices are models of real-world acoustic musical instruments. Rapid tactile feedback is important here due to the inherent nature of vibrating musical devices and the previous experience of the musician with real-world instruments. The inclusion of a tactile feedback network from a virtual device will allow for faster and more accurate playing [83] [84].

The glove offers several advantages over fixed actuator positioning within the instrument design processes. For one, the variable physical locating of such feedback devices can be overcome by placing the vibrating mechanisms directly in contact with the operator. In addition, the glove allows for the use of subtle vibrotactile feedback, which is much harder to implement in interfaces that incorporate a touch screen [84] [85]. Touch surface/screen devices do not intrinsically contain any tactile or kinaesthetic feedback, as there is no haptic indication of having pressed the screen. Vibrotactile feedback can be applied here without having to physically alter the interface mechanism. The inclusion of vibrotactile feedback in this circumstance can be applied to increase the quality of the user's experience with touch-based devices [76] [43]. Recent advances in touch surface technology are investigating the application of electrovibration for tactile feedback [86] [87]. These interfaces rely on constant movement and continuous contact between device and operator. Whilst this is advantageous in applications that require finger gestures, it is restrictive in others that require simple finger pressing to engage with the device, for example, a virtual piano keyboard. The ability to gauge the level of interaction and contact is complicated by the fact that movement of the hand upon the system in use is required.

3.4 Psychophysical Measurement of Vibration Thresholds: Absolute Sensitivity

The simplest measurement of tactile sensitivity to vibrotactile feedback is to determine the smallest amplitude of detection that can be perceived by a subject. Vibrotactile thresholds for stimuli have been presented in earlier studies [51] [88]. These findings provide us with a four-channel model of mechanoreception, which describes how the threshold of a neural channel is thought to change as the frequency of the vibration changes. The model presents the psychophysiological threshold of participants measured at particular frequencies, where the neural channel with the lowest threshold determines the absolute threshold. The threshold of high frequency detection is determined to be a product of stimulation of the Pacinian corpuscles, midrange frequencies by the Meissner’s corpuscles, and low frequencies by the Merkel disks. In the absence, damage, or lack of stimulation of the Pacinian corpuscles, the Ruffini corpuscles may be stimulated to detect high frequencies.

3.5 Vibration Thresholds: Experiment 1

The measurement of the absolute threshold of vibrotactile feedback served to advance the study of the sensory systems used for processing tactile information in haptic systems and the transducer technologies that can be used in its application. As mentioned earlier, this threshold is determined by a number of factors, such as the location of the stimulus, the size of the area being stimulated, and the frequency at which it is being vibrated. As our tactile system is susceptible to variation in its sensitivity to external stimuli, an experiment was conducted to confirm the possibility of successful vibrotactile feedback via the application of the Audio-Tactile Glove. Several measurements of threshold value were collected, averaged, and used to deduce an accurate estimation of the absolute threshold. The results of the experiment were expected to reinforce the characteristics of tactile sensation and indicate the minimum signal magnitude detectable across the frequency range of the glove [51] [88] [81]. The findings were used to chart the threshold of *just detectable* intensity levels of signals applied to the glove, outlining the minimum amplitude of frequencies detectable by users.

For this experiment, a variation of the *method of limits* was applied to determine the threshold of detection. Specifically, an *up-and-down* method was chosen, as it is a particularly efficient technique for determining thresholds and also provides satisfactory results when appropriate controls are observed. This method is less precise than constant stimuli techniques; however, it is less time consuming and can be observed in a wide variety of applications, for example, in audiometry. Additionally, when running constant stimuli experiments, it is common practice to give consideration of the thresholds determined by the method of limits as a general starting point for additional investigations.

3.5.1 Stimuli

In the experiment, a staircase method of limits (a classical psychophysical procedure) was applied to determine the absolute threshold of tactile stimulation for the perception of three types of waveform at a variety of frequencies. Three waveforms were applied to indicate if the minimum detection level was dependent on the complexity of the wave-shape. Specific frequencies within the bandwidth of the tactile range, 5 Hz to 1 kHz, were presented in random order via the Audio-Tactile Glove by outputting from a signal generator sine, saw, and square waveforms. The RMS voltage (Vrms) of the signal was measured by an oscilloscope and converted to decibels (dBv). This was repeated three times for each of the waveforms presented. The point at which a sensation was detected and no longer detected was recorded and the threshold was determined as a physical dimension that lay halfway between the last yes or no responses. Participants were asked to indicate their minimum perception of tactile stimulation applied across the specified vibrotactile range, as outlined earlier, by responding “yes” or “no”.

Participants were first presented with stimuli below the threshold of detection. The stimulus for the trial was then presented in an ascending series, followed by descending when the participant responded “yes”. That is to say, the value of the stimulus was increased in measured steps until the participant reported that the stimulus was detectable, indicated by the participant responding “yes”. At this point, the direction of change was reversed into a descending series, where the participant would respond “no” when the stimulus was no longer detected. This process was repeated until a sufficient number of response transition points were recorded. By adjusting the stimulus’ intensity by increasingly smaller amounts until the threshold of sensation was reached, the threshold of detection was determined. The final steps of which the stimulus was decreased or increased, determined an estimation of the threshold, which was dependent upon an average of the total values collected.

3.5.2 Participants

Ten postgraduate students (4 female, 6 male) aged 24 to 45 (M = 34.5) from University College Cork participated in the experiment. None of the participants indicated that they had had previous experience interacting with DMIs, but all were familiar with traditional musical instrument interaction. None of the participants were familiar with the Audio-Tactile glove or the term “tactile feedback”.

3.5.3 Apparatus

The experiment was conducted in a studio environment with all participants wearing audio isolation ear defenders to mask incidental sounds produced by the gloves. The vibrotactile stimulus was presented to the participants via the Audio-Tactile Gloves on both hands to account for left-right hand dominance. A signal generator was used to drive an amplifier, connected to both gloves, with three different waveform types across the frequency range defined below. The researcher, via an audio amplifier, gradually increased the amplitude of the signal being applied. The resultant input signal to the glove was metered and recorded via an oscilloscope with probes placed upon the input stage of the left glove.

3.5.4 Procedure

Participants were seated with their forearm resting on armrests, with both hands hanging loosely at the end. To prevent any visual cues, the participants were positioned facing 180° from test equipment with a barrier between. Three wave shapes provided the audio stimulus: sine, saw and square wave, presented in counterbalanced order. Each tone was applied in a five-second burst, in random order, across a frequency spectrum of 10 to 1000 Hz in twenty predetermined steps. The frequency of the tone selected was set at the signal generator and the amplitude was raised from zero until the participant could detect the onset of tactile stimulation. Prior to the moment of detection, no tactile stimulation would have been perceived. At the point of initial perception, the signal amplitude was lowered until the awareness of the signal was lost. These steps were repeated until a definitive threshold was acquired for each of the test frequencies. The amplitude of the signal was recorded and the frequency then adjusted. This procedure was repeated for all three wave-shapes.

3.5.5 Results

Figure 3.4 shows the mean thresholds for subject sensitivity to each of the waveforms tested. All participants presented with increased awareness of sine-wave stimulus across the frequency domain recorded. The square-wave signal was deemed to be the most difficult to perceive across this range. Participants were able to recognize frequencies below 20 Hz, describing them as simple “clicks”. As the applied signal’s frequency was increased beyond this point, the perception of vibration was reduced up to the 60 Hz mark. At this frequency, the sensitivity to applied signals increased and peaked across the range of 100 to 400 Hz, with peak sensitivity at 160 to 200 Hz. Participant sensitivity to the perception of applied signals reduced again above the peak sensitivity range. Participants indicated uncertainty of detection at higher frequencies as opposed to lower, and none were able to detect frequencies above 1000 Hz.

To test for an overall experimental effect of waveform type, a one-way repeated measure ANOVA (used as each subject was measured on the same continuous scale on three different occasions) was conducted to compare mean amplitudes for the sine, saw, and square waveforms across the frequency range measured. A significant effect for waveform type across all frequencies was found. Post-hoc comparisons were then implemented to indicate which of the waveforms were significantly different from the other. This revealed significant differences between all three of the waveform types, with $p < .001$ in all cases.

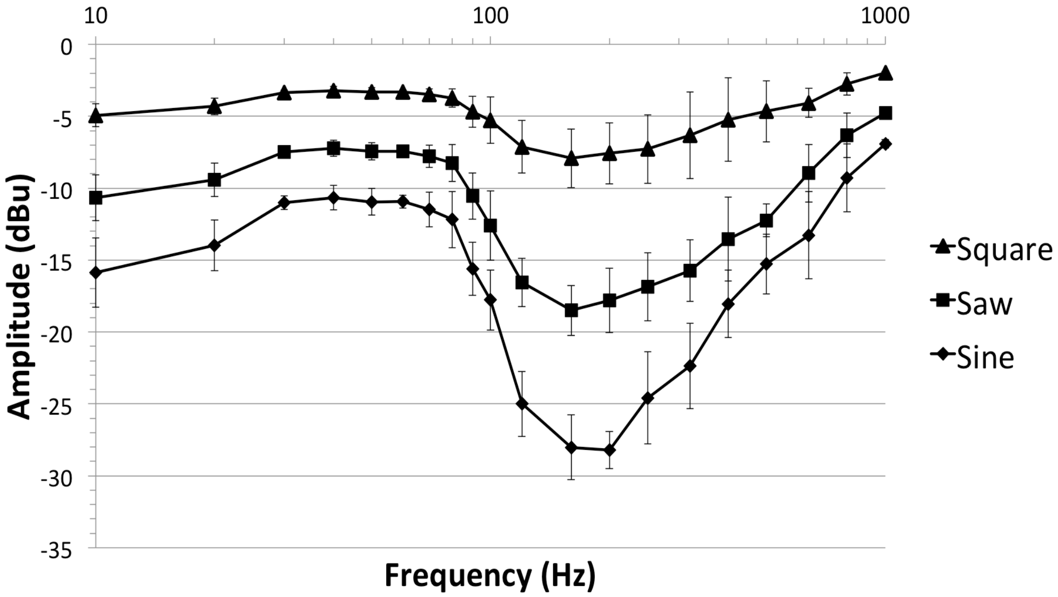


Figure 3.4: Mean threshold for subject sensitivity to sine, saw, and square waveforms.

3.5.6 Discussion of Results: Experiment 1

The experiment findings support previous research found in tactile perception materials discussed. The peak sensitivity range was found to be between 100 to 400 Hz as specified earlier. Although our participants indicated no detection of vibrotactile stimulation above 1000 Hz, research has suggested that humans are sensitive to vibrations at frequencies of 2 to 4 kHz [89]. However, amplitudes for detection in this range are required to be much higher than for peak sensitivity. As the actuator choice for the Audio-Tactile Glove are capable of producing frequencies in this range, possible further applications could be investigated.

The experiment also indicated that the Audio-Tactile glove can be applied to haptic models that require vibrotactile elements. This may be relevant for designers of DMIs and digital audio effects researchers who are considering tactile feedback in their designs, but are exploring different modes of application. The physical perception of tactile information being delivered concurrently with sonic events should allow for designers to explore appropriate feedback techniques without augmenting their interfaces. It is proposed that this will be particularly useful for researchers and designers of new musical interfaces, as it allows the end users to experience tactile feedback in a passive or active activity.

The incorporation of motion capture and wireless interactivity can allow researchers to investigate the application of vibrotactile feedback in bodiless interfaces. Virtual fields can be highlighted via Tactile Simulation Events (TSEs) and with the frequency response of the Audio-Tactile glove being much wider than fixed or narrow band actuators, 3D spatialisation may be made possible. This will assist in the creation of larger interactive spaces for artists to perform in. The Audio-Tactile Glove may also be applied to assistive technologies. For example, it may assist in the rendering of complex data into tactile information for the visually impaired. Another application in this field could be in the creation of tactile cues for the deaf or hearing impaired. This function could aid in the inclusion of otherwise ignored or dissuaded musicians. Vibrotactile feedback has been successfully applied via fixed vibration matrices for semi-autonomous wheelchair guidance and hand rehabilitation; the inclusion of a small, wide frequency transducer may expand these areas further [90] [91]. Other demonstrations and informal observations of the Audio-Tactile Glove have indicated that the increased tactile response from DMIs, when wearing the device during operation, can significantly increase user engagement. This has been observed as particularly relevant for users of new musical devices or devices that produce non-traditional audio outputs.

3.6 Vibrotactile Discrimination of Pure and Complex Waveforms: Experiment 2

This experiment measured the participants' ability to discriminate between pure and complex waveforms based upon vibrotactile stimulus alone. Subjective same/different awareness was captured for paired combinations of sine, saw, and square waveforms at a fixed fundamental frequency of 160 Hz (f_0). Each arrangement was presented non-sequentially via the Audio-Tactile glove. Audio and bone conduction stimulus were removed via headphones and tactile noise masking respectively. The results from earlier experiments have indicated that humans possess the ability to distinguish between different instrument timbres via vibrotactile stimulation presented asynchronously to the lumbar region [92]. It is proposed within this thesis that this form of interaction may be developed further to advance DMI extra-auditory interactions.

3.6.1 Stimuli

The vibrotactile stimuli applied during all experiment two conditions were sine, saw, and square waveforms of 160 Hz (referred to as S_1, S_2, and S_3 respectively from here). This particular frequency was chosen as it was discovered to have the lowest sub-threshold of perception in our earlier experiments conducted with the Audio-Tactile glove [93]. This frequency lies between the musical notes D3# and E3 (equal temperament scale), removing any advantage a musician may have through experience. The output amplitude of each waveform sample was adjusted to fit within the tactile sensitivity range of 160 Hz (Figure 3.4). Output levels from the test equipment to the vibrotactile gloves were pre-set to the following parameters: S_1 = -25 dBu, S_2 = -17 dBu, and S_3 = -8 dBu. Waveforms were outputted via a digital-analogue audio converter (Avid Fast Track C400) with a sampling frequency of 96 kHz and 24-bit resolution. The audio output was routed through output channel one of the converter and split to the left and right gloves in parallel, as in experiment one. Participants were presented with digitally generated waveforms using Audacity (an open source wave editing software) at the pre-set fundamental (f_0 = 160 Hz). Waveform clips were recorded and then randomly selected from an audio library. Each clip consisted of a 2-second waveform sample, a one second inter-stimulus time (IST), followed by a second 2-second waveform sample.

Participants wore the Audio-Tactile gloves, with each of the six voice-coil actuators activated. Vibrotactile waveforms were delivered to each actuator in unison. The signal was applied to both hands simultaneously in order to control for increased dominant hand sensitivity and other variances of hand sensitivity that may have pre-existed for the participant. In order to mask incidental sound production from the gloves and bone conduction through the skeletal structure, a white noise signal was presented over Sennheiser HD 215 headphones at 60 dB SPL. The same white noise signal was applied to the lower mastoids via tactile exciters contained within a specially constructed collar. Validated bone conduction masking parameters were followed as suggested by Wilson et al. [94].

3.6.2 Participants

Thirty participants attended the session for this experiment. Physiological pre-testing was not performed on individual participants; however, participants self-reported as having no reduced feeling or other impairments of their hands. All participants were recruited from University College Cork and the surrounding community area. After initial pre-testing and set-up, three participants were removed from the study as they presented with a reduced sensitivity to vibrotactile stimuli; below that of the average levels recorded in the Vibration Thresholds experiment for 160 Hz. However, this was expected due to the standard deviations measured around the subthreshold of detection. Of the remaining participants, seventeen self-identified as being musicians; having been formally trained or regularly performing in the last five years. For this group, the age range was 21 to 35 (M = 25.94, SD = 4.21) consisting of 10 males and 7 females. Of the remaining non-musical participants, their age ranged from 23 to 49 (M = 34.08, SD = 8.23) and the group consisted of 5 males and 5 females.

3.6.3 Experimental Conditions

The experiment examined the ability of participants to discriminate between different vibrotactile stimuli presented at the appropriate sub-threshold for the waveform type. For all experimental conditions, participants were seated in a studio environment with forearms resting on armrests and hands placed in a relaxed position. Participants were asked to make same-different judgements for each trial. This experimental procedure was chosen to remove any ambiguity in participants explaining the differences they experienced between the three waveforms presented. Participants were asked to indicate if the two stimuli were the same or different by saying “same” or “different”. The objective was not to determine the specific cue of the stimuli, but to simply determine the discriminability of each waveform. Three blocks of recorded trials followed a practice period of two blocks. Each trial consisted of the presentation of two stimuli, which were either the same or different. The waveform pairs were presented in counterbalanced order. All possible waveform pairs were presented within each block. Each block of samples contained three matched and six mismatched pairs. Thus, the recorded results consisted of 27 clips in total; 9 matched and 18 mismatched paired samples.

The earlier experiments with the Audio-Tactile Glove presented results in tactile detection levels, including the discrimination of complex waveforms [93]. The sub-threshold of detection for complex waveforms was measured as output amplitudes in dBu (Figure 3.4). These values were used to minimise perceived amplitude differences in waveforms for our current experiment. The sub-threshold of vibrotactile stimulus detection can be divided into distinct sub-ranges, pertaining to the frequencies that are cutaneously detectable and the waveform being applied. The stimuli presented during experimentation at f_0 were delivered with the adjusted output amplitudes dependent on the waveform; they were also applied in synchronous phase.

3.6.4 Results

To investigate if there were any significant changes in participant responses to waveform presentation order, a Wilcoxon Signed Rank Test was carried out (designed for use with repeated measures; when participants are measured under two different conditions). This test revealed that there was no statistically significant effect for the order of waveform presentation; S_1- S_2/S_2- S_1 (z = 0, p = 1), with no significant effect size (r = ns); S_2- S_3/S_2- S_3 (z = 1.13, p = .26), with a small effect size (r = 0.14); S_3-S_1/S_1- S_3 (z = 1.73, p = .083), with a medium effect size (r = 0.22). There was also no change in the median for each waveform pair. Therefore, it was deemed possible to collapse the proportion of correct response results across these complementary pairs. Table 3.1 shows the same-different responses for each stimulus pair after collapsing. This data was subjected to a Signal Detection Theory analysis and the effects of bias were removed. Specifically, hit and false alarm rate data was analysed to calculate a sensitivity measure of d` and an unbiased proportion correct probability was determined from Table 5.3 in the MacMillan and Creelman textbook [109]. A higher d` indicates that the signal could be more readily detected.

Table 3.1: Proportion correct for same-different independent observations.

	Response		Same-Different (Independent Observation)				
Stimulus Pair	Different	Same	Hit (H)	False Alarm (F)	z(H)-z(F)	p(c) unb	d'
S_1- S_2 or S_2- S_1	0.89	0.11	0.89	0.07	2.67	0.91	3.33
S_1- S_1	0.07	0.93	0.93	0.11			
S_2- S_3 or S_3- S_2	0.96	0.04	0.96	0.04	3.57	0.96	4.16
S_2- S_2	0.04	0.96	0.96	0.04			
S_1- S_3 or S_3- S_1	0.81	0.19	0.81	0.07	2.34	0.88	3.03
S_3- S_3	0.07	0.93	0.93	0.19			

To compare the adjusted mean percentage of correct answers for the musician and non-musician groups, a Mann-Whitney U Test was conducted (a technique used to test for differences between two independent groups). In this case, a non-parametric statistical test was selected due to its robustness for non-normality and the relatively small number of participants that were observed. There was found to be no significant difference in scores for musicians (Md = 0.98, n = 13) and non-musicians (Md = 0.98, n = 17); U = 69.5, z = –2.21, p = .086, r = .4.

3.6.5 Discussion of Results

The results from the second experiment identified that participants could successfully recognise different waveforms (or *haptic timbres*) based on waveform shape alone (as distinct from waveform envelope) when presented in isolation to the hand. These findings support previous research undertaken by Russo et al. relating to the vibrotactile discrimination of musical timbres [92]. The experiment here has expanded these findings further by applying the stimuli directly to our participants' hands via the Audio-Tactile Glove, compensating for waveform envelope shape, and perceived equality of stimulus amplitude. In addition to this, musicians and non-musicians were also compared and it was found that there was no significant difference in vibrational sensitivity that may have been attained through the extended use of acoustic musical instruments. The data gathered from this experiment supports a theoretical operation of combined critical band filtering that is carried out by the sensory receptor arrays within human glabrous skin; specifically, in the ventral portion the fingers and the surfaces of the palms of the hand at a fixed fundamental of 160 Hz. It is predicted that the stimulus of the four main types of mechanoreceptors outlined earlier and their individual responses to mechanical displacement function as frequency-tuned filters whilst experiencing complex tones. This filtering of complex tonality into component frequencies, with relative intensities, contributes to the tactile perception of differing timbres.

Studying the subjective, contextual, and physiological gestural characteristics of musical instrument interactions, highlights the importance of feedback via primary, secondary, and other lesser pathways from instrument to musician. The tactile component of haptic feedback, which is considered in this thesis, provides an insight into the complexity of primary/secondary and passive/active feedback in multimodal communications. During the playing of musical instruments, the auditory system takes on the role of primary feedback processor. In this context, the other senses operate as secondary feedback signals, primarily relating to the instrument's physical response to gestural inputs. In addition, worthy of note is the difference between active and passive feedback, as passive feedback was applied in our experiments. Passive feedback relates to the feedback provided through the physical characteristics of the system in use, that is, the manner in which the systems input mode responds when affected. Active feedback is produced by the system in response to a specific user action, a sound produced within for example. Further experimentation applied in DMI interactions may reveal supplementary information about the role of active feedback in explorative and musical performances.

3.7 Auditory Discrimination of Pure and Complex Waveforms Combined with Vibrotactile Feedback: Experiment 3

Here we present a final experiment to investigate the application of vibrotactile stimulus in auditory pitch differentiation detection tasks. Extra-auditory information in the form of vibrotactile feedback was expected to have some influence upon the frequency discrimination of auditory Just Noticeable Difference (JND) detection levels. The experiment explored the effects of vibrotactile feedback in combination with auditory to discriminate frequency shifts around 160 Hz. The potential for correctly identified positive and negative frequency changes for two randomly divided groups was measured and compared. The first group was given an audio only JND test and the second group was given the same test, but with additional vibrotactile stimulus delivered via the Audio-tactile Gloves. The results of the experiment suggest that vibrotactile feedback applied in musical interactions that involve the selection of specific pitches and the detection of pitch variation may have some effect upon a musician's ability to perceive these changes when presented synchronously with auditory stimulus.

3.7.1 Extended Background: Experiment 3

The manner in which auditory and haptic cues are integrated into musical performances with acoustic instruments are detailed in the findings of a number of studies, outlining the role therein of human senses beyond that of the auditory modality [47] [48] [55]. Other research has also shown that the neural substrates of both the auditory and tactile systems are shared at a much lower level than previously understood [95]. A cross-modal effect has been demonstrated in the tactile illusions that transpire from the modification of related audio stimuli, as seen in the “Parchment-skin illusion” [96]. Other auditory-tactile interactions have shown that tactile stimulus can influence auditory stimulus and vice-versa [97] [98] [99]. It can therefore be observed that auditory and tactile stimuli are capable of modifying or altering our perception of each when presented in unison. Although closely related to the work described so far, the experiment presented here distinguishes itself from others by primarily focusing on the detection of frequency change for both pure tone (sine wave) and complex waveforms (saw and square waves); and secondly, the musical ability of the participant was also considered.

Auditory and tactile feedback occurs in unison for most musical interactions that involve acoustic instruments, but tactile feedback itself rarely presents at a cognitive or decision making level. The function of vibrotactile cues and their input into the field of perceptual materials has been a major contributory factor in how music is perceived. These include the influences of tactile and auditory feedback upon a performer, the performer's understanding of the musical structure of a piece of music, and the portrayal of a score's content [35] [100] [101]. The conclusions found in such research suggests that multimodal sensory cues are responsible for indirectly augmenting the auditory perception of music. Unlike visual scores, haptic cues in a musical performance are captured via contact with vibrating sound-emanating objects. During a musical performance with an acoustic instrument, the control mechanisms of the performer rely on the multi-modal feedback produced by the instrument [10]. Feedback presents itself to the musician and they are then able to adjust and maneuver their bodies in response. Regardless of the manner of the interaction, via finger, hand, or lip placement, vibrotactile feedback remains constant with auditory feedback [10] [51]. The transmission of vibrations to the performer in these interactions are an integral feature that directly relates to the design requirements of the acoustic instrument in use.

Acoustic musical instruments provide vibratory feedback that is tightly coupled with the sound-generating module of the instrument. The relationship between gestural interface and sound generator is almost always inseparable and vibrations that are introduced outside of this relationship are considered as distracting or noisy. Digital Musical Instruments (DMIs) are capable of extending musical interactions beyond that of the acoustic experience and vibrotactile feedback may be applied here to further enhance the intercommunications that may be afforded through this medium.

The findings of Gillmeister and Eimer have highlighted the function of vibrotactile intensity enhancements when tactile stimulus is presented synchronously with auditory stimulus [97]. The interactions between the two stimuli produce mutual benefits and they follow principles of inverse effectiveness and the temporal rule of multisensory integration that has been discussed in previous research. It is therefore suggested that the parameters of feedback applied in DMI design should also include vibrotactile information relating to the sound source being generated. However, the application of vibratory data in a DMI interaction will ultimately depend on the musician's ability to process this information in relation to the audio/visual feedback they are already simultaneously receiving.

3.7.2 Previous Physiological and Psychophysiological Studies

The examinations presented so far have focused upon combined feedback applied to both auditory and tactile systems. Auditory and tactile communications result from sensory stimulation via physical mechanical pressure in the form of oscillations [51] [102]. Mechanical vibrations within the cochlea and against the mechanoreceptors of the skin activate neural impulses that are ultimately processed by the brain. The relationship between the neural processing of these two modalities of transduction has been discussed in earlier research [102]. Both audio and tactile stimuli overlap in the same frequency range. However, one limitation of interactions involving both hearing and touch is the increased sensitivity of the ear in comparison to the skin.

Previous experiments with audio frequency vibrotactile feedback have presented absolute thresholds of tactile detection for both simple and complex waveforms [93]. From this, the sub-thresholds of vibrotactile stimulus detection can be divided into distinct ranges pertaining to the frequencies that are cutaneously detectable and the waveforms being applied. This can also be seen in the absolute threshold of hearing, but over a much wider range. On average, the ear functions within an auditory range of approximately 20 to 20 kHz, while the tactile range of the skin encompasses a much narrower range of only 0.3 to 1 kHz. Within the overlapping ranges, vibrotactile information has been shown to stimulate the auditory cortex and tactile and auditory information may be perceived as interleaved signals [103] [104]. Furthermore, previous research has also shown that the auditory and vibrotactile systems combine whilst performing objective detection tasks, regardless of the relative phase or the temporal synchrony of the stimulus [94]. This indicates that both neural pathways of the auditory and tactile systems combine through a common or related network.

Other studies have shown evidence of interaction between auditory and somatosensory systems at a multitude of stages within the human central nervous system [105]. The combination of the two sensory modalities exceeds the predicted uni-sensory summation of the two stimuli alone, suggesting that multisensory convergences occur at a much lower level than previously believed. Enhancements in auditory processing through the addition of tactile feedback have been observed and this elevates the response speeds to those of suprathreshold stimuli [106]. It has also been observed that improvements in the intensity perception of faint tones can be achieved with extra-auditory stimulus [107]. Other studies have indicated that the detection of a stimulus can be enhanced when simultaneously registering with two or more sensory modalities

[2]. These findings demonstrate how the reinforcement of neural activity occurs when two modalities stimulate in near unison of time and place. More recent psychophysical studies have focused on the ability to discriminate between vibrotactile tonalities whilst being masked from an auditory source [102] [94] [92].

These findings support the theory that the simultaneous combination of tactile and audio stimulation positively influences the perceptual frequency discrimination of the sensory system. This is mainly attributed to the low-level integration of these two modalities in the cortical system. The relationships between the strengths of these two modes of stimulus should directly relate to the individual psychophysical models constructed for human senses. In this context, numerous examples of singular sensory modality interactions have been measured, but it is rarely the case in music that one singular sense is operating alone in any one interaction. In music, many events and occurrences seek to compete for combined sensory attention and a multitude of these are capable of stimulating in several ways at once. We have therefore chosen to focus our current study on audio frequency tactile stimulus as a supporting sensory input. Synchronous audio-tactile events are particularly ingrained in acoustic musical instrument performances where these combined perceptual aspects are innately integrated. However, they are rarely included in commercial digital artefacts that are applied in the creation of music. It is therefore suggested that vibrotactile feedback may be applied in these devices to improve the user's perception of musical pitch variation.

3.7.3 Pitch Discrimination of Pure and Complex Waveforms

This experiment was designed to measure the pitch perception abilities of two groups for pure and complex waveforms at a fundamental frequency of 160 Hz. Due to audio stimuli being the more appropriate sense applied in music, participants were instructed to focus upon the auditory stimulus when making judgements. The experiment was undertaken to highlight the effects of extra-auditory vibrotactile stimuli on JND measures. The context of this study was to investigate these relationships in a music domain; therefore, participants were asked to self-identify as musicians or as non-musician based upon a strict criterion.

3.7.4 Experiment Method

A two-alternative forced choice (2AFC) frequency discrimination task was used to measure the participants' sensitivity to the applied stimuli. This technique is theoretically uncontaminated by fluctuations in criterion, but a response bias towards one observations may still exist [108]. Although extreme response strategies are rare in 2AFC tasks, the forced choice design does not guarantee the complete absence of bias. Therefore, to measure true sensitivity, bias must be eliminated. This was achieved by calculating d' from hit and false-alarm data and correcting the proportion of correct responses for bias, $p(c)_{unb}$.

3.7.5 Participants

The participants were randomly divided into two groups by coin flip: Auditory-only (heads) or Auditory-Tactile (tails). The participants then identified as being musician or non-musician based upon having been formally trained and actively performing regularly in the last five years. The Auditory-only group consisted of 10 males and 5 females aged 22 to 49 (*MD* = 28; *SD* = 8.79). In this group, 7 participants identified as musicians and 8 as non-musicians. The Audio-Tactile group consisted of 8 males and 7 females aged 21 to 40 (*MD* = 28; *SD* = 6.26). In this group, 10 participants self-identified as musicians and 5 as non-musicians. Physiological pre-testing was not performed on individual participants; however, participants self-reported as having no hearing difficulties or other physical impairments.

3.7.6 Experiment Design

Participants were seated in a soundproofed studio and asked to evaluate the relative pitch of two short audio samples. For the Auditory-only group, dual mono audio stimuli were delivered via Sennheiser HD215 headphones at 60 dB SPL (conversational speech at 1m). Participants were given the opportunity to adjust the headphone volume for comfort, but only if required. For the combined Auditory-Tactile group, dual mono audio and vibrotactile stimuli were delivered to both ears and hands in unison via Sennheiser headphones and a vibrating glove device. The stimuli were applied to both hands simultaneously to control for increased dominant hand sensitivity or other variances of hand sensitivity that may have pre-existed.

3.7.7 Experiment Stimuli

Digital waveforms were generated using an open source wave editing software (Audacity) at a fundamental frequency of 160 Hz. The phase and synchrony of the applied waveforms were kept constant by delivering the stimulus with the same onset time and with constant stimulus and inter-stimulus times (IST). Samples were arranged into five-second clips. Each clip consisted of a 2-second waveform, a one second IST, and a further 2-second waveform. The two waveforms varied in frequency from each other by ± 0.25, 0.5, 0.8, 1, 1.5, 2, 3, 4, 6, 8, 12 Hz. Each waveform clip was stored and then presented to the participant three times during the experiment in a counterbalanced order. Waveforms were outputted via a digital-analogue audio converter (Avid Fast Track C400) with a sampling frequency of 96 kHz and 24-bit resolution. The audio-only signal was routed through output channel one of the converter directly to the headphones. The same signal was also routed through output channel 2 and split to the left and right hand vibrating devices in parallel. Peak-to-peak measurements of amplitude were taken at the input stage of the left-hand vibrating device.

3.7.8 Waveform Types

The auditory and vibrotactile stimuli applied during all experiment conditions were sine, saw, and square waveforms, with no aliasing for the square waveform. As different musical instruments each produce unique timbres, each instrument sounds quite different when they present with the same fundamental pitch. Therefore, complex waveforms were used in this study to represent the different instrumental tone qualities that a listener may be exposed to in a performance. The chosen waveforms displayed no harmonics (sine), odd harmonics only (saw), and odd and even harmonics (square) of the chosen fundamental. This allowed for the control of multidimensional aspects of waveform generation beyond frequency and amplitude while also considering the effect of timbre in the experiment.

The fundamental frequency of 160 Hz was chosen as it was observed as having the lowest sub-threshold of perception in earlier experiments. Furthermore, 160 Hz lies between the musical notes D3# and E3 (on an equal temperament scale), controlling for any advantage the musicians may have had through experience. The output amplitude of each waveform sample was adjusted to fit within the tactile sensitivity range for 160 Hz. Waveform output levels from the test equipment to the vibrotactile gloves were pre-set to the following parameters: sine = -28.02 dBu, saw = -18.5 dBu, and square = -7.91 dBu measured at the input stage of the left glove. Participants were asked to verbally verify that the amplitudes of each of the tactile stimuli were perceptually equal during the initial setup period and trial stages of the experiment.

For each participant, hit and false alarm data was transformed to calculate an independent observation for d'. This value was then used to define the unbiased proportion of correct 'Higher' responses, $p(c)_{unb}$ (Table 5.3 in Macmillan and Creelman, Detection theory: A user's guide" [109]), and averaged across all participants. A logistic function of mean $p(c)_{unb}$ was applied to fit data to a psychometric function for each waveform, (equation 1), where f = frequency and p = the unbiased proportion of responses that f was judged higher than 160 Hz. Following this, JND_{75} was calculated using equation 1.

$$JND_{75} = B - \frac{1}{A \log\frac{1-0.75}{0.75}} \quad \text{(equ.1)}$$

$$A(f - B) = -\log\frac{1\times p}{p} \quad \text{(equ. 2)}$$

3.7.9 Results: Experiment 3

Table 3.2: Descriptive Statistics

Auditory-only	Musicianship	PSE	JND_{75}	r^2	Mean	SD
Sine	Non-Musician	160.00	162.34	.86	.75	.09
	Musician	159.97	162.07	.84	.77	.07
Saw	Non-Musician	160.00	162.24	.85	.76	.08
	Musician	159.98	161.85	.8	.85	.09
Square	Non-Musician	160.00	162.04	.85	.8	.12
	Musician	159.97	161.95	.83	.86	.12
Auditory-Tactile						
Sine	Non-Musician	160.00	161.82	.79	.88	.07
	Musician	159.98	161.75	.74	.94	.06
Saw	Non-Musician	160.00	161.97	.83	.83	.16
	Musician	160.00	161.75	.75	.92	.06
Square	Non-Musician	160.00	161.8	.8	.89	.08
	Musician	160.00	161.73	.76	.94	.04

Table 3.3: Two-Way Between Groups ANOVA

Interaction Effect	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta^2
Grouping* Musicianship	< .001	1	< .001	.013	.91	< .001
Main Effect						
Grouping	.205	1	.21	26.08	< .001	.25
Waveform	.025	2	.01	1.56	.22	.04
Musicianship	.078	1	.08	9.954	.002	.11

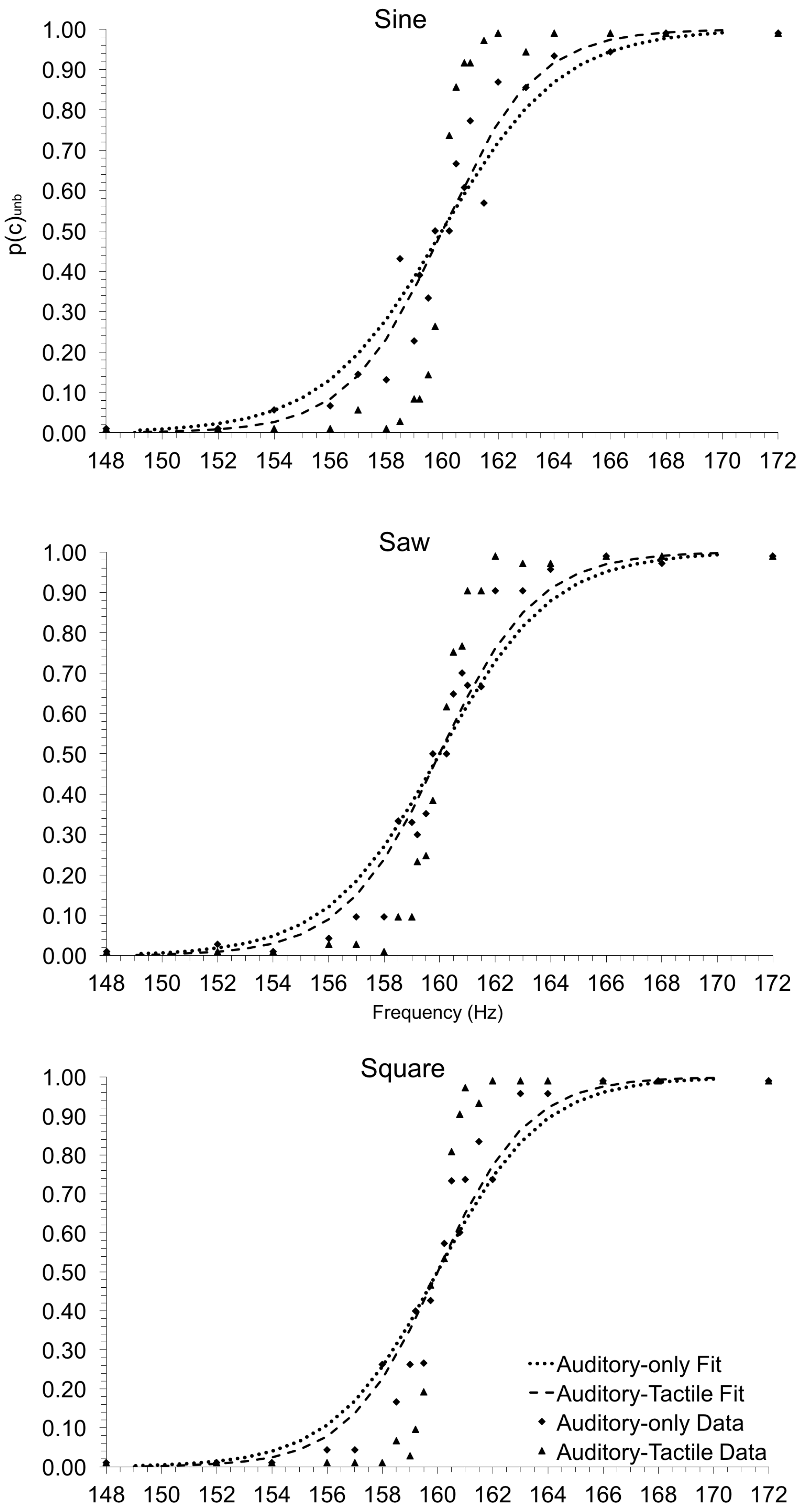


Figure 3.5: Psychometric functions for sine, saw, and square waveforms between Audio-only and Audio-Tactile groups.

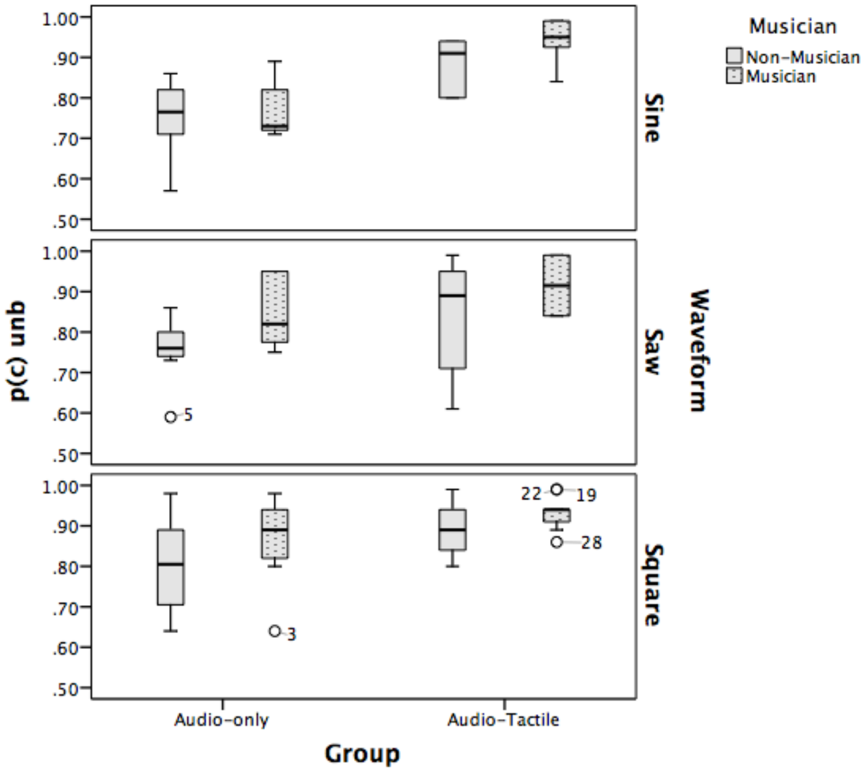


Figure 3.6: Box plots representing median $p(c)_{unb}$ across all waveforms and musicianship (outlying participants indicated by circles)

From the results presented, it was observed that the detection of frequency changes in the order of ± 12 Hz at a fundamental frequency of 160 Hz can be facilitated by the simultaneous cross-modal presentation of auditory and vibrotactile stimuli. When auditory-only feedback was combined with vibrotactile feedback there was seen to be a statistically significant improvement in the Audio-Tactile group's ability to discriminate between auditory frequency variations above that of levels when auditory stimulation was presented alone.

To explore the impact of test grouping and musicianship on the unbiased proportion of correct 'Higher' responses, a two-way between-group analysis of variance was conducted (a technique that looks at the individual and joint effect of two independent variables on one dependent variable). In this experiment, only the main effect for grouping reached statistical significance. This meant that the variables of waveform and musicianship did not present any interaction effect in the experiment results. In addition to this, there was found to be a significant increase in frequency discrimination within both groups for musicians, with a medium to large effect size. In many ways this is what would be expected from this group, as musicians spend many hours conducting pitch exercises as a part of their general training. This presents some indication that previous experience should be a factor of analysis in the examination of haptic feedback. However, as there was found to be no interaction effect between the independent variables of grouping and musicianship, this indicated that the number of musicians in each group were not responsible for the changes that occurred between the two groups. These findings are congruent with studies that suggest that there is a close relationship between auditory and somatosensory stimulation in the auditory cortex of the brain. This relationship has also been directly observed in fMRI observations that capture the mapping of audio-tactile co-activation in the auditory belt areas of the brain [110].

Interesting results were observed in the participants' responses to pure and complex waveforms. Although the main effect of waveform was not significant, the sinewave presented with a much more distinct curve between groups than for both of the complex waveforms. This indicated that in the application of extra-auditory vibrotactile feedback in pitch detection exercises, the complexity of the waveform has some influence upon the perception of pitch; however, this effect is less noticeable for more complex waveforms. This does not diminish the potential application of complex waveforms in vibrotactile feedback, but suggests that in real-world applications a balance between simple and complex waveforms must be explored. This also presents an ideal waveform type for examination in later chapters.

3.7.10 Discussion of Results: Experiment 3

The experiment presented interesting data relating to expected values of JND_{75} as the JND of the tactile system is observed as being much broader than that of the auditory. For example, the expected tactile only JND of a 150 Hz sinusoidal stimulus with amplitude held constant has been measured as ± 18% (27 Hz) of the fundamental [111], equating to 28.8 Hz at 160 Hz. In addition, in an auditory only JND experiment there would be expected to be a 3 Hz variation in JND for sinewave and 1 Hz for complex waveforms below 500 Hz [112]. As can be seen in Table 1, the JND_{75} results for the Audio-only group presented with an average of 2.33 Hz for sine waveforms, 2.22 Hz for saw, and 2.06 Hz for square waveforms. In the combined Audio-Tactile group, there were observed small improvements in JND_{75} values. For the sine waveforms, the JND was measured at 1.83 Hz and the observed JND for the complex waveforms measured as 1.89 Hz and 1.78 for saw and square respectively. This indicates that the JND for all waveforms was perceived relatively equal, with only a small improvement when vibrotactile information was included. However, although there is a relatively broad JND for the tactile system, when combined with auditory stimuli, it appeared to have some small practical effect upon this group's average JND values for all waveforms.

In conclusion of this experiment, the role of extra-auditory vibrotactile feedback was quantified and items of concern for future DMI design were formulated and studied. In respect of these findings and their potential application to musical interactions, it can be recommended that the adoption of a combined psychophysical model is required to reinforce the role of somatosensory integration in frequency discrimination tasks that are to be carried out in the DMI design analysis of Chapter 5. This will allow for the creation of multisensory interfaces that are transparent and intuitive for users to operate during musical exercises and performances.

3.8 Influences of Tactile feedback in the Evaluation of DMI Design and Computer Music Performance

As was discussed earlier, acoustic musical instruments convey information to the user in the form of audio, visual, and haptic stimulation. The physical properties of vibration generation in acoustic instruments cause the interface to vibrate in sympathy to the gestures applied to them. These vibrations qualify as tactile feedback, creating a tight relationship between the instrument and the person using it. In comparison, the majority of electronic and digital interfaces require no direct contact with a control surface, returning zero tactile feedback to the user. By combining both tactile with kinaesthetic feedback from a digital or virtual instrument, haptic information can be passed to the user, allowing for increased control in articulation. As the method of sound synthesis in DMIs and virtual instruments is usually dealt with separately, DMIs have been observed failing to close the feedback loop.

DMIs that require no physical contact with a device are often controlled via hand gestures; these are captured and then relayed as control data for the control of some synthesis parameters within an external audio synthesis engine. Bodiless and open-air instruments make use of video cameras and motion capturing (MOCAP) software to manipulate synthesis parameters [113] [114]. Other methods include ultrasonic or infrared sensors contained within a central transmitter [115] [116]. Historically, the most common form of bodiless interfaces incorporates a glove [117] [118]. These allowed for the capture of finger, hand, and arm movements. The capture of such small movements with no feedback to the performer present some interesting performance and design challenges. The performer is presented with visual and proprioceptive feedback relating to their body position along with the audio response of their actions. This is adequate for most applications, but it has been observed that performers who have mastered their instrument make use of haptic feedback cues in performance [119]. Additional to this, instruments that lack haptic feedback can also present a *disconnect* between performer and device, creating a sense of loss in the sound produced and how the sounds are derived from the movement [10].

The simplest method of introducing tactile feedback (a major factor of the overall haptic feedback system) is by allowing the instrument itself to take control of sound generation, for example via embedded speakers [10]. The use of vibrotactile feedback

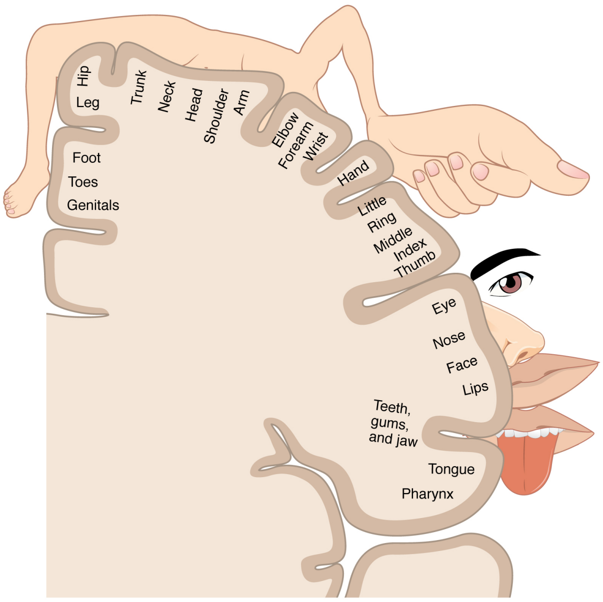


Figure 3.7: A cortical homunculus (a physical representation of the human body, located within the brain).

for the control of physically modelled sounds allows performers to distinguish between different modes of vibration, creating a virtual tactile range within which to operate. For bodiless controllers, the introduction of vibrotactile feedback creates virtual space for determining position, assisting in the positioning of the hand. This has been achieved via TSEs as seen in [120]. These techniques highlight that direct audio frequency vibrotactile feedback is not necessarily meaningful to the performer, but new vibration signals may be introduced to create feedback that is more meaningful. Another negative aspect is that in the application of these techniques a fixed or narrow bandwidth of frequency actuator retards the application of vibrotactile messaging.

By observing the similarities between touch and hearing, indication of a cross modal sensory interaction has been presented. This is apparent in terms of; the type of physical energy captured, the receptors used in their detection, and the relatively short overlap of the frequency domains. This is prevalent in most musical performance, the sound generation and tactile analysis frequently occur in tandem. In tasks that involve textural analysis of an object, the tactile system is dominant. However, in musical tasks, the auditory modality takes precedence. Due to the sensory dominance of hearing over tactile, the interaction between both generally goes unnoticed.

The sensations of tactile signals are bounded to a limited range, and an individual's sensitivity to a stimulus. Following this, it can be said vibrotactile feedback from a musical instrument is secondary to that of auditory feedback in a multimodal signal. Moreover, vibrotactile feedback in a musical performance is not the primary source of feedback, but it operates in support of the auditory cues received. Most musical instruments are played with the hands, fingers, or mouth, which happen to have the highest concentration of tactile receptors in the body. Enabling fine-grained manipulation of the playing of the instrument. Studies have shown that other parts of the body are sensitive to vibrotactile stimulus, but to a much lesser extent, see Figure 3.7).

3.9 Chapter Conclusions

Recent psychophysical studies have focused on the human ability to discriminate between vibrotactile tonalities whilst being masked from an auditory source [78] [121] [47]. Many of these experiments concentrate on the amplitude of fundamental sine waves and the point of which a subject can sense a vibrotactile signal of this sort. The experiments within this chapter distinguish themselves from the earlier works described in Chapter 2 by focusing on not only pure waveforms, but also including complex waveform detection in addition to combined multisensory experiences. The results of these experiments have served to validate findings in tactile detection theory materials, whilst including complex waveforms that contain not only the fundamental frequency, but also odd harmonics or odd and even harmonics with a controlled amplitude envelope shape.

In Experiment 1, the sub-threshold of detection for each of the wave-shapes presented was measured as output amplitudes in dBu. In Figure 3.3, the sub-thresholds of vibrotactile stimulus detection can be directly observed. This graph represents how the different waveform thresholds can each be divided into distinct tactile ranges, as is seen in the other research experiments outlined earlier. These ranges all pertain to frequencies that are cutaneously detectable in relationship to the waveform complexity of the stimulus. The main range for consideration for this thesis is that from 10 Hz to 1000 Hz, which corresponds with the accepted response range of the entire tactile system. Within this range, peak sensitivity occurred at around 160 Hz. With the amplitude of a tactile signal detection being dependent on not only the frequency, but the waveform shape being delivered too. For future experiments, a reduction in the participants' perception of waveform intensity differences will be achieved by using a fixed fundamental frequency and adhering to the waveform sub-threshold values discovered during our earlier experiments with vibrotactile feedback [47]. Therefore, the lowest sub-threshold of detection for 160 Hz will be used in later studies that include the active use of tactile feedback in DMI design.

The conclusions from the second experiment demonstrate how humans possess the ability to distinguish between different *haptic timbres* via vibrotactile stimulation alone; when presented asynchronously at a fundamental frequency of 160 Hz. This experiment was conducted to confirm that participants were indeed capable of distinguishing between pure sinusoidal and complex waveforms with non-sinusoidal periodic shape containing odd only (square) and odd and even (saw) harmonic content at 160 Hz. The experiment yielded positive results, with participants successfully identifying 92% of waveforms when presented asynchronously.

Finally, in Experiment 3, the role of vibrotactile feedback and its contribution to the detection of auditory perception of frequency changes at 160 Hz was investigated. These experiments have shown that vibrotactile feedback can affect the ability to perceive a positive or negative change in frequency when presented at 160 Hz. The sensitivity ranges of both systems were discussed, highlighting the overlap that occurs between them. In light of this overlap, research that points to a relationship between vibration perception and auditory processing in the brain was discussed. The JND abilities of two separate groups of participants was tested to remove any learning curve that may have occurred in the presentation of audio only or audio and tactile combined procedures. Group A was given an audio only test, whilst Group B was given the same test with concurrent tactile stimuli that was directly related to the audio stimuli. It was discovered that the group with simultaneous multimodal stimulus were able to correctly identify changes in frequency better than the audio only group. Group B identified 91% of frequency changes successfully, whilst Group A correctly identified only 79% on average. The mean percentile of correct frequency discriminations was then broken down for musicians and non-musicians. Musicians were observed as being capable of correctly identifying frequency changes beyond that of non-musicians in Group A, as well as observing a significant increase for musicians in the audio and tactile group, as would be expected.

In the final section, the potential meaning of these findings was discussed, as was their application in relation to musical interactions and DMI design. It is maintained that the adoption of a combined psychophysical model is required to reinforce the role of somatosensory integration in frequency discrimination tasks that are carried out on digital devices. This will allow researchers and DMI designers to combine multisensory interfaces that are transparent and intuitive to operate during a musical performance.

From the analysis of physiological and psychophysiological studies as presented in Chapter 3, informed decisions can now be made with regards to the design and development of new interfaces for musical expression. That is to say, the development of DMI that are capable of stimulating users in a meaningful way can now be formulated for Chapter 5 of this thesis. The parameters of stimuli presented are now clearly defined and will be applied in the development of DMIs that display expressive feedback for musicians to use in both pedagogical exercises and creative endeavours. However, in order to accurately measure the effects of feedback in these contexts, an exploration of evaluation techniques is required to formulate an accurate and fair portrayal these effects. To achieve this, the previous DMI evaluations that were explored in Chapter 2 will be expounded upon to extract significant evaluation data. Further to this, the field of Human-Computer Interaction will firstly be investigated for appropriate analysis techniques that can be applied in the DMI evaluations of Chapter 5.

Chapter 4: HCI Methodologies Applied in the Evaluation of Haptic DMIs

In Chapter 4 an analysis of techniques relating to the evaluation methodologies of DMIs derived from the field of HCI are presented. From this, choice aspects from existing evaluation models are selected and applied to an optimized evaluation for the rigorous assessment of new DMIs.

4.1 The Evaluation of Digital Musical Instruments

The evaluation of computer interface devices in HCI is a well-documented and established topic. There are a number of established and validated HCI evaluation techniques; however, none can be said to be fully compatible with respect to DMIs. User focused assessment is an integral part of an interface designer's requirement to quantify and evaluate their technology. Recent developments in user studies have shown an interest in the relationships that users develop with technology and the overall user experience. Previous research has neglected to incorporate and amalgamate these vital aspects in their approach to DMI evaluation. As this field is in a constant state of change, it is demonstrated here how specific aspects of the aforementioned evaluations can be incorporated into existing DMI evaluation strategies and how they can be applied to current DMI designs.

HCI is a highly complex multivariate discipline, which lacks an all-encompassing device evaluation framework. In relation to this, a new question is posed: in this context, is it possible to accurately evaluate a musical device? A number of researchers have endeavoured to answer this question in reference to DMI design and appraisal, sparking discussion about their proposed methodologies of measurement and if indeed, the performance of a DMI may be quantifiably measured at all. Further to this, examples of applied case studies are few, and it appears that designers are cautious to take up and apply these models of analysis to their own experimental devices (see Tables 4.1 to 4.3). Here some aspects of current and proposed HCI evaluation methods for DMIs shall be discussed, and their application to prototype devices explored.

Table 4.1: Survey of oral papers presented at NIME [57].

	NIME Conference Year		
Evaluation Type	2006	2007	2008
Not Applicable	8	9	7
None	18	14	15
Informal	12	8	6
Formal Quant.	1	2	3
Formal Qualit.	2	3	3
Total Formal	3 (9%)	5 (15%)	6 (22%)

Table 4.2: Analyzing NIME conference publications from 2009 [56].

	NIME Conference Year		
Evaluation Type	2009	2010	2011
Not Applicable	15	25	12
None	20	20	10
Informal	7	7	2
Formal Quant.	5	4	6
Formal Qualit.	3	5	3
Total Formal	8 (22%)	9 (25%)	9 (42%)

Table 4.3: Number of "*evaluations*" reported in NIME publications [122].

Evaluates?	2012	2013	2014
Not Applicable	24	41	56
No	39	35	41
Yes	20	29	40
Total	34%	45%	49%

4.2 Analyses Techniques

In HCI, a number of tools have been developed to measure design parameters, and the use of computers in specific contexts. These tools serve to direct interface designers away from generic, single purpose, interface-testing methods. In this vein, computer music performers can find themselves as DMI designers in a HCI context when evaluating interface technology. This can be observed in the techniques that are applied in DMI product design, which are informed through design practices and HCI research. Thusly, a strong connection can be seen between the traditions of HCI and DMI evaluation.

Functionality, usability, and user experience are evaluated in HCI studies to create a comprehensive representation of a device in use [57] [56]. For example, when playing music on a basic MIDI keyboard, many will agree that, in general, the usability of the interface is poor in comparison to that of performing on a grand piano. However, the experience may remain believable or natural for the performer. Additionally, different manufacturers incorporate various additional features in their products in order to attract potential customers with differing requirements. For these reasons, it is suggested that it may be possible to evaluate a DMI in terms of the general area of its technology usage. Specifically, it is recommended that the evaluation of a DMI device should encompass functionality, usability, and the user's experience using it, all of which are an integral part in the proposed evaluation framework.

Problems arise in DMI evaluation when consideration is given to the wide range of variables involved in musical performance. For live performances of computer music there are a multitude of contributing factors to a musician's experience, these include the consideration of simultaneous timing and rhythmic patterns, a performer's previous training with a specific instrument and their familiarity with other instruments within a collective ensemble. Coupled with this is the requirement to consider the multi-parametric control afforded at different levels, which are dependent upon the mechanical characteristics of the chosen instrument. Proposals have been made in the past to make a quantifiable and comparative analysis of devices over a series of short representative tasks. Additionally, the categorization of input devices to match tasks has also been suggested to adhere to specific and measurable objectives that match the operational characteristics of the individual device.

To appraise all critical aspects of a DMI, each evaluation area must be closely assessed for its applicability to the chosen device. There may also be reason to assess one-off DMIs with unique and augmentable sets of evaluation methods to achieve this. Therefore, it is important to firstly acknowledge that any investigation of a DMI's design may incorporate its own set of unique methodologies and assumptions, highlighting the necessity to carefully choose approaches that best fit the device for the three evaluation areas outlined earlier. For example, the appraisal of standard Usability Evaluation Methods (UEMs), such as time-on-task and number-of-errors for instance, cannot be used alone to assess a user's experience. Similarly, UEMs used to assess a device's functionality are not solely sufficient. In order for an accurate appraisal of a device, the evaluation must be careful not to reduce an analysis to any rigid or single base form.

4.2.1 Previous Evaluation Research

Notable examples of crossover between HCI-DMI evaluation methods can be seen in a number of previous publications. Research focused on the adaption of existing HCI tools and methods have been identified [123]. However, in practice the use of evaluation techniques, HCI and DMI crossovers or otherwise, are limited to a few examples [57] [56] [122]. Orio et al. bring together some of the most appropriate evaluation methods that apply to musical devices and discusses them in a musical context. They highlight target acquisition as a potential quantifiable evaluation method, underlining Fitts' Law and Meyer's Law in particular. In a musical context, consideration of *learnability*, *explorability*, *feature controllability*, and *timing controllability* were also emphasized as critical aspects in the evaluation of a controller's usability [123]. The mechanical characteristics of a DMI were also highlighted as having a categorical impact on device comparisons. Matching devices with similar, basic characteristics, or taxonomies is an imperative for organized and fair comparisons.

To organize DMI classifications, there have been a number of potential guidelines published. With the propagation of new interfaces for musical expression in digital music, it has been noted that the application of hardware interfaces, control surfaces, and gesture-based controllers are of considerable interest to musicians. The classification of custom devices for musical application has also received increased attention. Miranda and Wanderley proposed several distinct categories of DMI [38]. Their basic categorizations include instrument-like controllers, extended instruments, instrument-inspired controllers, and alternative controllers. Upon further examination, two major distinctions can be made between these groups. For instrument-like controllers, extended instruments, and instrument-inspired controllers, the instrument designer is restricted to a musician's musically refined motor control ability or familiarity of an instrument's mode of interaction, which is either practiced or is inherently familiar. In many alternative controllers, this familiarity is actively avoided, allowing for the use of non-traditional gesture vocabularies to be explored by a performer. Additionally, as the designer, composer, and performer may be the same person, the design of the instrument may be unique, which makes it difficult when formally assessing the device's performance as a DMI.

Wanderley and Orio further expand on their findings in this paper by introducing contextual events to use when comparing categorized devices. The expansion of categorical comparison was achieved by presenting an expanded list of circumstances specific to interactive computer music [124]. The contexts in which these categories are applied include: note-level control or musical instrument manipulation, score-level control, processing control or post-production activities, context related to traditional HCI or navigation, and interaction in multimedia installations. Additionally, the authors saw fit to include metaphoric situations, where generating music was not necessarily the primary focus of the interaction, such as interactions in the context of dance/music interfaces and in the control of computer games. These classifications were intended to assist in analysis and were not to be considered as fixed. The application of a single device in multiple contexts was also considered an important and distinguishable feature when contextualizing a device.

Keifer et al. explored and applied the findings made by Wanderley and Orio in a case study experiment on the usability of the Wii controller [125]. They found that whilst valuable data regarding their tested device's use as a music controller was insightful, they felt that their data was incomplete, as they did not measure the user's instantaneous musical experiences. Additionally, the concept of the 'third paradigm' in HCI was discussed in terms of DMI evaluation techniques. This paradigm is used to highlight the requirement for an ever-evolving selection of new evaluation techniques that suit the ubiquitous nature of computing in daily life. In essence, the third paradigm places embodied interaction at its centre. This means that all user actions, interactions, and knowledge are experienced and embodied within them and that they find meaning and construct meanings in specific contexts and situations [126].

Finally, a framework for evaluating DMIs was proposed by O'Modhrain in 2011 [59]. O'Modhrain examined the role of the various participants in the evaluation of the design process in a DMI context. At each stage in the design and development of the DMI the requisite participant (for example the inventor, manufacturer, or musician) was given a formative role in the evaluation of a product's design. As such, the evaluation of a design taken from the perspective of an audience, performer/composer, designer, and manufacturer is observed. The goal of each stakeholder is different and their means of assessment varies accordingly. That said, each perspective is necessary and should occur at different stages in an instrument's design cycle. O'Modhrain provides a conceptual scaffolding to bring together the various interested parties invested in the design process and explores the possibility of related or similar goals in an evaluation process.

4.2.2 Potential Assessment Techniques and Considerations

It is proposed that to accurately assess and compare DMIs, they must first be categorized to ensure that the devices being compared have equivalent input capture methodologies, resolutions, and establish their suitability for the particular test task formulated. A general categorization should be made, identifying the basic elements of the instrument and the mechanical principles behind its operation. Following this, the characteristics of the DMI being analysed should be extended to include the physical variables involved in its manipulation. The Taxonomy of Input Devices should be used to refine the classification variables to two basic forms (force and position) and the derivatives found from the six possible degrees of freedom of each (translation and rotation in three directions) [127]. These include the range of continuous and discrete values as generated by the DMI.

Table 4.4: Key Characteristics of Different Stakeholders in DMI Design Evaluation, extracted from O'Modhrain (2011) [59].

Possible Evaluation Goals				
Stakeholder	Enjoyment	Playability	Robustness	Achievement of Design Specifications
Performer / Composer	Reflective practice, development of repertoire, long-term engagement (longitudinal study)	Quantitative methods for evaluation of user interface, mapping, etc.	Quantitative methods for hardware / software testing	
Designer	Observation, questionnaire, informal feedback	Quantitative methods for user interface evaluation		Use cases, feedback regarding stakeholder satisfaction

For the second step of an evaluation, contextualization of evaluation goals must be stated. The context of an evaluation can shift the focus or perspective of the evaluation process, for example, who is evaluating the device and why? For this, the framework presented by O'Modhrain in 2011 should serve as a reference guide [59]. Given the idiosyncratic design process carried out by most DMI designers, it is suggested that evaluation goals from the viewpoint of performer/composer and designer should be amalgamated in most evaluations following this framework; however, this is not to say other stakeholders should be ignored. To further clarify, this is not to dismiss the perspectives of the audience or the manufacturer, but to highlight that the role a DMI designer often plays as both the performer/composer and designer. Table 4.4 highlights aspects of device evaluation that best fits for these two stakeholder groups. From following these first steps of analysis, an evaluation should be enabled to draw upon existing HCI evaluation techniques and augment them to suit the chosen device's categorization, design taxonomy, and consideration of stakeholder requirements.

After fully categorizing, contextualizing, and identifying the stakeholders, consideration of HCI paradigms that are relevant to computing for specific applications should then be made. However, given the current state of DMI evaluation, the same evaluation techniques as would be applicable to a Windows, Icons, Menus, and Pointers (WIMP) system cannot be directly applied. Nevertheless, HCI techniques may still be borrowed to assess a musical device's functionality, usability, and the musician's overall user experience.

In the evaluation framework proposed, functionality refers solely to the technical capabilities of the device, making it possible to quantify what exactly the device does and how well it does it. This generally incorporates an analysis of the device's usefulness and reliability. In HCI, the characteristics of a usability analysis seek to quantify the interaction between the user and the device in such a way as to ascertain if the device is capable of undertaking the tasks it is supposed to. It is important that any prototype devices used in an evaluation be close to the final form, both in terms of design and functionality. Having a tangible working model of a device is key for a successful evaluation. Prototypes need to be functional, where gestures can be captured with precision, and in turn they need to be responsive in sound generation without any noticeable latency. In contrast to this, the measurement of a user's experience focuses on the qualitative relationship a user develops towards a device. This rests with the user's previous exposure to the device, its derivatives, or similar products that are available or the user has been exposed to via the media or advertising. In addition, this includes the deeper emotional state of the user in relation to the device in use, for example how they felt about their experience and if it meets their expectations of the device as a musical instrument.

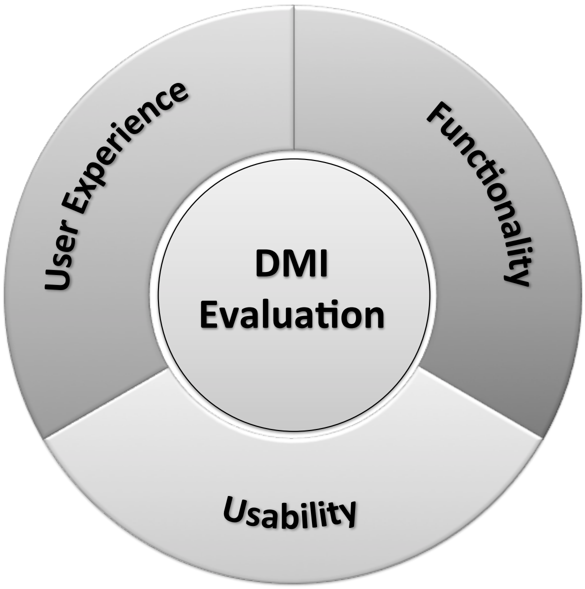


Figure 4.1: A framework of DMI evaluation (adapted from [124]).

These three factors, although unique, do not operate independently of each other. For example, usability is not considered as a defining device characteristic. However, the physicality of a device, in terms of its functionality and how it is delivered to the user, directly influences its usability. Also, a system's aesthetic beauty can influence the user's perception of usability and their physical experience with the device before actually using it. Finally, a device's usability directly influences the user's experience, as poor usability will almost certainly lead to a negative user experience. Therefore, we see the assessment of each of these areas is best achieved through the application of multiple HCI techniques and is not focused on any one alone.

Functionality assessment is used to determine if the device's features afforded to the user are practical, as well as evaluating the performance, consistency, and the sturdiness of the applied design. To validate the functionality of a DMI, it must be capable of completing certain performance tasks, in other words, how it might function as a musical instrument. Additionally, it must also be considered how a musician might evaluate a device during a performance. This includes their own subjective opinion of their performance, and the artistic freedoms afforded to them by the device must be measured. Therefore, a device that is being used to complete musical tasks for functionality testing must also include the incorporation of elements of usability and/or user experience in its analysis.

Table 4.5: Musical tasks linked with evaluation techniques from HCI.

Musical Tasks		Existing HCI Functionality Evaluation Methodologies
Selecting an isolated tone: simple triggering to varying parameters such as pitch, loudness, and timbre.		Target Acquisition - Fitts' Law.
Musical gestures: glissandi, trills, grace notes, etc.		Pursuit Tracking - Control:Display ratio.
Selecting scales and arpeggios at different speed, range, and articulation.		Constrained Linear Motion Tracking.
Creating phrase contours: from monotonic to random.	Select an existing HCI methodology that best fits the musical task you wish to evaluate	Constrained Circular Motion Tracking.
Ability to modulate timbre, amplitude or pitch for a given note and inside a phrase.		Free-Hand Inking – subjective evaluation of facsimile signature.
Playing rhythms at different speeds and combining tones or pre-recorded materials.		Aimed movements composed as sub-movements - Meyer's Law.
Synchronisation of musical processes.		Measuring trajectory movements - Steering Law.
		Circular motion path tracking and varying trajectories path tracking

The musical tasks used to examine a device's effectiveness as an instrument, should be simple, even if these tasks appear non-musical [128] [129]. This is due to simple tasks being only a formative phase of a more complete device evaluation and should therefore not be considered in their entirety as a complete evaluation. Evaluation techniques such as Fitts' Law, Meyer's Law, and Steering Law [124], although basic and somewhat reductive and non-music centred in design, can be augmented to accurately measure and compare the functional performance aspects of a DMI.

Given the multiplicity of current DMI designs, to evaluate the functionality of a design aspect, what is to be measured must be carefully considered. This is especially relevant to device comparison studies where the task must be achievable by all interfaces being compared. A list of suggested musical tasks was made by Orio [124], as can be seen in

Table 4.5, left column. Additionally, it is suggested here that some HCI evaluation techniques can be adapted to test a device's functionality in simple tasks. The outline presented in Table 4.5 is not representative of all musical tasks, and other HCI assessment techniques should also be considered. The breadth of both fields cannot be easily reduced to fit into so few categorical interactions, but the flexibility afforded in both can be manipulated to fit multiple conditions.

Usability assessment is used in HCI analyses to raise issues of *efficiency*, *effectiveness*, and *user satisfaction*. Further descriptions of device *transparency*, *learnability*, and *feedback mechanisms* can be drawn from analysing this data. The measure of usability is defined in ISO 9241-11 as "quality in use" [65]. Therefore, when investigating usability analysis techniques, the following usability definition should be reproduced: "… the extent to which a product can be used by specified users to achieve specific goals with effectiveness, efficiency, and satisfaction [65]." Beyond the ISO standard, there are a number of case studies that outline evaluation methodologies to assess a design's usability. However, care must be taken to choose an appropriate usability evaluation technique, which when applied to DMI devices, supports a high level of confidence in the findings. The chosen UEM must be capable of extrapolating the relevant information from the analysis. Known areas of concern in musical interactions include *Learnability*, *Explorability*, *Feature Controllability*, and *Timing Controllability* [123]. These can be expanded upon further to branch out the usability aspects of each to include other factors.

These may include:

- The demands a device places upon a user, such as cognitive load, physical exertion, temporal demands that lead to fatigue and so forth.
- How a device is perceived to affect a user's performance, the work involved in completing the task, and measuring frustration levels.

Learnability, as described in ISO 9241-11, is defined as the time required to learn how to use an instrument. Learnability also incorporates the user's familiarity with the device or related devices, which is a notoriously difficult parameter to measure. However, a contextual study of usability should highlight learnability and playability issues that may arise from this. Findings should reflect the performer's previous training with specific instruments and their familiarity with other instruments within a traditional ensemble and DMIs in computer music. This type of information can be used to evaluate the amount of effort required to accomplish a task. Additionally, high levels of insecurity, discouragement, irritation, stress, and annoyance will reduce how much effort a performer will put into learning and applying the intricacies and nuances a device may bestow upon them. However, if a device is too easy to learn how to master, the user will be as equally dissuaded from its use.

Explorability represents the number of functions and capabilities afforded to the user and how they are implemented. When investigating this element, researchers should be aware that all input parameters may be individually assessed for functionality and those assumptions could be made for inputs that share the same or similar mechanical principles of operation. This should assist in the analysis of any multi-parametric control that is given, which is can also be dependent upon the mechanical characteristics of the chosen instrument.

Feature Controllability is the perceived accuracy, resolution, and range of a device. The ergonomic implications of a device's operation in terms of accuracy of movement, given the resolution and range of input gestures that are possible, allows designers and users to evaluate if they have fully achieved the capabilities of their design specifications or musical intentions. If they have not, users will evaluate their success in accomplishing a task negatively.

Timing Controllability is the fundamental difference between classical HCI observations and musical interactions, that is, the central role of timing in all actions executed. The measurement of input during a time-based exercise and its effect upon performance should also consider the simultaneous timing and rhythmic patterns that are central to musical performance. The temporal demands of a task should be achievable and flexible to a user's needs.

From this list of DMI considerations it can be seen that the use of a generic System Usability Scale (SUS) derived from existing HCI literature may easily be applied [130]. The SUS quickly outputs a number that represents a near instant measure of usability. Previously, it has been applied in the investigation and evaluation of many products over the last 20 years; it has therefore been successfully applied to validate psychometric questioning. However, it can be argued that the standardized questions of a SUS analysis do not lend themselves to device evaluation in the 21st century. Therefore, it is suggested that it may be necessary to augment and adapt SUS for the unique requirements of musical tasks.

Further to this, the application of the NASA Task Load Index (NASA-TLX) has been observed as an effective measure of usability issues that are unique to DMIs. Therefore, this analysis technique may also be considered in usability testing of these devices [131]. This assessment technique has also been successfully applied many times to numerous studies that have provided a worthy resource for many usability-focused activities. Relating specifically to *Learnability*, *Explorability*, *Feature Controllability*, and *Timing Controllability*, the NASA-TLX measures on a number of comparative scales. The scales of the NASA-TLX measure the following demands; *Mental*, *Physical*, *Temporal*, *Performance*, *Effort*, and *Frustration Level*. Using this set of six subscales, the overall workload can be analysed in order to extrapolate information pertaining to the individual factors of *Learnability*, *Explorability*, *Feature Controllability*, and *Timing Controllability*. The definition of each subscale can be seen in Table 4.6.

Table 4.6: NASA-TLX rating scale definitions extracted from Hart (1988) [131].

Subscale	Description
Mental	How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical	How much physical activity was required? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal	How much time pressure did you feel due to the rate or pace at which the task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	How successful do you think you were in accomplishing the goals of the task set by the experimenter? How satisfied were you with your performance in accomplishing these goals?
Effort	How hard did you have to work to accomplish your level of performance?
Frustration	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Each aspect of usability in HCI can be analysed independently. Specifically, *efficiency*, *effectiveness*, and *user satisfaction* data can be collected from a combination of different sources. *Efficiency* can be established by measuring the mental effort required to apply a DMI in a specific task; for example, a low mental effort would indicate a high efficiency in operation. This data can be collected using a modified post-task self-report or a Subject Mental Effort Questionnaire (SMEQ) [132] and a Single Ease Question

(SEQ) [133]. Data collected from functionality testing to ascertain device effectiveness can also be used. Functionality data can be applied to support additional usability study findings, for example, when a user perceives a change in time-on-task when there is no actual measured difference. Finally, the satisfaction of a user can also be measured using a modified Consumer Product Questionnaire (CPQ) [134]. For a researcher to address the areas of concern outlined earlier, they can modify each of these methods of HCI usability testing. Additionally, they may also attain specific knowledge depending upon the device being tested and the overall aims of the research being undertaken.

Assessing a user's experience is a relatively new and innovative area of investigation within the field of HCI. A number of appraisal methodologies exist, but they remain under-developed due to being in the early stages of their creation. Additionally, the evocative nature of the relationship a musician develops with certain types of musical instruments can be idiosyncratic and diverse in its formative stages. Moreover, any data collected during a user experience testing is altogether subjective in nature. Measurements are difficult to quantify and can be dependent on a number of contributing influences, such as psychological or social factors [68]. An example might include personal opinions on aesthetics, a user's exposure to advertising, or the social desirability of certain technologies.

User experience can be measured in a number of ways; however, three particular methods shall be expanded upon on here. The first method to be detailed is that of a simple preference of use report that can be used to summarize a device preference in comparison with other devices. Secondly, a post-task User Experience Questionnaire (UEQ) can be conducted [135]. Finally, it is proposed that qualitative data should be collected relating to the contributing factors of a participant's experience whilst performing both functionality and musical tasks by using a Critical Incidents Technique (CIT) analysis [136]. In addition, to link in task data to post-task, empathy mapping should also be conducted. The adaptation and implementation of these techniques serves to provide a flexible, validated, and constrained user experience measure for comparison.

4.3 Chapter Conclusion

Models of evaluation exist in both fields of DMI design and HCI that can serve as guidelines for future DMI appraisals and comparisons. Currently, DMIs are often evaluated idiosyncratically, and structured well-established evaluation methods from other areas are somewhat ignored. In this chapter, the investigation and presentation of several existing methods of device evaluation have been suggested. Specifically, a number of steps have been highlighted to ensure that a complete and in-depth device appraisal can be carried out. In device appraisal, the need for established, rigorous, and flexible techniques is stressed. The field of HCI contains many validated techniques that have been successfully applied over many years. However, the evaluation of a musical device is often far more complex in practice than a conventional computer interface or device. Therefore, experimentation must be undertaken to find an appropriate evaluation technique that best fits a device.

A suggested framework of analysis can be seen in Figure 4.2. When applying this framework, the initial stages of a device's evaluation should include the capture of low-level device characteristics, creating a generalized device description. Following this, a device should be reduced to its physical variables in terms of its taxonomy of input. The second step should contextualize a device's evaluation in terms of stakeholder, questioning who is evaluating the device and why. These initial steps will serve to inform the evaluation and comparison of functionality studies that follow.

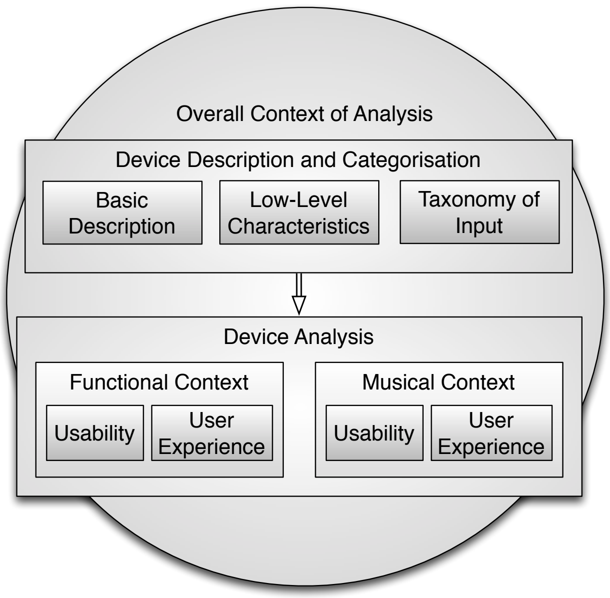


Figure 4.2: A framework of analysis devised from combining existing HCI and DMI analysis techniques.

Devices are required to be capable of undertaking the analysis task and must be analogous in operation if they are to be compared. A variety of potential HCI paradigms exist that can be augmented to best fit the categorization and contextualization outlined in the first stage. The main categories to measure include a device's functionality, usability, and the user's experience with the device. Functionality testing should include an element of analysis of the usability and user experience, as functionality testing is able to highlight any potential issues in this area before a more explorative study is carried out in a creative context. Usability and user experience in a musical context requires a less structured study than a functional one; as musicians must be given time to evaluate a device in a natural setting over time. The application of multiple HCI questioning techniques should also be applied to highlight important usability and user experience data in a real-world application of the device.

With the development of an appropriate framework of analysis for the investigation of device feedback, it is now fully possible to not only apply the physiological and psychophysiological findings of Chapter 3 to the design of a new DMI for evaluation in Chapter 5, but to also evaluate the effects of these principles upon the users of DMI in a Computer Music context. Therefore, in Chapter 5 of this thesis, the findings of Chapter 3 and 4 will be applied to design and develop a new DMI and investigate the multiple parameters of a DMI in use.

Chapter 5: Analysis of Haptic Feedback in DMI Interactions

To analyse the role of haptic feedback in DMI performance an experiment was conducted to measure *functionality*, *usability*, and *user experience* across four separate feedback stages: haptic, force, tactile, and no feedback. The framework was formulated from existing HCI evaluation methods, as discussed in Chapter 4. It applied a number of validated analysis techniques to assess the performance of two prototype DMIs that were capable of displaying the unique feedback elements mentioned. The study involved a four-part analysis of feedback:

1. Contextualisation of the experiment.
2. Description and categorisation of the devices.
3. Functionality evaluation.
4. Exploration of the device's effectiveness as a tool in a creative context.

The results presented in this chapter serve to outline the constituent components of the interface and present both quantitative and qualitative data relating to feedback in DMI interactions.

5.1 Introduction to DMI Analysis

This chapter presents the results of an experiment that evaluated and compared two prototype DMIs, the Haptic Bowl and the Non-Haptic Bowl. To structure the experiment formally, the framework of analysis discussed in Chapter 4 was applied [58]. Usability and user experience information was captured when undertaking functional and practical exercises in music performed with DMIs. The fundamental goal of the experiment was to measure the different feedback stage's *functionality*, *usability*, and the *user's experiences* in these two contexts. An audio-related task was chosen to quantitatively maintain objectivity in the analysis of feedback and the investigative methodologies that were applied. An analysis of this data presented no initial issues of function leading to a more explorative analysis. In the explorative study, a music-focussed analysis was performed to capture contextually important data. Post-task structured interviews were conducted immediately after each feedback stage to elicit related data.

The final stage of analysis, involving a focussed set of case studies, explored the application of the devices in a creative and explorative context. According to the framework presented in Chapter 4, to assess the effectiveness of feedback, a study of the devices in a musical context must also be performed. These studies were carried out separately to assess the musical affordances of the device and are discussed in detail in the final section of this chapter. The separation of this stage ensured that the selected participants had the opportunity to evaluate the feedback types in a performance and explorative context rather than a sterile laboratory environment. Post-study questioning was recorded and the participants were asked to verbally evaluate the feedback applied.

5.2 Device Description: The Bowls

To analyse the role of haptic feedback in DMI interactions, a number of prototype devices were constructed based upon the feedback principles discussed in Chapter 3 (The Bowls, Figure 5.1). Each device was designed to represent DMIs with a variety of feedback capabilities and a number of input gesture types were explored. From this assortment, two devices were selected that could display the unique characteristics of haptic feedback in isolation and afford the user freedom of movement in a 3D space around the device. Specifically, the Haptic Bowl and the Non-Haptic Bowl were chosen for this analysis.

Figure 5.1: The Bowl Interfaces (Left) and Operator for Scale (Right).

The Haptic Bowl is an isotonic, zero-order, alternative controller that was developed from a console game interface. The internal mechanisms of a GameTrak tethered spatial position controller were removed and relocated into a more robust and aesthetically pleasing shell. All of the original Human Interface Device (HID) circuitry was removed and replaced with an Arduino Uno smd edition. The HID upgrade reduced communication latencies and allowed for the development of further device functionality through the addition of auxiliary buttons and switches. The controller has very little in the way of performer movement restrictions, as physical contact with the device is reduced to two tethers that connect the user via gloves. Control of the device requires the performer to visualise an area in three dimensions, with each hand tethered to the device within this space.

The Non-Haptic Bowl is also an isotonic, zero-order, alternative controller based upon PING))) ultrasonic transducers and basic infrared (IR) MOCAP cameras. The ultrasonic components were arranged as digital inputs, via an Arduino Micro, and the MOCAP cameras were created from modified Logitech C170 web cameras with visual light filters covering their optical sensor (and internal IR filters removed). An IR light emitting diode (LED) embedded in a ring was then used to provide a tracking source for these MOCAP cameras. The constituent components are all contained within an aluminium shell, similar in size and shape as the Haptic Bowl. The use of these sensors best matched the input capabilities of the Haptic Bowl, ensuring a comparable interaction. This input device has fewer movement restrictions than the Haptic Bowl, as no physical contact with the device is required. Control of the Non-Haptic device also required the performer to visualise an area in three dimensions, with input gestures captured within a comparable space to that of the Haptic Bowl.

5.2.1 Feedback

In addition to the user's aural, visual, and proprioceptive awareness, haptic feedback components were incorporated into the input devices to communicate performance data back to the user. In the Haptic Bowl, additional feedback was included in the form of strengthened spring force return mechanisms for both tethers and audio frequency vibrotactile feedback delivered via actuators embedded in gloves. The audio-related vibrotactile feedback was supplied via a Bluetooth speaker embedded within the Haptic Bowl (a modified Logitech X100 Mobile Wireless Speaker) and connected via an audio connection on the top of the device to the vibrotactile actuators contained within the Audio-Tactile Gloves. It was possible to apply audio frequency vibrotactile feedback to the Non-Haptic bowl via the gloved actuators. For the Non-Haptic Bowl the audio output from a laptop was routed to the same type of Bluetooth speaker, but this was kept external from the device to demonstrate the disconnect of these feedback sources in

DMI designs. From combinations formulated around these feedback techniques, it was possible to create the four feedback profiles to be investigated:

1. Haptic feedback (force and vibrotactile feedback – Haptic Bowl)
2. Force feedback (force feedback only – Haptic Bowl)
3. Tactile feedback (vibrotactile feedback only – Non-Haptic Bowl)
4. No feedback (no physical feedback – Non-Haptic Bowl)

These combinations operated within the predefined requirements for sensory feedback as outlined in Chapter 3.

5.3 Analysis of Feedback in DMI Interactions

In Part 1 of the assessment the overall study was contextualised. In Part 2, a general categorisation of the device was formulated to identify the basic input elements of each device. Following this, the input characteristics were further reduced to the physical variables that were to be manipulated. Finally, the taxonomy of the device was used to further reduce these classification variables down to their most basic forms. At this point, the precise categorisation and comparison of the devices ensured that they were analogous enough in operation to be compared fairly. In Part 3 of the analysis a functionality analysis that best fit both DMIs input methodologies was selected. Finally, in Part 4 an analysis of feedback in musical tasks was completed. The final part of the analysis was conducted in a case-by-case study; allowing the different feedback stages to be applied and evaluated in a musical-task orientated context.

5.4 Part 1: Context of analysis

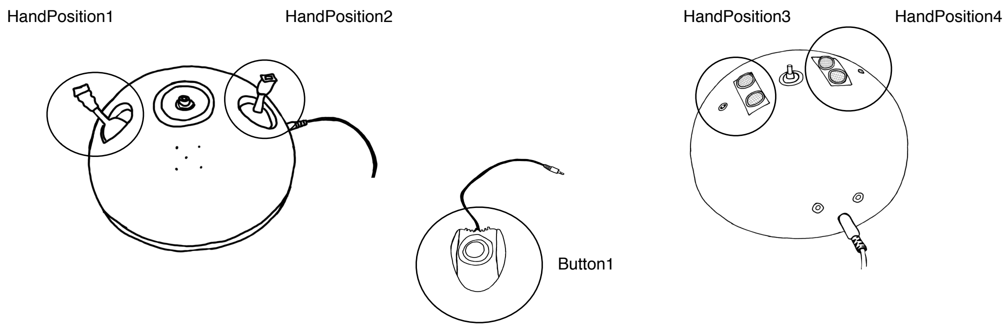
In Chapter 4 it was seen that traditional evaluation methodologies in HCI were evaluated as being unsuitable for the direct evaluation of DMIs without prior contextualisation and augmentation. This is due to the complex coupling of action and response in an audio interaction. These two interaction factors operate within the tightly linked processes of a focused spatiotemporal task. Therefore, if this process is interrupted for an evaluation, such as for a questionnaire or thinking-aloud protocols, the participants are inevitably separated from their instantaneous thoughts and therefore from achieving their goals. Due to this, any system of analysis that is applied outside of the interaction will be disconnected from the task being evaluated. Similar problems exist in other areas of study, for example in the evaluation of gaming experience. To counter this, adaptive and reflective models have been developed in HCI that concentrate on specific elements of an interaction and these techniques have been augmented to evaluate the participants' experience in specific contexts. In the study presented in this chapter, a number of validated HCI techniques are applied that combat the potential for task evaluation disconnect. The evaluation context was therefore augmented to fit that of the performer/composer and designer's perspective. As discussed in Chapter 4, these stakeholders concern themselves with how a device works, how it is interacted with, and how the overall design of a system responds to an interaction. Therefore, the experiment conducted was designed to objectively evaluate the performance of feedback within this context and not to evaluate the musical performance of the participant.

To achieve these objectives, two separate feedback focussed experiments were devised and applied to quantify the performance of DMI feedback in audio-related and musical tasks. Secondly, validated questionnaires (as discussed in Chapter 4) were issued to quantify the *usability* of the device. This was achieved by issuing SEQ, SMEQ, and NASA-TLX questionnaires. Finally, user experience focussed methodologies were executed to evaluate how the participants *experienced* the interaction. Although post-task user experience questioning is problematic, due to the user *disconnect* issues discussed, validated techniques were applied to accurately evaluate each of the feedback stages. Firstly, a preference of use question was posed to the participants to evaluate their opinion on the practical application of feedback in their own performances. Secondly, a UEQ was completed to collect quantitative data about the participant's impressions of their experience. This was followed by a moderately structured post-task user experience questionnaire. The interview was formulated around the areas of concern highlighted in Chapter 4; this was then subjected to a content analysis. The content analysis topics were designed to elicit a number of critical incidents, previously discussed in Chapters 1, 2, and 4. For the functionality study, empathy mapping was used to correlate the participants' expressed thoughts in the post-task interview with their actions during the task.

Across all experimental contexts described so far, the number of musically skilled participants is expected to vary. This is due to the availability of appropriately skilled individuals obtainable within the timeframe restrictions and the locale of the experiments. For these reasons, the number of participants for each stage of the analysis is logically expected to vary. However, wherever possible, robust statistical analyses techniques should be applied to gain insight and knowledge into any potential trends that can be extrapolated from the data collected. A more rigorous statistical analysis is therefore not required when exploring possible trends. A brief explanation of the different analysis types will also be presented to explain their function in the analysis of the data. The findings and trends gathered from the experiments are discussed further in the conclusions of this chapter and considered later in Chapter 6.

5.5 Part 2: Detailed Device Description

In this part of the analysis, each of the Bowl devices were subjected to a thorough breakdown of input metaphors applied in their construction. This included an analysis of their Primitive Movement Vocabulary and the Composite Design each device employs. Each will be described in the following section.



Type	HandPosition1 = HandPosition2	HandPosition3 = HandPosition4	Button1
Manipulation	dP_{xyz}	dP_{xyz}	P_z
Input	x, y [0 > 70 Deg], z [0 > 3 m]	x, y [0 > 70 Deg], z [0 > 1 m]	z [0-Max_z]
State	d	d	up/down
Resolution fn	f_{xyz}	f_{xyz}	T1(f_z)
Output	x, y [0 > 1023], z [0 > 1023]	x, y [-1 > +1], z [0 > 1023]	z [0-1]
Works	User defined	User defined	User defined

Figure 5.2: Analysis of primitive input for both devices.

5.5.1 Primitive Movement Vocabulary

Figure 5.2 describes the basic controls incorporated in both devices using primitive movement vocabulary. This vocabulary model presents six points of interest when discussing how an input device transduces physical movements into logical movement coefficients for measurement [127]. As each hand was manoeuvred in the three-dimensional virtual space, the Cartesian X, Y, and Z coordinates of the hand movements were captured. The manipulation operators of these planes of movement were measured continuously through the input domain operators and then translated as relative gesture input data. Specifically, azimuth, medial, and frontal planes of movement over a domain set of 0° to 70° were measured and a Z-plane over a distance range of 0 to 3 meters for the Haptic Bowl and 0 to 1 meter for the Non-Haptic Bowl.

The 10-bit analogue inputs of the Arduino (used to process input and interface with a PC) operated within a range of 0 to 1023. This range was repeated over the input domain of each hand. The button mechanism operated over a single plane, in an up-down manner, with a binary output of 0 or 1 (ON or OFF). The purpose of the device was user defined, enabling users to map the multiple inputs to any software application they desire via serial data.

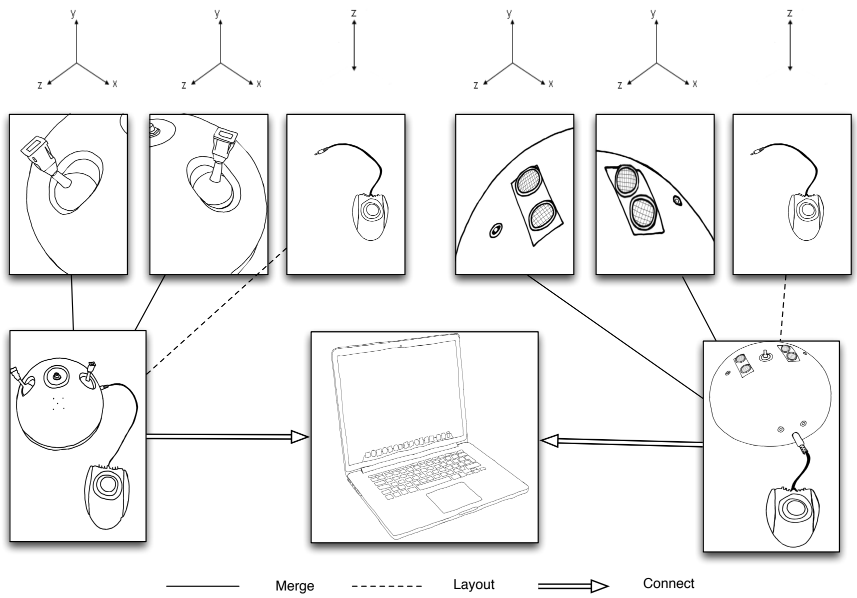


Figure 5.3: Composition operators used to describe the Haptic and Non-Haptic Bowl.

5.5.2 Composite Design

Thus far, the discussion of simple control and multidimensional aspects of the device have been focused upon. In the analysis of input capabilities, each of the prototype DMI are composed of a collection of one-dimensional elements that combined to form multidimensional input devices. For the following analysis, three main compositional operator factors were considered [137]:

- Operators that can be connected.
- Operators that can be laid out together.
- The operator domain sets that can be merged.

The devices modelled were based upon a combination of these three fundamental operators. Therefore, it can be concluded that both Bowl devices involved the merging of generic three-dimensional sliders. For an accurate description of both devices, the composition operators were required for consideration, as seen in Figure 5.3.

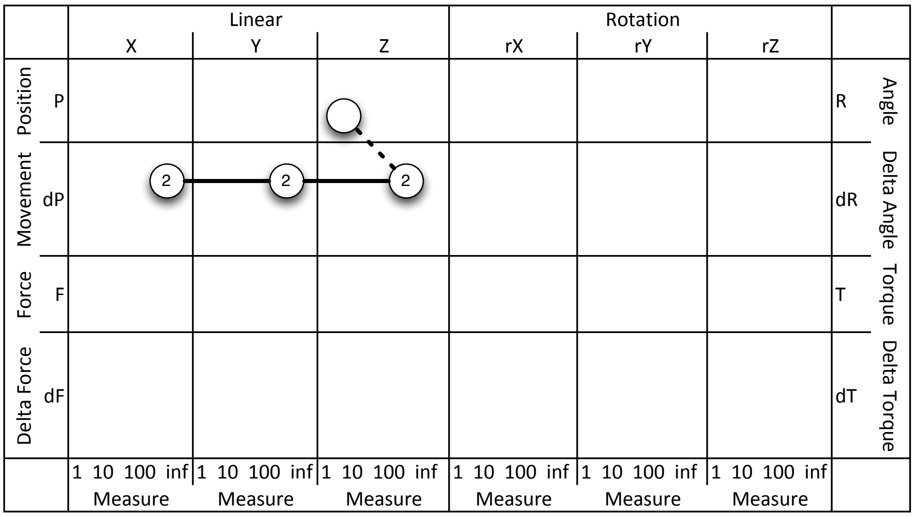


Figure 5.4: Input device taxonomy to describe both Bowl devices

5.5.3 Input Device Taxonomy

Figure 5.4 presents the input taxonomy of both devices derived from analysis techniques discussed in Chapter 4. In this examination, the device has input properties presented on the vertical axis as physical characteristics and along the horizontal as linear or rotary measures [137]. The circles indicated that both devices were capable of gesture capture in three dimensions. Circles were placed to highlight the linear movement along the X, Y, and Z planes. Additionally, the horizontal placement of the circles indicated the number of values that could be measured (0 to 1023). The path between the discrete elements indicated the manner in which they were connected. The black lines represented a merge composition of the X, Y, and Z components. The circles represented the individual elements with the numbers within signifying the number of identical inputs. The dashed line represented the layout composition of the foot-switch, whose values ranged from 0 to 1.

5.6 Part 3: Functionality Testing

To assess the functionality of the feedback elements from both devices, an experiment was devised that required participants to use the interface in a non-musical audio task. This task was designed to provide quantitative data that could be used to accurately compare each feedback stage. From analysing the functional mechanisms of the device, a Fitts' Law style experiment was designed. In addition to this, the following usability and user experience questionnaires were completed post-task:

- Single Ease of use Question (SEQ) [133].

- Subjective Mental Effort Question (SMEQ) [133].
- Pen and paper NASA Task Load Index Questionnaire (NASA-TLX) [131].
- User Experience Questionnaire (UEQ) [135].
- Open ended questioning and informal interview for Critical Incident Technique analysis (CIT) [136] and empathy mapping.

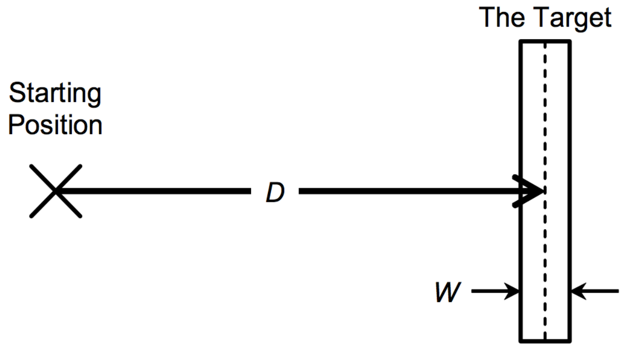


Figure 5.5: Fitts' Law movement model.

5.6.1 Adapting Fitts' Law

Fitts' Law is used in HCI to describe the relationships between movement time, distance, and target size when performing rapid aimed movements, see Figure 5.5. According to Fitts, the time it takes to move and point to a target of a specified width and distance is a logarithmic function of the spatial relative error [138]. Whilst this logarithmic relationship may not exist beyond a Windows, Icons, Menus, Pointer (WIMP) system, the experimental procedures can be followed to produce data for analysis. In this experiment, a participant's ability to rapidly aim their movements within a predetermined audio spectrum towards a specified target frequency was measured. Essentially, physical distance was remapped to audio frequency distance, where the start position corresponded to a point below 20 Hz and a target position that laid slightly less than 1 kHz. The target's' width was predetermined as a physiological constant of 3 Hz for sine-wave signals below 500 Hz, increasing by approximately 0.6% as frequency is increased towards 1 kHz [139].

5.6.2 Participants

Twelve musicians participated in the experiment. All participants were recruited from University College Cork and the surrounding community area. The participants were aged 22 to 36 (M = 27.25, SD = 4.64). The group consisted of 10 males and 2 females.

All of the participants self-identified as being musicians, having been formally trained or regularly performing in the past five years.

5.6.3 Methodology

All stages of the experiment were conducted in an acoustically treated studio. The USB output from each device was connected to a 2012 MacBook Pro Retina. The input data from the devices were converted into Open Sound Control (OSC) messages and outputted as User Datagram Protocol (UDP) information over port 12001. Pure Data (PD) then received and processed this data. Within PD, both input values of Z-plane movement were used to create a virtual Theremin. The right hand controlled the pitch, and the left hand the volume. The normal operational range of both devices was altered to fit within an effective working range of 30 cm; this range lay slightly above an average waist height of 80 cm (the average height in Ireland, as of 2007, is 170 cm and a waist to height calculated as a ratio of 0.48). The foot-switch was employed by the participant to indicate the start and end of each test.

Participants were presented with each feedback stage in counterbalanced order. After a brief demonstration, participants were given five minutes to familiarise themselves with the operation of the device. For ecological validity, participants were required to wear the device's gloves throughout all experimental stages. Following this, subjects were then given a further five minutes to practice the experimental procedure. The total time-on-task varied significantly between participants and experiment stages. Participants were required to listen to a specific frequency and then seek and select the target frequency with the device as quickly and as accurately as possible. The listening time required for remembering the target pitch varied between participants; however, the total listening time varied from only 5 to 10 seconds maximum. The start position for all stages was with hands resting in a neutral position at the waist. Participants used the foot-switch to start and finish recording movement data for each frequency. For each run of the experiment, eleven frequencies were selected in counterbalanced order across a range of 110 Hz to 987.77 Hz. All frequencies in the experiment had a relative pitch value. Participants performed three runs of the 11 frequency exercises, with a brief rest between each. A USB serial-to-UDP Processing patch was used to capture input movement data and the time taken to perform the task, this data was outputted as a .csv file for analysis. After each feedback stage of the experiment, participants were asked to complete a post-task evaluation questionnaire and informal interview.

Table 5.1: Move Time ANOVA for all feedback stages.

Frequency	Wilks' Lambda	F (3, 9)	p =	Eta^2
110	0.33	5.97	.02*	.67
130.81	0.70	1.26	.35	.30
174.61	0.67	1.46	.29	.33
220	0.86	0.50	.69	.14
261.6	0.34	5.96	.02*	.67
349.23	0.82	0.67	.59	.18
440	0.43	4.03	.05	.57
523.25	0.61	1.93	.20	.39
698.47	0.69	1.36	.32	.31
880	0.32	6.41	.01*	.68
987.77	0.57	2.23	.15	.43

* mean difference significant at p = .05 level

5.6.4 Functionality Results

The results from the Fitts' Law style evaluation can be seen in Table 5.3. Across the entire frequency range measured (110 to 975.83 Hz), the mean move time for each stage was as follows; haptic feedback (M = 6 s, SD = 0.48), force feedback (M = 6.25 s, SD = 0.69), tactile feedback (M = 6.78 s, SD = 0.9), and for no feedback (M = 7.47 s, SD = 0.84). Although there were observable variations in the mean move time between the different feedback stages, Figure 5.6 and 5.7, an analysis of variance was conducted to examine if these variations were statistically significant for the participant group. The ANOVA (used as each subject was measured on the same continuous scale on four different occasions) yielded significant variations for all feedback stages and with post-hoc testing, three significant differences between feedback stages and move time were found, see Table 5.1. Of these three, the move time for haptic feedback was significantly different from the no feedback stage at 110 Hz (p = .02) and 261.6 Hz (p = 0.02), and at 880 Hz, force feedback was significantly different from no feedback (p = 0.01).

Table 5.2: Frequency selected ANOVA for all feedback stages.

Frequency	Wilks' Lambda	F (3, 9)	p =	Eta^2
110	0.68	1.44	0.30	0.32
130.81	0.47	3.43	0.07	0.53
174.61	0.86	0.49	0.70	0.14
220	0.71	1.21	0.36	0.29
261.6	0.56	2.38	0.14	0.44
349.23	0.73	1.13	0.39	0.27
440	0.67	1.50	0.28	0.33
523.25	0.92	0.27	0.85	0.08
698.47	0.52	2.74	0.11	0.48
880	0.81	0.69	0.58	0.19
987.77	0.05	53.44	0.00*	0.95

* mean difference significant at the p = .05 level

For the individual feedback stages, on average, participants were able to target and select frequencies well within the predetermined target size of 3 Hz for all frequencies below and including 261.6 Hz, as can be seen in Table 5.2 and 5.3. The mean and standard deviation from target frequencies was measured as follows; haptic feedback (M = 0.41 Hz, SD = 0.24), force feedback (M = 0.33 Hz, SD = 0.25), tactile feedback (M = 1.03 Hz, SD = 0.62), and no feedback (M = 1.07 Hz, SD = 0.87). As expected, the accuracy of pitch selection decreased with frequency increments from here on. Above 261.6 Hz and up to and including 523.25 Hz, the standard deviation from target pitch increased, but remained within the expected deviation range; haptic feedback (M = 0.9 Hz, SD = 0.65), force feedback (M = 0.78 Hz, SD = 0.4), tactile feedback (M = 1.7 Hz, SD = 0.98), and no feedback (M = 1.15 Hz, SD = 0.48). Beyond this range, above 523.25 Hz up to and including 975.83 Hz, the standard deviation increased further; haptic feedback (M = 4.21 Hz, SD = 2.21), force feedback (M = 5.36 Hz, SD = 4.73), tactile feedback (M = 5.1 Hz, SD = 4.18), and no feedback (M = 9.6 Hz, SD = 3.43). Notably, the no feedback stage of the experiment exceeded the expected deviation constant of 6 Hz for this range by 3 Hz. Although there were noticeable variations in the accuracy of target selection across the feedback stages, there was found to be no significant effect of feedback on the accuracy of frequency selection with p > .05 for all feedback types.

Table 5.3: Deviation from target for feedback stages

Feedback	< 261.6 Hz	SD	261.1 > 523.25	SD	523.25 >	SD
Haptic	0.41	0.24	0.90	0.65	4.21	2.21
Force	0.33	0.25	0.78	0.40	5.36	4.73
Tactile	1.03	0.62	1.70	0.98	5.10	4.18
No Feedback	1.07	0.87	1.15	0.48	9.60	3.43

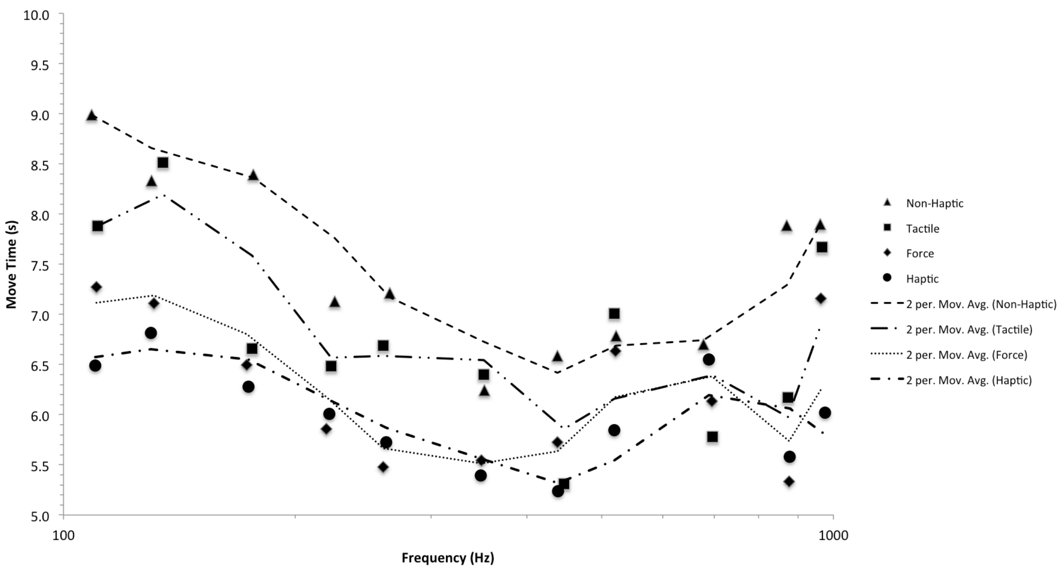


Figure 5.6: Mean Move Time (MT) over frequency for all feedback stages.

Table 5.4: Feedback accuracy and move times.

Target Frequency (Hz)	110	130.81	174.61	220	261.6	349.23	440	523.25	698.47	880	987.77
Haptic Feedback											
Mean Actual Selected (Hz)	109.96	129.79	173.79	221.38	262.63	348.33	438.75	519.21	688.67	877.54	974.75
SD	1.36	2.40	1.52	1.85	3.98	3.50	2.78	7.14	11.89	5.99	13.27
Mean deviation from target	0.02	0.51	0.41	0.69	0.51	0.45	0.63	2.02	4.90	1.23	6.51
Mean Move Time (s)	6.49	6.82	6.28	6.01	5.73	5.40	5.24	5.85	6.55	5.58	6.02
SD	1.79	3.15	2.43	2.65	1.98	1.96	1.56	2.04	1.56	1.53	1.77
Force Feedback											
Mean Actual Selected (Hz)	110.42	131.08	173.08	219.58	260.08	348.96	437.71	521.08	695.08	875.29	963.71
SD	2.29	3.32	4.94	4.47	4.42	2.30	6.13	6.22	7.82	10.30	33.57
Mean deviation from target	0.21	0.14	0.76	0.21	0.76	0.14	1.15	1.08	1.69	2.35	12.03
Mean Move Time (s)	7.27	7.11	6.50	5.86	5.48	5.55	5.73	6.63	6.14	5.34	7.16
SD	2.23	2.19	2.55	2.73	2.05	2.39	2.26	1.76	1.39	1.47	2.25
Tactile Feedback											
Mean Actual Selected (Hz)	110.73	134.71	175.73	222.45	260.20	351.24	446.45	519.54	696.44	873.10	966.08
SD	4.91	4.96	6.88	5.54	7.20	7.03	10.99	7.81	8.98	10.38	26.14
Mean deviation from target	0.37	1.95	0.56	1.23	0.70	1.00	3.23	1.85	1.02	3.45	10.85
Mean Move Time (s)	7.88	8.51	6.66	6.48	6.69	6.40	5.31	7.01	5.78	6.17	7.67
SD	2.15	2.59	3.21	2.40	2.08	2.90	1.40	2.73	1.75	2.42	3.56
No Feedback											
Mean Actual Selected (Hz)	108.77	130.19	176.24	225.10	265.12	352.05	438.16	522.24	678.36	869.62	960.66
SD	3.90	5.13	11.23	7.24	7.81	10.66	8.37	7.74	22.36	15.64	21.45
Mean deviation from target	0.62	0.31	0.81	2.55	1.76	1.41	0.92	0.50	10.06	5.19	13.55
Mean Move Time (s)	8.99	8.33	8.39	7.13	7.21	6.24	6.59	6.79	6.70	7.89	7.90
SD	3.05	3.42	3.37	2.97	3.08	3.37	2.01	3.53	2.65	2.91	3.35

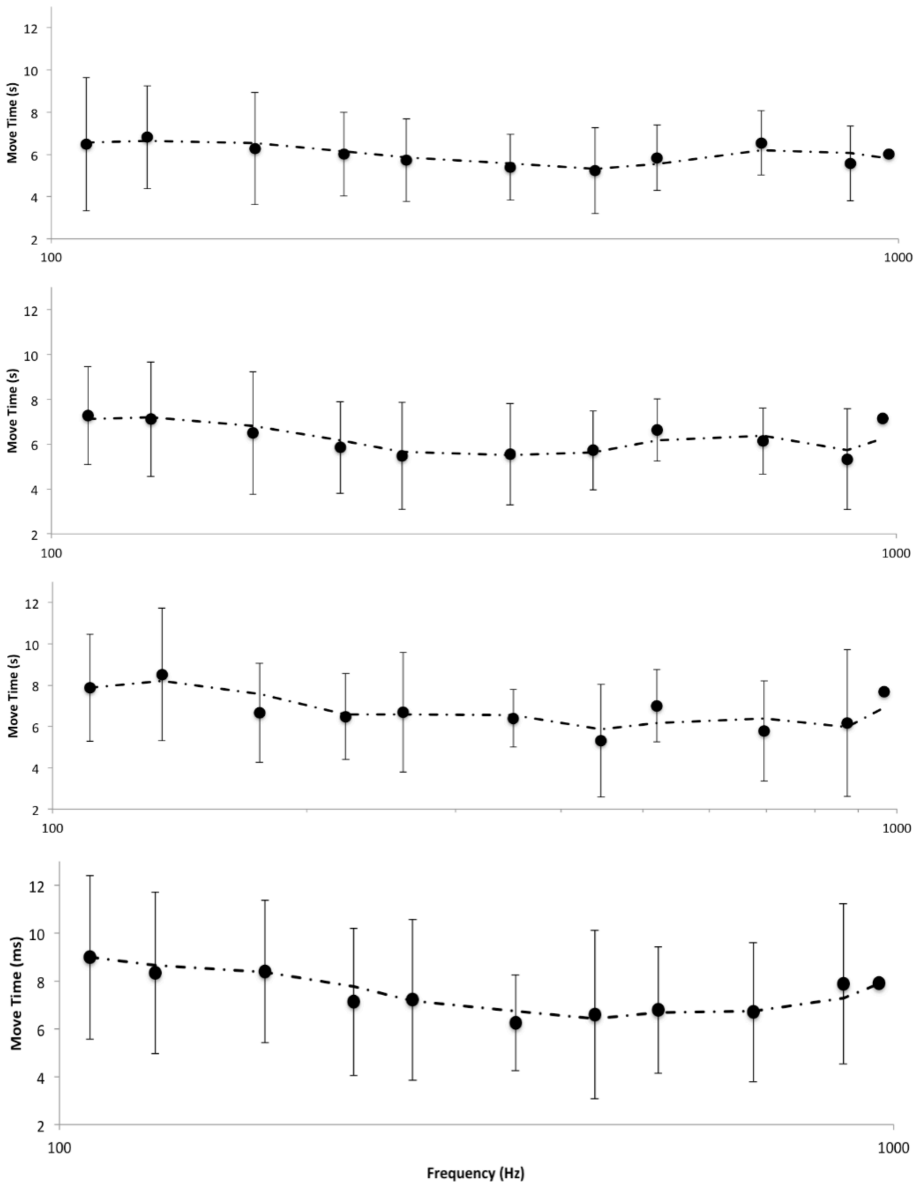


Figure 5.7: Mean move time standard deviations for haptic, force, tactile, and no feedback stages of the experiment

5.6.5 Usability Results

The post-task questioning with concern to SEQ answers can be seen in Figure 5.8. With the SEQ, the participants were given the opportunity to consider their own performance and factor this into their response. Users had to fit their rating of performance based upon the range of answers available (7 in total) and respond to their interpretation of the difficulty of the task accordingly [133]. For the individual feedback stages of the experiment, the SEQ median score for each stage was measured as follows; haptic feedback = *neither difficult nor easy / somewhat easy* (Md = 4.5, IQR = 3), force feedback = *neither difficult nor easy / somewhat easy* (Md = 4.5, IQR = 3), tactile feedback = *somewhat difficult* (Md = 3, IQR = 0.5), no feedback = *mostly difficult* (Md = 2, IQR = 1).

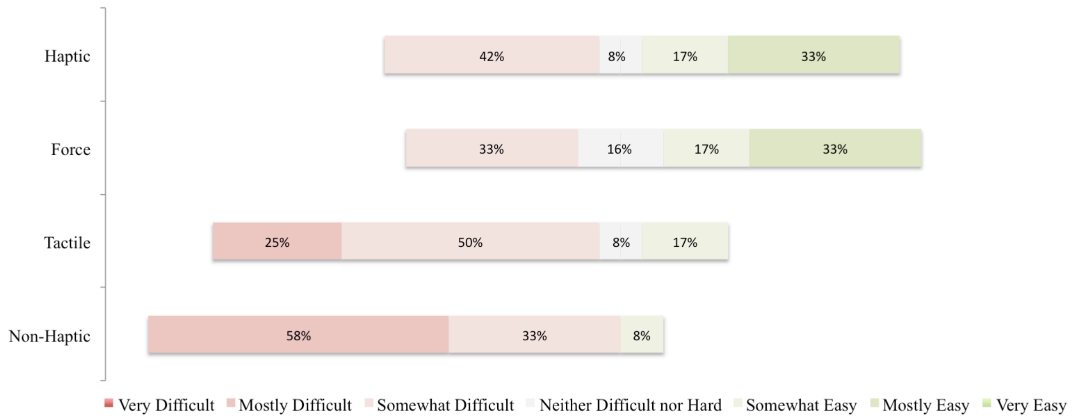


Figure 5.8: Diverging stacked bar chart for SEQ answers.

For the haptic feedback stage, a large portion of users (42%) found that the task was *somewhat difficult* for them to complete, the performance of perceived ease of use increased in difficulty for each feedback stage after this until the perception of performance decreased to a rating of *very difficult* (58%) for the no feedback stage. When verbally questioned on this, participants expressed that whilst they were fully engaged in the task, the perceived difficulty of performance using the devices was as it would be if they were performing for the first time with any new instrument. This increase in cognitive load moved them to consider their performance more critically, regardless of the recorded consistencies in the individuals' move time and accuracy results across the feedback stages. Participants were unaware of their actual move time and accuracy scores at this point.

A repeated measures Friedman Test (a test used when you take the same sample of participants and measure them under four different conditions) was used to reveal any statistically significant effects of feedback upon SEQ answers across the four different feedback stages; the results of which were as follows: x^2 (3, n = 12) = 31.75, p < .001. Following this, a Wilcoxon Signed Ranks analysis of variance was conducted to explore the impact of device feedback on SEQ answers (a test used with repeated measures data; when participants are measured under four different conditions). There was found to be a statistically significant effect of feedback on device scores for the feedback stages highlighted in Table 5.5. A medium effect size was measured from .34 to .45. Post-hoc comparisons indicated that the score for the no feedback stage of the experiment was significantly different from the haptic and force stages after Bonferroni adjustment. There were found to be no significant differences between haptic and force feedback and the tactile and no feedback stages. This indicated that the participants' perception of task difficulty was significantly different from no feedback when force feedback was presented in the interaction and that tactile feedback played no role in this perception rating.

Table 5.5: Wilcoxon Signed Ranks Test.

Feedback Stage		Z	p =	r =
Haptic	Force	0.00	ns	.00
	Tactile	-2.88	.004*	.42
	No Feedback	-3.13	.002*	.45
Force	Haptic	0.00	ns	.00
	Tactile	-3.07	.002*	.44
	No Feedback	-3.11	.002*	.45
Tactile	Haptic	-2.88	.004*	.42
	Force	-3.07	.002*	.44
	No Feedback	-2.33	.02	.34
No Feedback	Force	-3.11	.002*	.45
	Tactile	-2.33	.02	.34
	Haptic	-3.13	.002*	.45

* Significant with Bonferroni adjustment.

In comparison to the SEQ, the SMEQ presented a near-continuous response choice for the participants to choose from, Figure 5.9. Theoretically, this allowed the participants to be more precise in regards to their estimation of the device's usability. The premise of this scale was to elicit an indication of the user's thoughts towards the amount of mental effort they exerted during the task. The mean value of the SMEQ answers for each feedback type was calculated as follows; haptic feedback ($M = 45$, $SD = 22.16$), force feedback ($M = 45.42$, $SD = 16.98$), tactile feedback ($M = 62.17$, $SD = 13.59$), no feedback ($M = 71.25$, $SD = 12.08$). This corresponds to an evaluation of *some amount of effort* for the majority of users during the haptic feedback stage, *a reasonable amount of effort* for the force feedback stage, and a *fair amount of effort* for the tactile and no feedback stage. These results support the usability analysis of the SEQ. However, this scale measured the amount of effort the participants *felt* they invested rather than the amount of effort *demanded* from them.

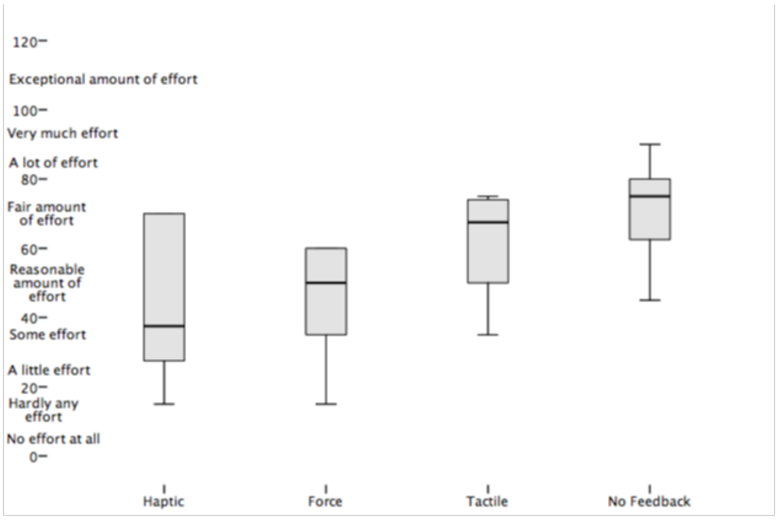


Figure 5.9: Box plots representing mean SMEQ answers.

Table 5.6: Pairwise comparison of feedback stages for SMEQ answers.

Feedback Stage		Mean Difference	Std. Error	p =
Haptic	Force	-0.42	2.851	ns
	Tactile	-17.17	3.914	.01*
	No Feedback	-26.25	5.042	.00*
Force	Haptic	0.42	2.851	ns
	Tactile	-16.75	2.706	.00*
	No Feedback	-25.83	4.212	.00*
Tactile	Haptic	17.17	3.914	.01*
	Force	16.75	2.706	.00*
	No Feedback	-9.08	2.207	.01*
No Feedback	Haptic	26.25	5.042	.00*
	Force	25.83	4.212	.00*
	Tactile	9.08	2.207	.01*

* Significant with Bonferroni adjustment.

As this data fulfilled the requirements for parametric testing, a repeated measures ANOVA (as each subject was measured on the same continuous scale on four different occasions) was conducted to compare scores on the SMEQ scale, with the mean and standard deviations as presented above. There was found to be a significant effect for feedback, Wilks' Lambda = .21, $F(3, 9) = 11$, $p = .002$, multivariate partial eta squared = .79. A pairwise comparison can be seen in Table 5.6. The post-hoc comparisons indicated that the score for the no feedback stage of the experiment (M = 71.25, SD =

12.08) was significantly different from the haptic (M = 45, SD = 22.16), force (M = 45.42, SD = 16.98), and tactile (M = 62.17, SD = 13.59) stages. This was also true of the tactile stage of the experiment. There was found to be no significant effect between haptic and force feedback stages. These results indicated that feedback played some part in the reduction of participants' perception of mental demand.

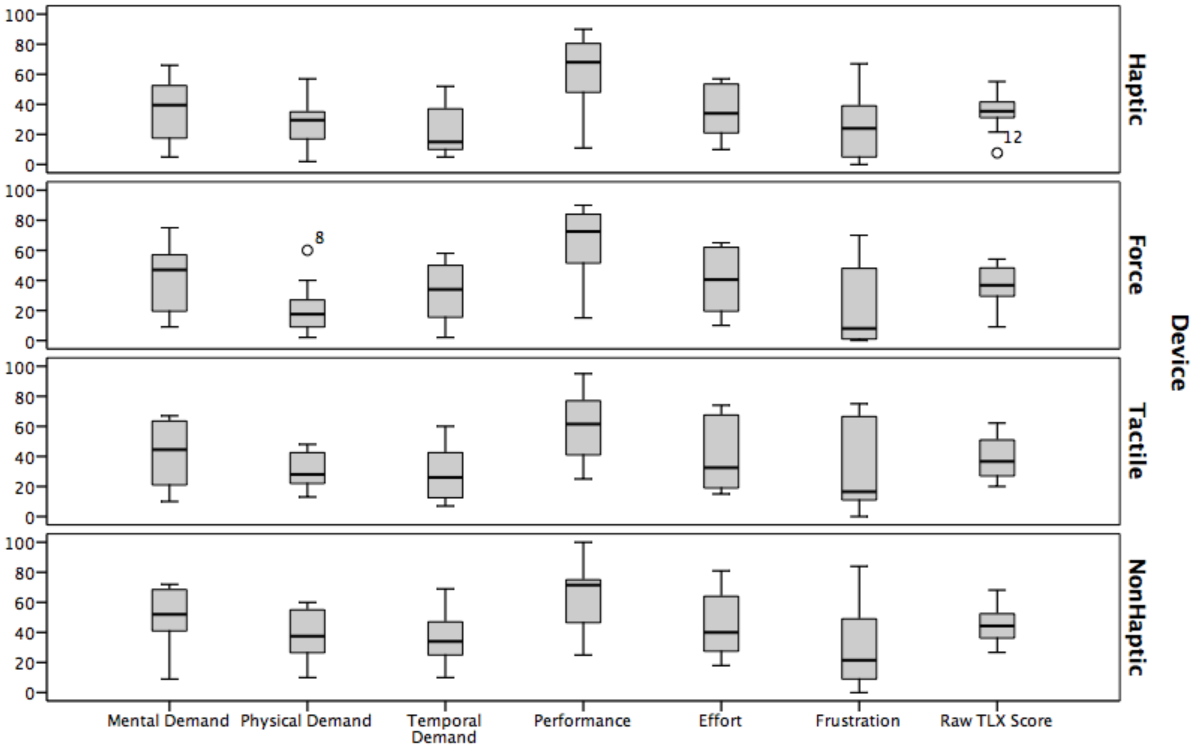


Figure 5.10: Mean NASA-TLX subscale ratings for usability

Following the evaluation of perceived effort, the participant's subjective workload was recorded with a paper and pencil NASA-TLX assessment questionnaire. For this, the total workload was divided into six TLX subscales, the results of which can be seen in Figure 5.10. The NASA-TLX scales all presented with a good internal consistency. The individual components can also be seen in Table 5.7.

The first indicator in the NASA-TLX subscale required the user to signify how demanding they found the task in terms of its complexity. The mean level of perceived mental activity required for the task was measured as follows; haptic feedback (M = 36.33, SD = 20.36), force feedback (M = 41.58, SD = 22.37), tactile feedback (M = 41.42, SD = 22.06), no feedback (M = 50.58, SD = 20.36). These results denoted that a somewhat small amount of mental and perceptual activity was required, indicating that the task was simple to complete for all feedback stages.

Next, the mean physical demand of the task was measured as; haptic feedback (M = 28.67, SD = 16.27), force feedback (M = 21.17, SD = 16.14), tactile feedback (M =

30.58, SD = 11.97), no feedback (M = 39, SD = 17.24). This showed that the participants found the task relatively easy to complete, indicating that a reasonable amount of physical activity was demanded from them in completion of the task.

In terms of temporal demand, that is, the time pressure felt in performing the task, the mean user rating of the experiment was; haptic feedback (M = 23, SD = 17.49), force feedback (M = 31.17, SD = 18.43), tactile feedback (M = 28.33, SD = 17.4), no feedback (M = 36.83, SD = 17.83). These scores indicated that the pace of the task was realistic and that participants were not rushed, had plenty of time to complete the task without pressure, and that the task elements were presented within a realistic period.

In the self-evaluation of performance in the TLX questionnaire, participants indicated that they were relatively unsatisfied with their performance; haptic feedback (M = 64.17, SD = 22.88), force feedback (M = 65.75, SD = 22.05), tactile feedback (M = 60.33, SD = 21.41), no feedback (M = 65.25, SD = 21.66). The users' satisfaction with the success of their performance corroborates with the earlier findings of negative self-satisfaction in performance of the task. It also highlighted some difficulties in the completion of the task and that a raised mental awareness was required during its execution. Notably, all feedback stages were rated equally negatively, with no significant effect of feedback. Therefore, although a negative evaluation of performance was recorded, there was no distinction between the performance of the different feedback stages, as was present in the SEQ and SMEQ.

In contrast to the self-evaluation of performance, participants indicated that they worked only somewhat hard mentally and physically to accomplish their level of performance; haptic feedback (M = 35.75, SD = 17.85), force feedback (M = 39.92, SD = 21.81), tactile feedback (M = 40.42, SD = 23.98), no feedback (M = 45.35, SD = 21.39). This indicated that the participants did not feel that they had worked particularly hard to reach their overall level of performance, even though an unsatisfactory evaluation of performance was measured.

Next, participants recorded that they were not irritated or stressed by the task. The TLX measured relatively low frustration levels, weighting towards a relaxed attitude during the experiment; haptic feedback (M = 25.83, SD = 23.56), force feedback (M = 22.58, SD = 26.36), tactile feedback (M = 31.58, SD = 29.26), no feedback (M = 30.33, SD = 27.36). These results indicated that although participants were relatively unsatisfied with their performance, they were not stressed or ired because of this.

Finally, a mean overall 'raw TLX' measure of workload was calculated as follows; haptic feedback (M = 35.64, SD = 13), force feedback (M = 37.02, SD = 13.14), tactile feedback (M = 38.78, SD = 14.73), no feedback (M = 44.56, SD = 11.91). Due to time restrictions, a pairwise comparison of each dimension was not deemed necessary and thus, not completed.

Table 5.7: NASA-TLX score data comparisons.

TLX Category	Alpha	Wilks' Lambda	F (3, 9)	p =	Eta^2
Mental Demand	0.74	0.49	3.16	.08	.51
Physical Demand	0.82	0.42	4.22	.04	.58
Temporal Demand	0.73	0.51	2.86	.10	.49
Performance	0.84	0.49	3.10	.82	.51
Effort	0.72	0.85	0.54	.67	.15
Frustration	0.74	0.68	1.41	.30	.32
Raw TLX Score	0.70	0.49	3.14	.08	.51

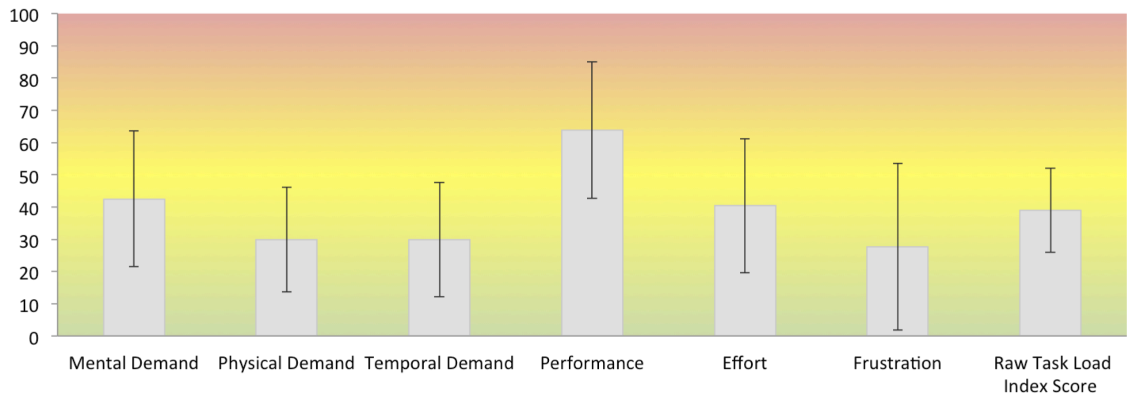


Figure 5.11: Average NASA-TLX rating for all feedback stages.

The data collected fulfilled parametric testing requirements, therefore a repeated measures ANOVA (used as each subject was measured on a continuous scale on four different occasions) was conducted to compare scores for the different feedback stages. Although there were some noticeable variations in the mean scores for each category and feedback types, no significant effects of feedback were recorded at the $p < .05$ levels for all categories except for Physical Effort: ($F(3, 9) = 4.22$, $p = .04$, Partial $Eta^2 = .58$). Post-hoc testing for Physical Effort revealed that there was a significant difference in mean scores for perceived effort between the no feedback and tactile feedback stages of the experiment (Mean Difference = 8.42, p = 0.046). This indicated that participants regarded the different feedback types as equally usable across all of the

TLX categories except for Physical Effort, where there was a difference in scores between the tactile and no feedback stages. The average NASA-TLX usability analysis based upon these observations can be seen in Figure 5.11.

5.6.6 User Experience Results

The final stage of the functionality analysis incorporated a post-task assessment of the users' experiences. A questionnaire was used to measure user experience quickly, simply, and as immediately as possible [135]. Six critical aspects of experience were captured via the UEQ questionnaire: *Attractiveness*, *Perspicuity*, *Efficiency*, *Dependability*, *Stimulation*, and *Novelty*, see Figure 5.12.

Table 5.8: Descriptive data for user experience.

User Experience Scale	Wilks' Lambda	F (3, 9)	p =	Eta^2
Attractiveness	0.63	1.79	.22	.37
Perspicuity	0.71	1.23	.35	.29
Efficiency	0.35	5.63	.02	.65
Dependability	0.24	9.45	< .001	.76
Stimulation	0.97	0.09	.96	.03
Novelty	0.36	5.41	.02	.64

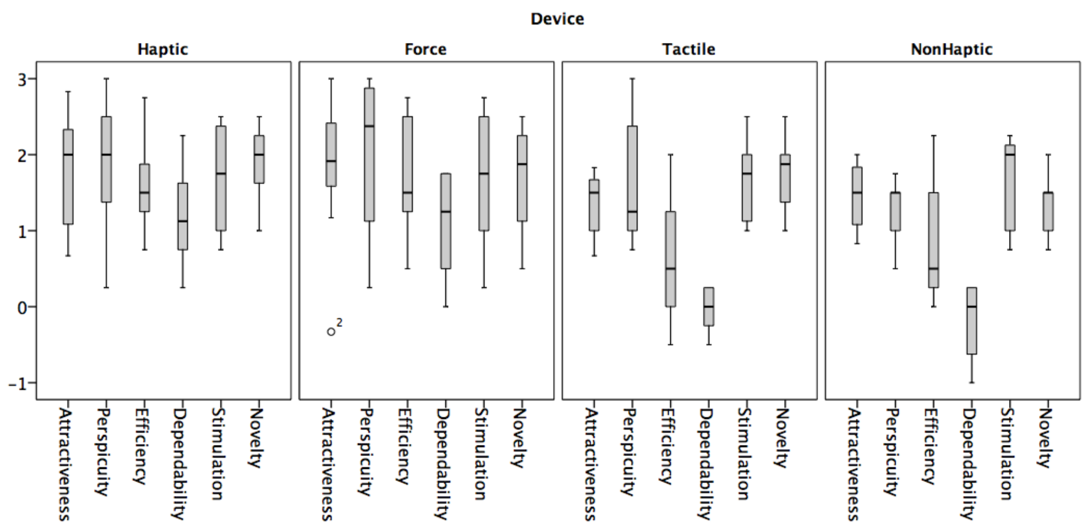


Figure 5.12: UEQ results (outliers are indicated with circles).

The overall internal consistency of user experience scales was acceptable, with an alpha value of .88. However, there were poor internal consistencies for some of the feedback stages analysed, highlighting some disparity between participant answers. The maximum range was measured as -3 (very bad) and +3 (very good). However, these maximum ratings are reportedly unlikely in user studies; therefore, a more restrictive range was applied to compensate for different answer tendencies of the participants. For user experience measures on this scale, mean values between -0.8 and 0.8 are representative of a neutral evaluation of the corresponding dimension. Values greater 0.8 represent a positive evaluation and values below -0.8 represent a negative evaluation. A repeated measures ANOVA (used as each subject was measured on a continuous scale on four different circumstances) was conducted to compare scores on the user experience questionnaire. It revealed that there were statistically significant variations in user experience answers for Efficiency, Dependability, and Novelty category ratings at the $p < 0.05$ level, see Table 5.8 and Figure 5.12. However, pairwise comparisons of Novelty with adjustments for multiple comparisons (Bonferroni) revealed no significant differences between feedback stages. The categories of Efficiency and Dependability in the UEQ questionnaire relate to the user's experience of the ergonomic quality aspects that were applied in the design of the Bowl devices. Participants evaluated their experience of device *efficiency* in the chosen task from being *quick* and *organised* for haptic feedback, reducing towards a more neutral rating as feedback was reduced in the order of force, tactile, and no feedback respectively. Similarly, the participants' experience of *dependability* of the feedback stages showed the same downwards trend, with experience ratings of *predictable* and *secure* behaviour for haptic and force feedback being high and a much more neutral rating for tactile and no feedback.

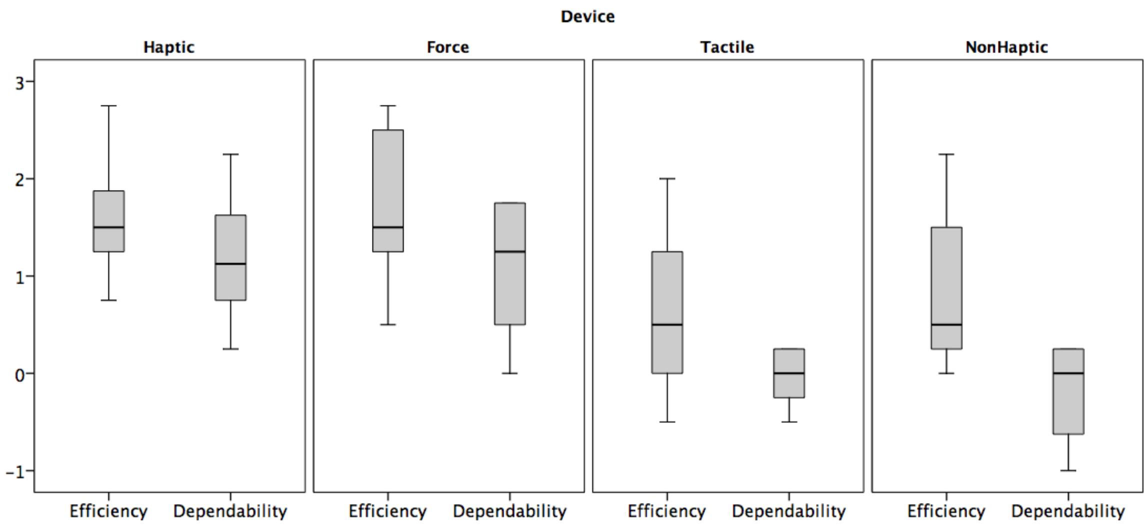


Figure 5.13: Box plots for Efficiency and Dependability.

From these findings it can be seen that participants rated the different feedback stages relatively equally for the categories of Attractiveness, Perspicuity, Stimulation, and Novelty. Post-hoc comparisons with Bonferroni adjustment indicated that the mean score for Efficiency for force feedback was significantly different from the no feedback stage. In addition, the same test revealed that there were statistically significant effects between *dependability* ratings for haptic and force feedback and tactile and no feedback, as seen in Table 5.9 and Figure 5.13. This significance highlights a perceived *efficiency* rating between the feedback stages of force, tactile, and no feedback. This perceived difference is interesting due to the lack of significant differences in measured performance.

Table 5.9: Pairwise comparisons of UEQ results.

		Efficiency (p =)	Dependability (p =)
Haptic	Force	ns	ns
	Tactile	.10	.00*
	No Feedback	.15	.00*
Force	Haptic	ns	ns
	Tactile	.03	.00*
	No Feedback	.01*	.00*
Tactile	Haptic	.10	.00*
	Force	.03	.00*
	No Feedback	ns	ns
No Feedback	Haptic	.15	.00*
	Force	.01*	.00*
	Tactile	ns	ns

5.6.7 User Experience Questionnaire and Interviews

Participants were asked if they would use each device (feedback stage) to perform with outside of the experiment. Participants varied in their answers across the different feedback stages; haptic feedback *somewhat often* (Md = 5, IQR = 1.5), force feedback *neither often nor occasionally* (Md = 4, IQR = 2), tactile feedback *occasionally / neither often nor occasionally* (Md = 3.5, IQR = 1.25), no feedback *occasionally* (Md = 3, IQR = 2).

The majority of participants were pleased with their evaluation of feedback performance for the haptic device and thought that they would use the device *somewhat or most often*

(50%). However, 20% of the participants thought that they would use the device *neither often nor not very often*. These users indicated that they did not have an opinion about usage preference, as they would not normally use a computer interface to make music. Finally, 40% of users indicated that they would only use the haptic interface *somewhat seldom*. When questioned, these users indicated that they were not particularly inspired by the functionality experiment, but suggested that if they could expand or explore the devices' parameters further they might have rated it more favourably. The estimated usage ratings for the different device feedback stages noticeably reduced from the haptic stage through to the no feedback stage see Figure 5.14. Participants who were not accustomed to performing with computer interfaces indicated that they felt increasingly negative towards devices as feedback was reduced.

Figure 5.14: Diverging stacked bar chart for participant preference of use evaluation.

For this type of data, robust non-parametric data analysis was required. A Friedman Test (used when the same sample of participants are measured under four different conditions) was used to reveal any statistically significant difference in device use answers across the four different feedback stages; the results were as such: x^2 (3, n =12) = 25.05, $p < .001$. Following this, a post-hoc Wilcoxon Signed Ranks test was conducted to explore the impact of device feedback on estimated use answers, see Table 5.10. There was found to be a statistically significant difference at the $p < .0125$ levels in device scores between the haptic and all other feedback stages. A medium to large effect size was observed from .24 to .44. Post-hoc comparisons indicated that the score for the haptic stage (Md = 5, IQR = 1.5) was significantly different from the other feedback stages at the $p = .0125$ level. There were also significant differences in results between the no feedback (Md = 3, IQR = 2) and force (Md = 4, IQR = 2) and tactile (Md = 3.5, IQR = 1.25) feedback stages.

Table 5.10: Wilcoxon Signed Ranks Test.

Feedback Stage		Z	p =	r =
Haptic	Force	-2.53	.011*	.37
	Tactile	-3.071	.002*	.44
	No Feedback	-2.84	.005*	.41
Force	Haptic	-2.53	.011*	.37
	Tactile	-2.449	.014	.35
	No Feedback	-2.636	.008*	.38
Tactile	Haptic	-3.071	.002*	.44
	Force	-2.449	.014	.35
	No Feedback	-1.667	.096	.24
No Feedback	Force	-2.84	.005*	.41
	Tactile	-2.636	.008*	.38
	Haptic	-1.667	.096	.24

* Significant with Bonferroni adjustment.

5.6.8 Interview Data Analysis

The next stage of the functionality experiment was to gather retrospective data via an open-ended questionnaire and interview-style evaluation of the different feedback stages. Participants were asked open-ended questions to gauge their opinions about the different feedback stages. These questions were then expanded upon in an interview, with care taken not to bias the participants' responses. A CIT analysis was conducted based upon the participant's answers to record the users' *attitudes* to the different feedback types. Content analysis techniques were applied to categorise the responses into the areas of concern outlined in Chapter 4, seen in Tables 5.11 to 5.14.

5.6.8.1 Haptic Feedback

Participants were inclined to be positive about the haptic feedback stage of the experiment and were pleased with the amount of feedback that was delivered via the device mechanisms, as can be seen Figure 5.15. It was noted that participants were more vocal about their experience at this stage than for the tactile and no feedback stages. Table 5.11 shows the results of the content analysis of the haptic feedback study. The table highlights Personal Preference as the most reported aspects of user experience at this stage. The Personal Preference comments highlighted the overall *enjoyment* of participants when interacting with the device. For example:

Positive:

- "Lots of fun to play."
- "Haptics are necessary to turn a device into an actual musical instrument."
- "It translates well into the digital domain."

While the majority of Personal Preference comments were positive, participants highlighted some negative ergonomic aspects of the interaction.

Negative:

- "I thought that the tactile feedback should be applied to the back of the hand, so it was always against the skin."
- "The foot-pedal was frustrating to use."

Comments about Playability mainly focussed on the difficulties experienced during the task. For example:

Positive:

- "The haptic feedback helps you adjust easily."
- "It wasn't difficult to play, being able to hear and feel the sound makes for a pleasant playing experience."
- "I think having the extra point of reference allowed me to resolve pitch more easily."

Negative:

- "Quite large movements to achieve higher pitches."
- "Difficult to alter the attack."
- "I found the exercise harder with haptic feedback as it required more concentration."

The majority of comments in the Playability category were positive. These comments demonstrated an appreciation for the increased performance information provided in haptic feedback. Participants expressed a liking for a traditional feel to the interface that increased their *attention* to their actions. This shows that if care is taken to provide haptic feedback in DMI designs, the end user gains an increased *sense of awareness* of their interaction, without involving complicated mechanisms or processing.

The Comparison to other musical instruments category produced a number of interesting responses in comparison to the other feedback stages. Specifically, comments that compared the device directly with acoustic instruments provided an interesting insight into the combination of force and tactile feedback. For example:

Positive:

- "Feeling the vibrations makes it feel more like a traditional instrument."
- "[It's] closer to a classical instrument experience."
- "You can feel the vibration produced by the instrument [it's] like holding a real vibrating instrument."
- "The tuning of just intervals on a violin has the same touch feeling as this."

Negative:

- "There's less nuance."
- "It feels slightly more restrictive than a traditional instrument."
- "It would take a lot of practice to play an actual melody."

The Learnability category also yielded some interesting feedback comments in comparison to the other feedback stages and the frequency response of the hands to vibrotactile feedback. Interestingly, Learnability was seen more positively here than for the force and tactile feedback alone. These findings have been observed in other research areas, most notably in [140]. Some comments were as such:

Positive:

- "It was easier to learn how to use than the other devices."
- "A small learning curve."

Negative:

- "It was a bit more difficult to find higher pitches."

The category containing the most negative remarks was Tempo. The comments expressed here all indicated that a tempo based task would be very problematic to perform and positive comments indicated that it would be challenging to accomplish. For example:

Positive:

- "Maybe? It was easier to control with haptic feedback, but it would still be difficult."

Negative:

- "It would be very difficult to play fast tempos."

Table 5.11: Content analysis for haptic feedback comments.

CIT Categories	Positive Comments	Negative Comments	Total
Personal Preference	17	2	19
Playability	11	4	15
Comparison to other musical instruments	9	4	13
Learnability	11	2	13
Comparison to other DMIs	9	3	12
Explorability	6	4	10
Tempo	5	5	10
Total	68	24	92

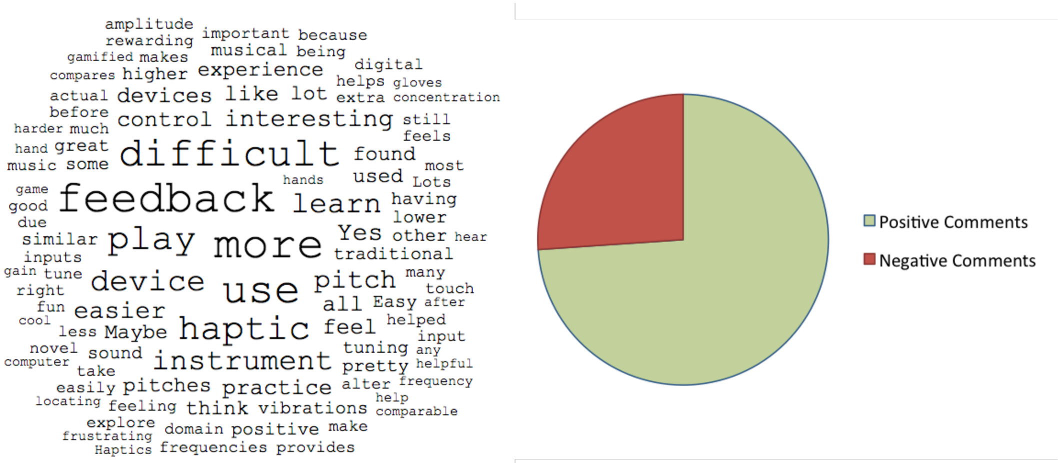


Figure 5.15: Frequency word cloud and total positive and negative comments for haptic feedback.

5.6.8.2 Force Feedback

Table 5.12 shows the results of the content analysis of the force feedback stage of the experiment. It is worth noting that this stage of the experiment received the same number of positive comments as the haptic stage; however, it also received more negative comments, see Figure 5.16. As with the haptic feedback stage, it received noticeably more comments than the tactile and no feedback stages of the experiment. Again, the category that contained the most comments was the Personal Preference

The Personal Preference category of the force feedback stage contained comments discussing the *novelty* of the design and how the users found it *interesting* to use. There were also a number of positive comments focussing on *simplicity* and *accessibility* of the interface. However, some comments fixated negatively on the manner in which *pitch selection* was achieved and the *quality of sound* reproduction from the small, embedded speaker. For example:

Positive:

- “I think it's a really interesting device.”
- “It's very novel and fun.”
- “A good idea to interact with sound.”

Negative:

- “Needs a cleaner low-end speaker.”
- “I would have liked to create and hear more sounds.”
- “Different ways to select a pitch after you find it would be better.”
- category; however, the categories following this varied from the haptic feedback stage.

Participants were more inclined to refer to other instruments in the Comparison to other musical instruments category compared to the haptic feedback stage; however, some comments were critical of the *lack of input gestures* available to use. As such:

Positive:

- “Whilst it still has things in common with a Theremin, the added feedback is more helpful than just seeing where your hand is.”

- "Having force feedback, I felt I was playing an instrument rather than just moving over a beam."
- "Sliding pitches were almost the same as on musical instruments."
- "The physicality of this device makes it more fun."
- "Less nuances available, that is, different sounds from different bow strokes, etc."

Negative:

- "The violin I play is more intuitive in some ways, but this is physically draining."
- "It's unusual to be tied to an instrument."
- "As it is now, it doesn't have as many uses as a real instrument would, but that's the nature of building these instruments that have specific uses in mind."

Comments in the Playability category discussed the implication of physical requirements for playing the device, either praising its *accessibility* or commenting on the interface requirements for *interaction*. For example:

Positive:

- "Not difficult to play, very low strain on the body."
- "The sounds were very responsive to movement."

Negative:

- "Being short made pulling the amplitude up hard."
- "When I'd try to press the button with my foot, the pitch hand would waiver."
- "I found it hard to gauge exactly where notes/tones would be without a reference frame."
- "It's not always easy to 'feel' the sensitivity of the hands, especially for pitch."

The group containing the most negative remarks was again the Tempo category. Comments made here referred to issues of *envelope attack time*, *jumps in pitch*, and concerns about *accuracy*.

Negative:

- "The attack of each sound was hard to alternate, so rhythm was difficult."
- "I could use tempo with some practice, but jumps of pitch will still be difficult."
- "Probably, but I would guess that my accuracy for pitch would drop."

Table 5.12: Content analysis for force feedback comments.

CIT Categories	Positive Comments	Negative Comments	Total
Personal Preference	15	5	20
Comparison to other musical instruments	11	7	18
Playability	9	7	16
Comparison to other DMIs	14	1	15
Learnability	11	0	11
Explorability	6	4	10
Tempo	2	8	10
Total	68	32	100

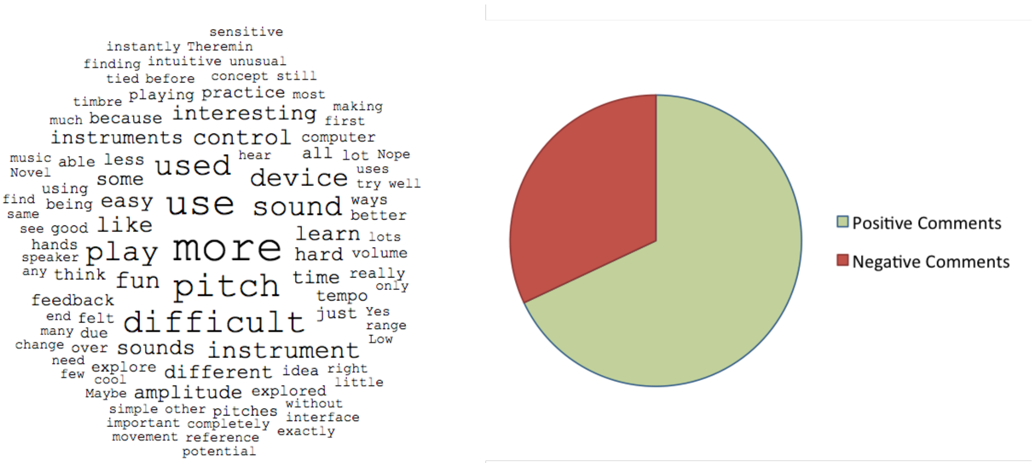


Figure 5.16: Frequency word cloud and total positive and negative comments for force feedback.

5.6.8.3 Tactile Feedback

Table 5.13 shows the results of the content analysis of the tactile feedback stage and Figure 5.17 illustrates how participants were more conservative with comments made; suggesting that there were not as many aspects of this feedback stage that were worthy of note. However, there may also be a cultural norm present in participant responses. The categories that contained the most responses were Personal Preference, Comparison to other musical instruments, and Playability.

The Personal Preference category contained the largest amount of participant comments. This category also contained the most positive comments. These comments mainly reflected how the participants felt about the interaction as a whole and their curiosity about tactile feedback. For example:

Positive:

- "I really like the vibrating glove feedback."
- "Very fun and novel to use."
- "Feeling was involved as well as hearing, I liked it."
- "I liked this device better with tactile feedback."
- "It makes me feel more connected to a physical instrument even though I'm playing in the air."

However, some participants viewed the interaction as unpredictable and inaccurate. As such:

Negative:

- "I think I took more time to find the correct pitches because it was sensitive to movement."
- "If I could increase accuracy, it would be great."
- "A great concept that needs refining."

Comments in the Comparison to other musical instruments category talked about how the interactions were in comparison to the participants' own instruments and accuracy. For example:

Positive:

- "The gloves give it a tactile sensation not unlike the buzzing violin on your shoulder."
- "It's a lot more fun than a regular instrument."
- "It was good to feel the vibrations; it made it feel more like an actual 'analogue' instrument"

Negative:

- "Instruments can be plucked etc., this cannot."
- "Instruments [have a] much more precise range of pitches."

The Playability category contained the highest number of negative comments. The participants focused on a perceived lack of accuracy and precision in their movements. For example:

Negative:

- "It was difficult to get a consistent pitch."
- "It was difficult to play because of a lack of spatial positioning feedback."
- "The lack of feedback made it difficult to play."
- "It didn't feel so precise."

Table 5.13: Content analysis for tactile feedback comments.

CIT Categories	Positive Comments	Negative Comments	Total
Personal Preference	9	4	13
Comparison to other musical instruments	5	4	9
Playability	1	8	9
Comparison to other DMIs	5	3	8
Learnability	7	1	8
Explorability	6	1	7
Tempo	0	6	6
Total	37	23	60

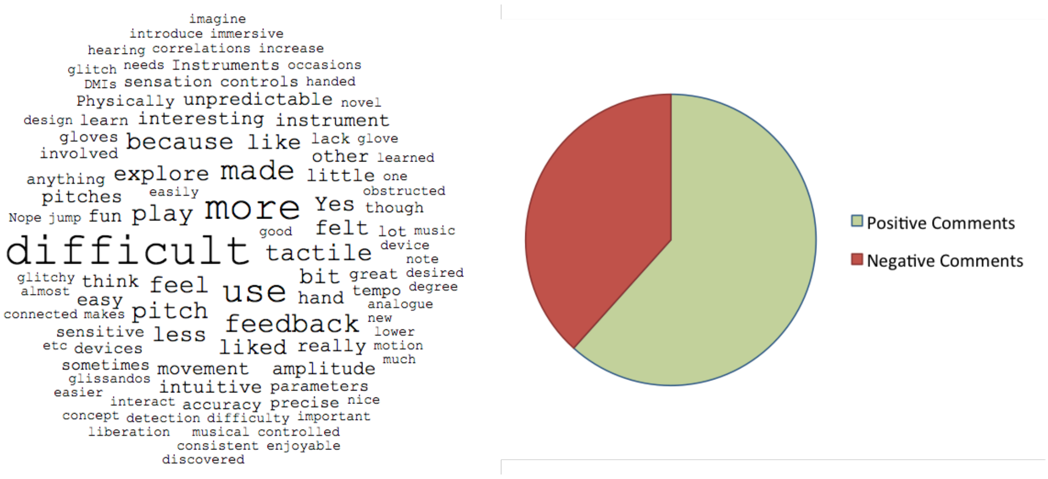


Figure 5.17: Frequency word cloud and total positive and negative comments for tactile feedback.

5.6.8.4 No Feedback

Finally, the results from the no feedback stage of the experiment can be seen in Table 5.14 and Figure 5.18. This feedback stage yielded a high number of comments about Personal Preference, Comparison to other DMIs, and Playability issues.

The negative Personal Preference comments highlighted the participants' frustrations at the lack of feedback provided. Positive comments were directed to the *novelty* and *fun-factor* of the interaction. For example:

Positive:

- "Overall a good concept because it's fun to use."
- "[It's] fun to use and to replicate the frequencies could have practical use in music pedagogy."

Negative:

- "[The] lack of feedback makes it hard to use."
- "It's not clear where the pick-up areas are for the sensors and hard to get the maximum and minimum ranges."
- "I found it hard to figure out the range."

Participants were more inclined to compare the no feedback stage of the experiment with other DMIs, as seen in the Comparison to other DMIs category. Many of the comparisons were negative, focussing again on the perceived inaccuracy of their movements. Positive comments highlighted the differences to other DMI interactions. For example:

Positive:

- "It's a whole lot more fun to use."
- "Most other interfaces involve sitting down."
- "The pitch tracking was similar to other devices I've used."

Negative:

- "It felt pretty glitchy."
- "It felt inaccurate."
- "It's a tad harder to use than other DMIs."
- "Initially it felt difficult to coordinate the footswitch and the hand sensor."

As with the tactile feedback stage of the experiment, the Playability category contained the most negative comments. These comments mainly focused on the perceived accuracy of the interaction, with a few comments about creative application. For example:

Positive:

- "It depends on what you want to do with it."
- "I'd play alien music with it."

Negative:

- "It's not too responsive."
- "No feedback makes it difficult to play."
- "Pretty good and interesting, but also hard to use."
- "[It] felt unpredictable."

Table 5.14: Content analysis for no feedback comments.

CIT Categories	Positive Comments	Negative Comments	Total
Personal Preference	5	7	12
Comparison to other DMIs	4	7	11
Playability	3	8	11
Comparison to other musical instruments	4	6	10
Learnability	7	1	8
Explorability	5	2	7
Tempo	1	6	7
Total	29	37	66

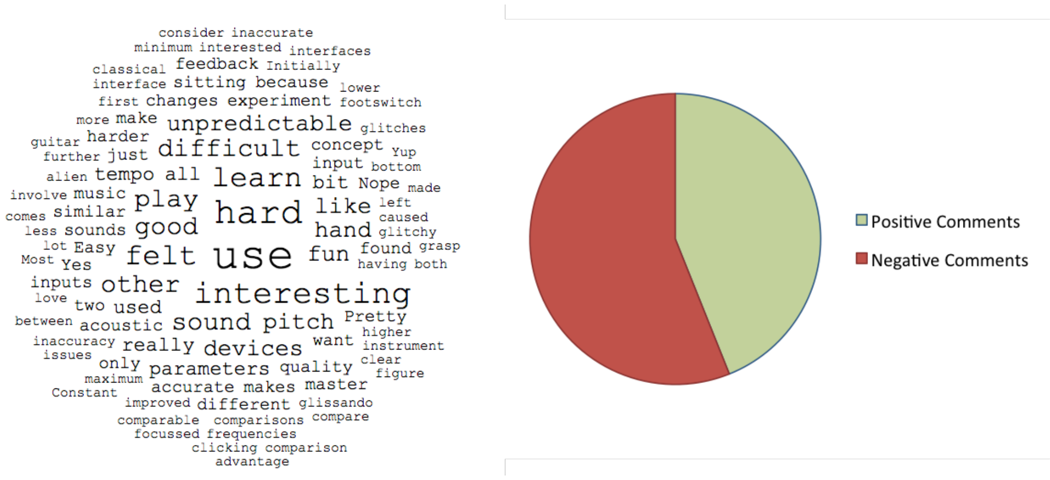


Figure 5.18: Frequency word cloud and total positive and negative comments for no feedback.

Table 5.15: Percentage of positive and negative comments.

Feedback Stage	Positive Comments (%)	Negative Comments (%)	Total Number of Comments
Haptic	74	26	92
Force	68	32	100
Tactile	58	42	64
No feedback	44	56	66
Total	63	37	322

5.6.9 Empathy Mapping

Empathy mapping is applied in User Experience studies to understand or to form *empathy* for the end users. It is typically used in consideration of how a person is feeling and to understand better what they are thinking. This is done by recording what the participants were thinking, feeling, doing, seeing, and hearing as they were performing tasks with the devices presented. With this data, it is possible to create a general persona post-experiment to raise issues specific to the context of the analysis. It is helpful to create Empathy Maps to reveal causalities of a user's movements, their choices, and the judgements they made during the task in a way that the participants may not be able to articulate post-task.

Empathy mapping data was recorded during the functionality study to capture instantaneous data about the participants' experience without interrupting the task. Observations about what the participants said aloud, sentiments towards the device, their physical performance, and how they used prior information of other devices during the experiment were recorded to validate and potentially expand upon the post-task questionnaire and interview data presented above. As can be seen in Figures 5.19 to 5.22, there was little deviation from observed actions and verbal explanations of answers in the interview.

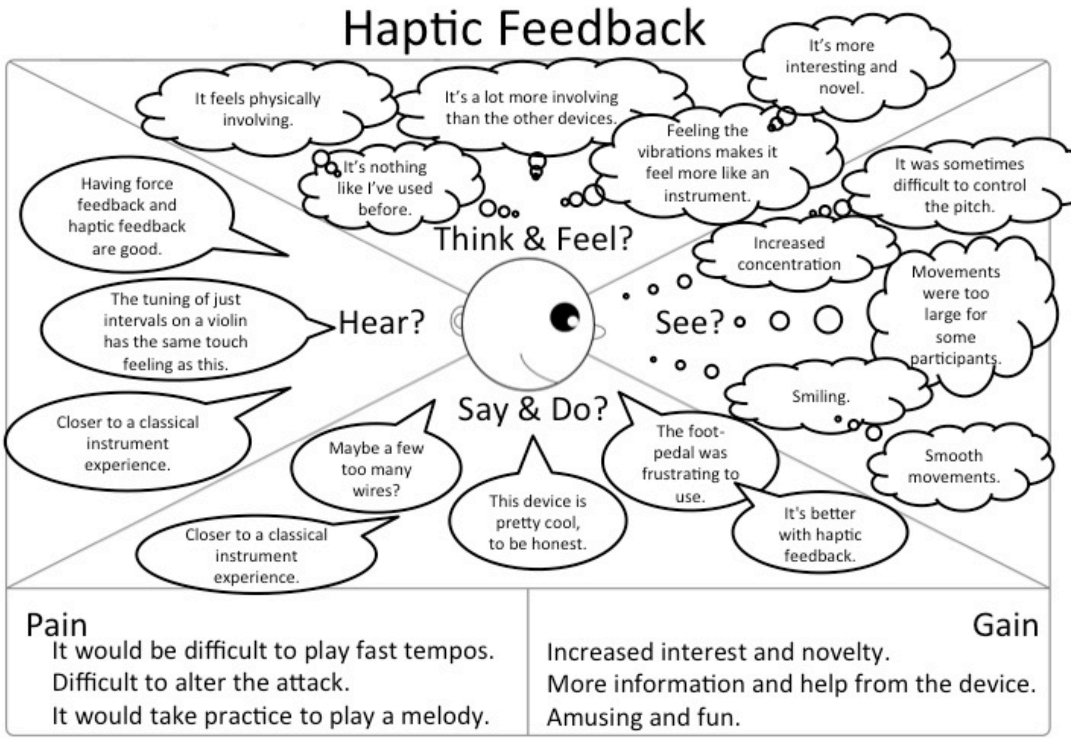


Figure 5.19: Empathy Mapping for Haptic Feedback.

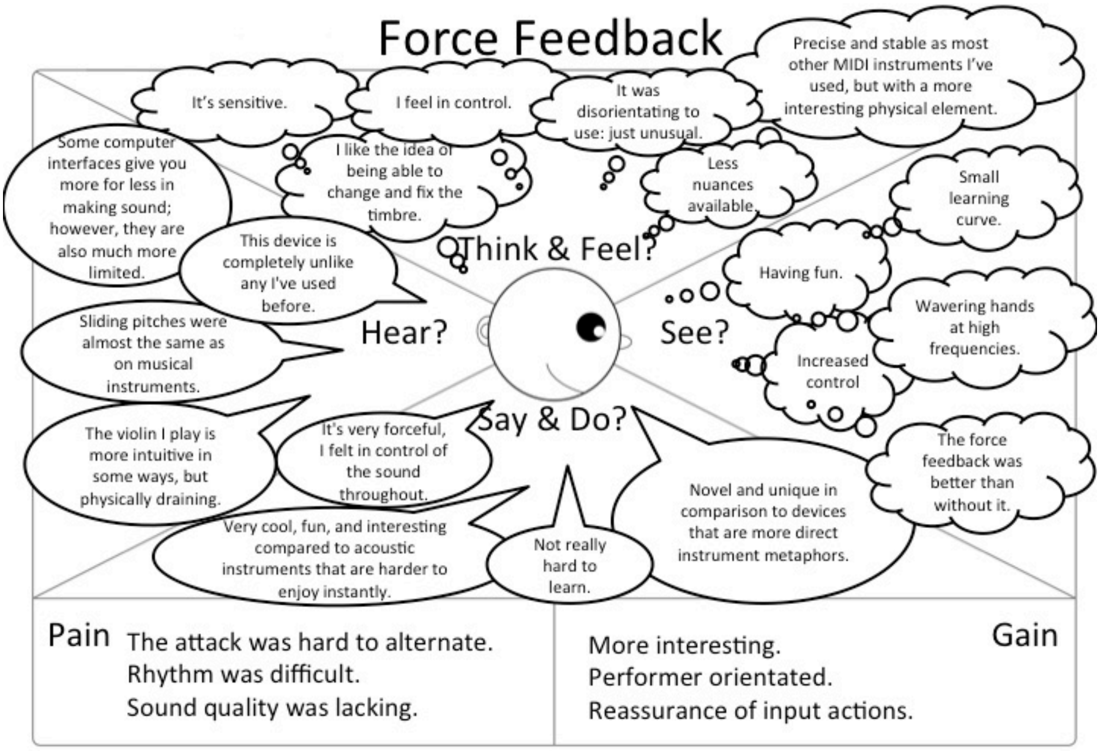


Figure 5.20: Empathy Mapping for Force Feedback.

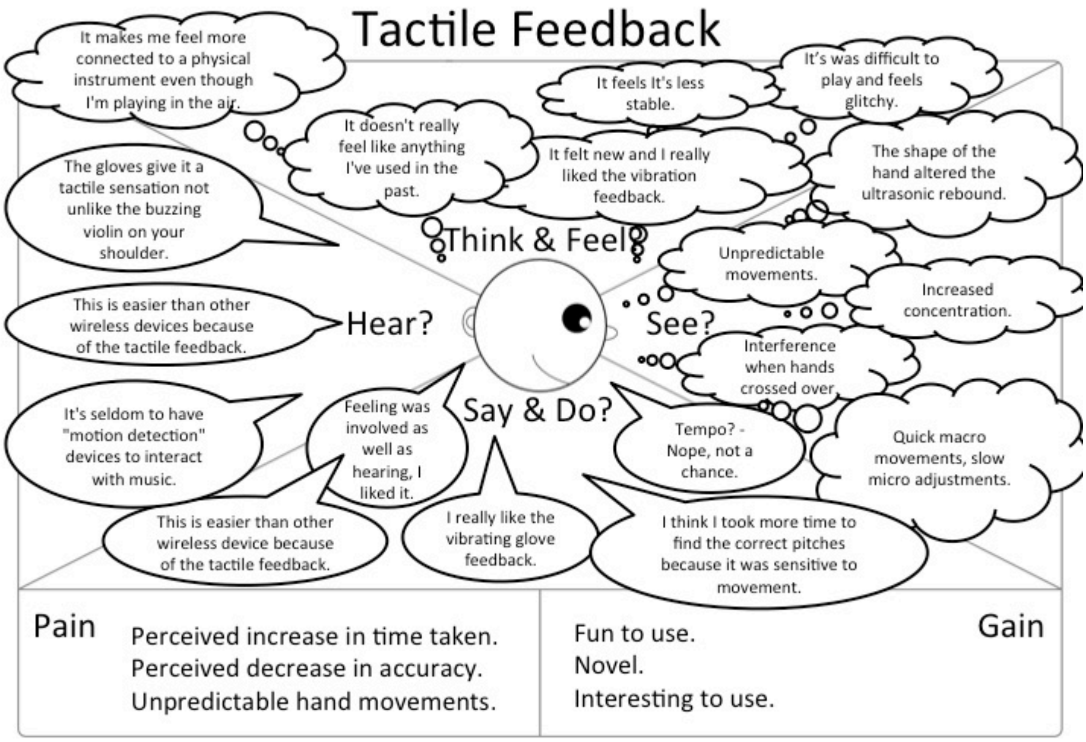


Figure 5.21: Empathy Mapping for Tactile Feedback

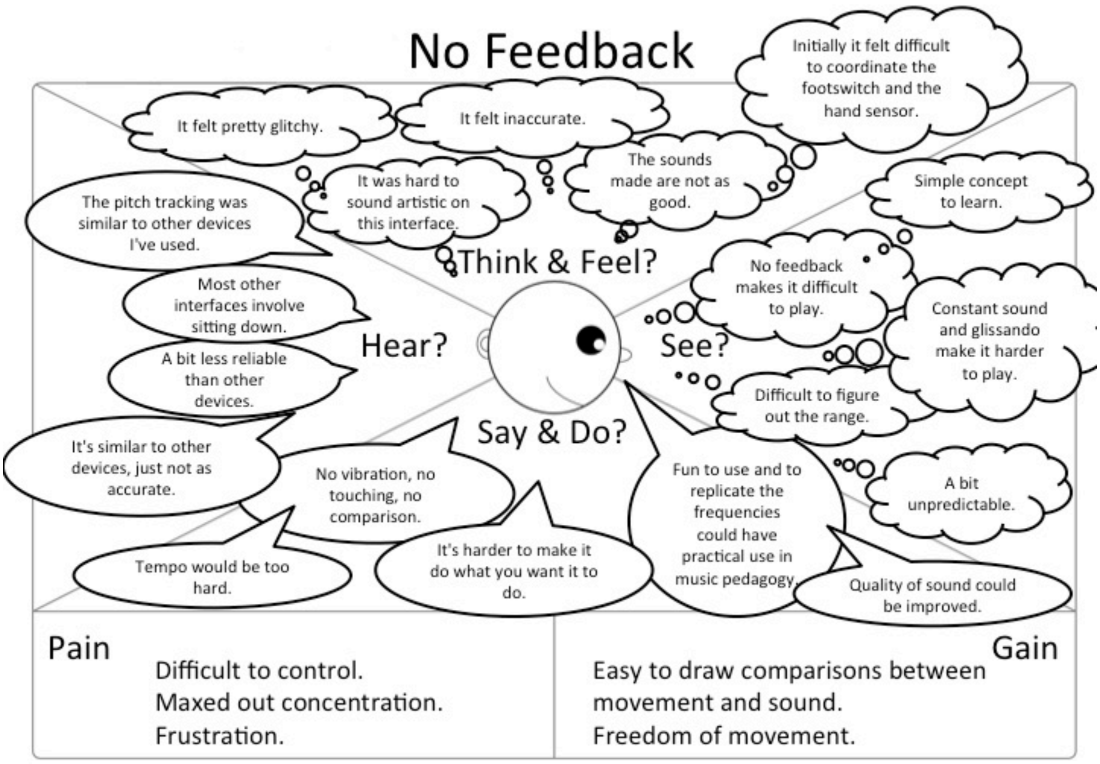


Figure 5.22: Empathy Mapping for No Feedback

5.7 Part 4: Explorative Testing

Following the functionality analysis, an examination of feedback was executed in explorative case-by-case studies. In this analysis, the different feedback types were applied in both musical exercises and in the exploration of feedback in creative applications. The effects of feedback were observed and recorded as they were in the experiment presented in Part 3. However, the tasks undertaken were designed to measure the performance potential of the different feedback stages in a more creative context than was previously observed. This approach explored a qualitative approach to the evaluation of DMIs in *longitudinal* type studies [141]; with focus remaining on the same issues examined in Part 3 of the analysis.

Measuring a participant's experiences when playing music or working with a DMI was highlighted as being a highly complex operation (discussed in Chapters 2 and 4). However, the formal evaluation of experience over time, although challenging, has been the focus of recent HCI studies [142] [143]. Through the application of HCI evaluation tools, the importance of *learnability* and *explorability* in a constrained evaluation has been identified as requiring extended periods to assess. As discussed in Chapter 2, many evaluations of DMIs do not afford the participant adequate time to explore and evaluate these aspects, as was seen in Part 3. Therefore, to incorporate the issues that longitudinal approaches are adept to exposing, an experiment was devised to investigate experiences in real-world applications of feedback.

Although Part 3 was successful in its appraisal of feedback in a task-based evaluation, it provided some inconclusive information pertaining to the perceived *usability* of the different feedback stages. This result underpins the requirement for alternative methods of DMI evaluation to be applied in the field of Computer Music and that understanding the user's *experience* of *usability* in a creative context is far more complex than in traditional human-computer interactions. Similar findings have been observed in HCI, for example the concept of the '*third paradigm*' (mentioned in Chapter 4). With reference to this, the potential to oversee device embodiment has been supported from the findings of Part 3. That is to say, in Part 3 of the analysis, although the implementation of quantitative and qualitative analyses of interaction factors were successful, the outputted data arguably failed to account for the *process* of the interaction, giving clear evidence of context-in-use affecting the participants' usability ratings. Therefore, for a holistic evaluation of DMI feedback, data collected from contextual applications must be included.

5.7.1 Pilot Study: Musical Context Analysis

The musical context analysis enabled the investigative process to take place over an extended period of time and allowed for the exploration of DMI integration in real-world contexts. With an investigation that involved creativity, it was important that the participants were not rushed or restricted, that they were given an adequate amount of time to explore and assess the different feedback stages without constraint. This provided accurate and representational data of the participant's experiences with the different feedback types.

The main goal of the pilot study was to gain knowledge of the application of feedback in creative and explorative tasks by focussing on how the participants integrated them into their real-world working process. As the appraisal of an individual's creativity and musicality is arguably subjective in its evaluation, the user's proficiency in original composition and skill in the execution of music tasks was not assessed. However, in this study the participants' self-evaluation of the performance of the *device* was instead focused upon. Each participant was requested to consider the strengths and weaknesses of the input metaphors afforded by the different feedback stages and to attempt to personalise their application and performance to best suit. This style of analysis was selected to represent the more qualitative analyses types discussed in Chapter 2 and address the requirements for a music based analysis as discussed in Chapter 4. In addition, the devices' *usability* and the *user's experience* when applying the different feedback types were recorded and analysed as in Part 3.

The significance of the changes in participant responses to the feedback types presented was concluded via visual differences observed in the data. This technique was applied; as statistical significance was difficult to determine for single-subject experimental procedures. Single-subject conditioning studies are common in physiological and psychological measures; however, it can be argued that the objectivity of this particular method of analysis can be subjective and researcher biased results could potentially have been observed. However, although previous device analyses in the evaluation of DMIs in musical contexts have been described as idiosyncratic (as discussed in Chapter 2) by following a structured analysis methodology, it was possible to reduce researcher interpretations of data. It was also important to acknowledge that levels of statistical significance and practical (or clinical) meaningfulness could also present quite differently in studies of this type. Therefore, care was taken to elaborate only upon significant differences with the same clarity of deduction and extraction of meaning and interpretation as has been reported in the supporting literature. Therefore, the interpretation of data was based upon the same important aspects that were highlighted in Part 3 of this analysis.

5.7.2 Participants

Four musicians participated in this explorative study. All participants were recruited from the previous experiment. The participants were aged 22 to 29 (M = 24.5, SD = 2.69). The group consisted of 3 males and 1 female. All of the participants self-identified as being musicians, having been formally trained or regularly performing Computer Music in the past five years. The participants self-identified their prior knowledge and experience as follows:

Participant 1

Participant 1 is a classically trained composer. He completed his BMus in 2015. His current works incorporate mixes of both chamber instruments and electronics, drawing from a wide variety of styles.

Participant 2

Participant 2 is a multi-disciplined musician, teacher, and researcher. He holds a BA in Visual Art, an MSc in Interactive Media, and is presently pursuing a PhD in Applied Psychology / Human-Computer Interaction. His current research focuses on the use of augmented and virtual reality interaction technologies in education. He has created several audio-visual installations and are specialised in the application of alternative forms of input interaction for virtual reality devices. He has played the electric bass for 13 years and is a self-taught double bassist, drummer, guitarist, and pianist. He creates experimental electronic music under the alias Diobhal. Currently, he is employed as a UI/UX and Graphic Designer.

Participant 3

Participant 3 is a multimedia engineer who applies a vast array of mediums to express his creativity. He is a self-taught guitarist with no formal background in music theory. However, he enjoys exploring and creating new music through experience and has been composing in this way for many years. He is currently working as a software prototyping engineer. In this role, his skills and expertise are applied in the exploration of new paradigms for interactive technology in a *Design Thinking* led environment.

Participant 4

Participant 4 is a multimedia artist interested in the use of technology as artistic practice, as a means to generate ideas, and as a medium with which to create. She has created audio-visual installations and live performance environments internationally, and is currently pursuing a PhD in Digital Arts through the Department of Music, UCC.

5.7.3 Methodology

All case studies took place in a sound proofed recording studio and lasted from 2 to 4 hours. As in Part 3, the USB output from each device was connected to a 2012 MacBook Pro Retina. The input data from the devices were converted in Processing into OSC messages and outputted as UDP information over port 12001. PD was used to receive and processed this data. A polyphonic sound generator was programmed in PD that incorporated variable pitch, amplitude, and an attack, decay, sustain, release (ADSR) envelope generator. The inputted gesture data was used to control each element of the sound generator. The right hand X/Y/Z input stages of the bowl devices controlled the following parameters respectively: attack, sustain, and frequency. The left hand X/Y/Z input was used to control decay, release, and total volume.

Participants were given a preselected list of musical exercises to perform and were asked post-task to evaluate the feedback's performance in the execution of these tasks. The simple tasks were as suggested by Orio and Wanderley [124] and discussed in Chapter 4. The participants were requested to consider the device's application in these tasks and to then attempt to apply them to short experts of music. Sheet music was provided to give the participants some direction [140], but exploration and free play was encouraged to investigate the potential application of the feedback types in a variety of different performance contexts. Each feedback stage was evaluated independently post-task after an appropriate period had passed. This varied from 30 to 60 minutes depending on the participant. A post-task questionnaire was completed for each feedback stage followed by a brief interview to expand upon the opinions expressed during the study.

Prior to the study, the participants were encouraged to consider the application of the input parameters in their own compositions. Therefore, after the completion and evaluation of the different feedback stages in musical exercises, the participants incorporated the control metaphors into their own works. Participants 1 and 2 chose to emulate the function of the device unaltered in context from that of Part 3. However, further sound control functionality was added to expand the input controls beyond the one-dimensional pitch and volume control applied earlier. The Bowl devices were applied as note-level controllers for the same digital sound generator used for the exploration of musical exercises. However, the participants were encouraged and facilitated in the editing and personalisation of this program to suit their own ideas and tastes.

For participant 3, an electric guitar and amplifier were moved into the studio to accommodate their interest in exploring the application of the Bowl devices in conjunction with this instrument. As a guitarist, the participant had an interest in developing a guitar effects patch programmed in Pure Data. Therefore, prior to the experiment, a basic effects program was written based upon the requests of the musician. The effects were achieved via a simple real-time audio patch with the right hand X/Y/Z input stages of the bowl devices controlling the following parameters respectively: reverb, pitch bend, and delay volume. Vibrotactile feedback was provided in the same manner as the previous case studies. For this participant, the contextual function of the device was altered from that of the functionality experiment and the two previous case studies. This change was implemented to accommodate for the application of the Bowl devices in an *extended instrument* context, changing from a note-level control context to a processing control activity. This is validated and described by Wanderley and Orio [124] and was discussed briefly in Chapter 4.

Finally, for participant 4, a 46-inch monitor was moved into the studio to accommodate the participant's interests in video and sound manipulation. As a multimedia artist, the participant decided upon developing an audio-visual patch programmed in MAX/MSP (a visual programming language). The program was written by the participant and was a simple real-time video patch with the X/Y/Z input stages controlling the following parameters respectively: blur width, origin, and video alpha channels, with one video per hand. Each input was also mapped to a sinusoidal oscillator that outputted frequencies from 0 to 1024 Hz across the input range of the devices used, providing tactile and audio feedback relating to three dimensional hand position. The augmentation of function due to this audio-visual application altered the application context to a metaphorical processing control or post-production activity.

5.7.4 Results of Explorative Study

Although the context of use was somewhat altered between case studies, the relationship between the application of feedback and the manner in which it was discussed remained consistent. In the explorative study, *usability* and *user experience* data were gathered to compensate for the difficulties of evaluating functionality in a musical context. Although the number of participants in the pilot study was considered too low for a statistical analysis, a visual examination of the combined data highlighted practical significances between the different feedback stages. Further to this, the *usability* and *user experience* data was gathered about each feedback stage to later compare statistical and practical variations observed earlier. As an indication of these factors, the explorability experiment provided a more extensive experiment and period for the participants to adequately and accurately judge these factors.

In the application of longitudinal-style methodologies, the participants all expressed an appreciation for extra free-exploration time in the execution of musical tasks. This was deemed important, as the participants wished to explore the application capabilities of the DMIs with the same constraints they would apply for any new devices applied in creative applications.

5.7.5 Analysis of Feedback in Musical Tasks

To evaluate the different feedback types in music-based tasks, the participants were asked to verbally self-appraise the performance of the feedback types in musical exercises. A CIT analysis was carried out to evaluate the participant's responses to the following music-based exercises:

1. Generate isolated tones, from simple triggering to varying characteristics of pitch, loudness, and timbre.
2. Perform musical gestures specific to the device, such as glissandi, trills, grace notes, and so on.
3. Play simple scales and arpeggios altering speed, range, and articulation.
4. Repeat phrases with different contours and variations of structure.
5. Play continuous feature modulation (e.g. timbre, amplitude or pitch) both for a given note and inside a phrase.

6. Play simple rhythms at different speeds combining tones or pre-recorded material.

5.7.5.1 Haptic Feedback

> Generate isolated tones, from simple triggering to varying characteristics of pitch, loudness, and timbre:

For this type of musical exercise, the participants expressed mixed opinions about the perceived performance of the device. Both positive and negative attributes were identified as affecting the performance of these exercises; this was conveyed as follows:

Positive:

- "Varying the different characteristics of the sound generator was OK…"
- "It was easy to trigger isolated tones with this device."

Negative:

- "…it was still a little difficult."
- "Controlling the patch was difficult as the accuracy didn't seem that good."
- "While interacting with the device you had to accommodate for latencies, making it harder to use."

> Perform musical gestures specific to the device, such as glissandi, trills, grace notes, and so on.

Basic musical gestures were assessed as being easier at slower tempos and more difficult at faster measures; however, it was highlighted that with practice they could be achieved and therefore become easier. This was stated as follows:

Positive:

- "Basic musical gestures were less difficult and were achievable with time and patience."
- "Glissandi, trills, and grace notes were all very easy to perform."
- "Aimed glissandi and trills were easy at a slow tempo, as were pitch bends and vibrato too."

> Play simple scales and arpeggios altering speed, range, and articulation.

Simple scales and arpeggios were considered easy to perform, but only within the limitations of the sound generator. All participants were able to adapt the short musical excerpts to fit within the constraints of the DMI. For example:

Positive:

- "Simple scales and phrase contours could be controlled well."
- "Simple scales were OK and arpeggios were fine at most speeds."

Negative:

- "They had to be adjusted to fit within the range of the sound generator."
- "It was hard to modify the effects whilst performing difficult tasks."

> Repeat phrases with different contours and variations of structure.

In the manipulation of phrases, the participants were comfortable playing the music presented to them and altering it to fit their own ideas. Initially, the participants required both the sheet music and a short audio rendition to memorise the different phrases. However, once familiar, they could confidently play without assistance. This was expressed as follows:

Positive:

- "Controlling the sound generator for single notes and phrases was easiest for single features."
- "Phrases with different contours were easy to control."
- "I could emphasize certain parts of a phrase easy enough when playing…"

Negative:

- "…only when playing slowly."

> Play continuous feature modulation (e.g. timbre, amplitude or pitch) both for a given note and inside a phrase.

To evaluate the different features afforded via the interface, participants performed a variety of different styles of music. In addition to this, the participants were allowed to introduce variation in the presented music to explore modulations in the performance of these scores. In their evaluation of this category, the participants expressed the following:

Positive:

- "The modulation of amplitude and pitch worked quite nicely."
- "The continuous modulation of the different features worked quite well at slow tempos…"

Negative:

- "Balancing the other features was hard to do at the same time."
- "…they were a little harder at faster paced tempos."

> Play simple rhythms at different speeds combining tones or pre-recorded material.

In the final category of musical exercises, the participants were asked to comment upon the possibility to vary the tempos of the presented scores and then discuss the difficulties presented when playing along with other sources of music. These comments were mainly positive, indicating that the feedback was influential in applications that required consideration of tempo. The comments were as follows:

Positive:

- "…it could be better with practice."
- "The foot pedal worked fine for controlling simple rhythms."
- "Whilst playing simpler rhythms, I could choreograph dancing into the task to get the required effects - this was a lot of fun to explore."

Negative:

- "Performing simple rhythms at different speeds was hard…"

Table 5.16: CIT Results for haptic feedback.

CIT Category	Positive Comments	Negative Comments	Total
1	2	3	5
2	3	0	3
3	2	2	4
4	3	1	4
5	2	2	4
6	3	1	4
Total	15	9	24

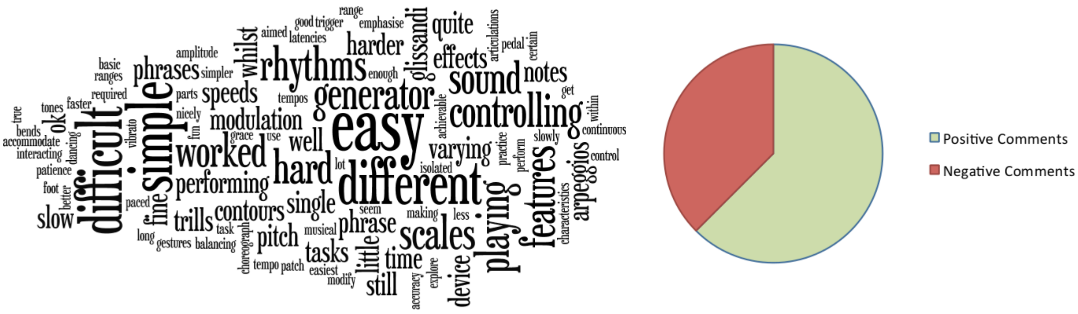


Figure 5.23: Frequency word cloud and total positive and negative comments for haptic feedback.

Force Feedback

> Generate isolated tones, from simple triggering to varying characteristics of pitch, loudness, and timbre:

For the force feedback stage, the control of single tones was evaluated both positively and negatively. The main issue with this feedback stage was thought to be the participants' self-evaluation of accuracy in selecting precise pitches. However, it was also judged as being easier than the tactile/no feedback stages. Comments made were:

Positive:

- "…less so [difficult] than the other feedback stages."
- "Isolated tones were easy to perform… "

Negative:

- "This device wasn't too good at getting precise timbres."
- "It was slightly more difficult to trigger isolated tones… "

> Perform musical gestures specific to the device, such as glissandi, trills, grace notes, and so on.

Gestures were thought to be more difficult at faster tempos than at slower, although this varied in importance between participants. For example:

Positive:

- "[Easy] …as were the other basic musical gestures."

Negative:

- "Musical gestures, scales, phrase contours etc. were hard to perform."
- "…it wasn't so great at fast paced movements due to latency issues."

> Play simple scales and arpeggios altering speed, range, and articulation.

There were very few comments made about scales and arpeggios for this feedback stage. This was due to the participants being undecided about the performance of the device in these actions. For example:

Positive:

- "Simple scales were pretty easy."

Negative:

- "It was hard to synchronise both the playing of the guitar and creating different effects."

> Repeat phrases with different contours and variations of structure.

Phrases were generally seen to be easy to perform. However, comfort in the different performances was dependent upon the chosen tempo.

Positive:

- "Phrases were performed with little difficulty… "
- "…the controller was easy to use."

Negative:

- "…it was good for slow tempos only."

> Play continuous feature modulation (e.g. timbre, amplitude or pitch) both for a given note and inside a phrase.

This category received the most comments for the force feedback stage. The continuous control of features was considered more difficult than the haptic feedback stage, with more time required in achieving an acceptable performance. Some comments were as follows:

Positive:

- "This was OK…"
- "…the device allowed for playing without interruption…"
- "Continuous effects, such as delay and reverb, were good."

Negative:

- "…difficult to master."
- "…this feedback required a little more time to perform with first; I couldn't get them right straight away."
- "…not for fast changes."

> Play simple rhythms at different speeds combining tones or pre-recorded material.

There were mixed thoughts on the application of force feedback in exercises that required rhythms to be performed in combination with other materials. These feelings were expressed as follows:

Positive:

- "…[they were] learnable."

Negative:

- "Creating and performing simple rhythms was difficult… "
- "…simple rhythms; I'd need more time to practice."
- "…it was still difficult to coordinate all of my actions."

Table 5.17: CIT Results for force feedback.

CIT Category	Positive Comments	Negative Comments	Total
1	2	2	4
2	3	0	3
3	1	1	2
4	2	1	3
5	3	3	6
6	1	3	4
Total	12	10	22

Figure 5.24: Frequency word cloud and total positive and negative comments for force feedback.

5.7.5.2 Tactile Feedback

> Generate isolated tones, from simple triggering to varying characteristics of pitch, loudness, and timbre:

Controlling the different functions of the sound generator was done so enthusiastically; however, this opinion varied between participants. It was also apparent that the participants preferred tactile feedback to no feedback and force feedback over tactile. For example:

Positive:

- "The performance of isolated tones was achievable."
- "...quite easy."
- "…it was easier with tactile feedback than without it."

Negative:

- "…glissandi, trills etc. were hard to perform with any accuracy."
- "Controlling the different parameters of the patch was difficult."

> Perform musical gestures specific to the device, such as glissandi, trills, grace notes, and so on.

Again, for this category of the investigation, a preference for tactile feedback over no feedback was expressed. However, the control of the sound generator was still perceived as being difficult. This was expressed as follows:

Positive:

- "…it was easier with the tactile feedback than without it."

Negative:

- "The performance of the device at selecting and triggering the various characteristics of the patch was quite difficult to master… "
- "Basic gestures were hard to do."
- "…glissandi and so on were hard to perform."

> Play simple scales and arpeggios at different speed, range, and articulation.

In the performance of scales and arpeggios, the participants felt that the accuracy of this feedback stage was severely lacking. All participants felt that movements with any precision were difficult to achieve. For example:

Negative:

- "…scales, arpeggios, and creating phrase contours were hard to get right."
- "Scales and arpeggios were very hard… "
- "I couldn't perform simple scales or arpeggios with any semblance of nuance."
- "It was too difficult to make precise movements."

- Repeat phrases with different contours and variations of structure.

Most participants considered creating a variety of phrases impartially with this feedback type. There were difficulties, but they could potentially be overcome with some training and practice. Comments were made as such:

Positive:

- "…creating different phrase contours was fine."
- "I could create different phrase contours ok… "
- "…easier over time."

Negative:

- "Modulating the different features in a continuous manner was hard…"
- "It was difficult to make movements that were controllable."
- "… only when playing slowly."

- Play continuous feature modulation (e.g. timbre, amplitude or pitch) both for a given note and inside a phrase.

The continuous feedback received by the participant, in relation to the sound produced, was thought to be a positive feature. The feedback was considered to assist in pitch and intensity precision; however, some of the other parameters were much harder to control. This was expressed as such:

Positive:

- "Controlling the overall amplitude modulation was fine… "
- "The good point about the continuous modulation of different effect features was that I could feel them in my hand."
- "…controlling the reverb and delay intensity felt good."

Negative:

- "…the other parameters were not so good."

> Play simple rhythms at different speeds combining tones or pre-recorded material.

The application of the tactile feedback stage in the performance of rhythms was thought to be very difficult for all participants. However, tactile feedback was also thought to be advantageous over no feedback whatsoever. The transparency of movement and latency issues were thought to be somewhat lacking in controlling other materials. For example:

Positive:

- "Simple rhythms were not as difficult to perform as the no feedback stage."

Negative:

- "Rhythms were very difficult to perform accurately."
- "I don't see how I could use this device to control other instruments or pre-recorded materials on a computer."

Table 5.18: CIT Results for tactile feedback.

CIT Category	Positive Comments	Negative Comments	Total
1	3	2	5
2	1	3	4
3	0	4	4
4	3	3	6
5	3	1	4
6	1	2	3
Total	11	15	26

Figure 5.25: Frequency word cloud and total positive and negative comments for tactile feedback.

5.7.5.3 No Feedback

> Generate isolated tones, from simple triggering to varying characteristics of pitch, loudness, and timbre:

All participants considered controlling the different characteristics of the sound generator as being difficult. However, they also thought that further control might be achievable given more time with the device. Additionally, a perceived reduction in the responsiveness of the device was expressed. Comments made were as such:

Positive:

- "Selecting isolated tones was achievable…"

Negative:

- "…it had a steep learning curve."
- "Isolated tones were difficult to play …"
- "…it felt a bit jittery with loads of latency"

> Perform musical gestures specific to the device, such as glissandi, trills, grace notes, and so on.

Basic musical gestures were thought to be difficult to perform with any accuracy. All participants expressed similar opinions. For example:

Negative:

- "…basic musical gestures were quite hard to perform."
- "Basic musical gestures were hard… "
- "…all difficult to do with any accuracy."

> Play simple scales and arpeggios altering speed, range, and articulation.

The level of precision afforded to the users was considered poor. As a result, scales and arpeggios were very difficult. This was expressed as follows:

Negative:

- "Simple scales and arpeggios were very hard to play."
- "There was no way you could have any level of control for scales and arpeggios at any speed."

- Repeat phrases with different contours and variations of structure.

As accurate control was not achievable, some of the participants did not comment on phrase contours. However, one participant thought that they were achievable and commented as follows:

Positive:

  - "Control within different phrases was ok."

- Play continuous feature modulation (e.g. timbre, amplitude or pitch) both for a given note and inside a phrase.

In the control of continuous features of the sound generator, the participants expressed a requirement for more time and practice. Control was achievable, but it took a longer time in comparison to the other feedback stages. For example:

Positive:

  - "Modulating continuous features, such as amplitude and pitch, could be done well over time."
  - "Controlling within different phrases was ok… "
  - "I could control the amplitude without problem… "
  - "The only good thing I think about this device is that it was good for triggering the reverb and delay effects."

Negative:

  - "It just took a bit of practice."
  - "…when playing something really slow and simple."
  - "…I had problems controlling the other parameters."

- Play simple rhythms at different speeds combining tones or pre-recorded material.

When performing rhythms with no feedback, the participants preferred slower tempos over faster. In addition, when controlling different parameters, the participants struggled to perceive scenarios where the precise control of external parameters would be viable. For example:

Positive:

- "Slow tempos were the easiest to match… "

Negative:

- "… faster tempos were tough going."
- "Simple rhythms were difficult to perform."
- "It would be really difficult to control anything else on the computer."

Table 5.19: CIT Results for no feedback.

CIT Category	Positive Comments	Negative Comments	Total
1	1	3	4
2	0	3	3
3	0	2	2
4	1	0	1
5	4	3	7
6	1	3	4
Total	7	14	21

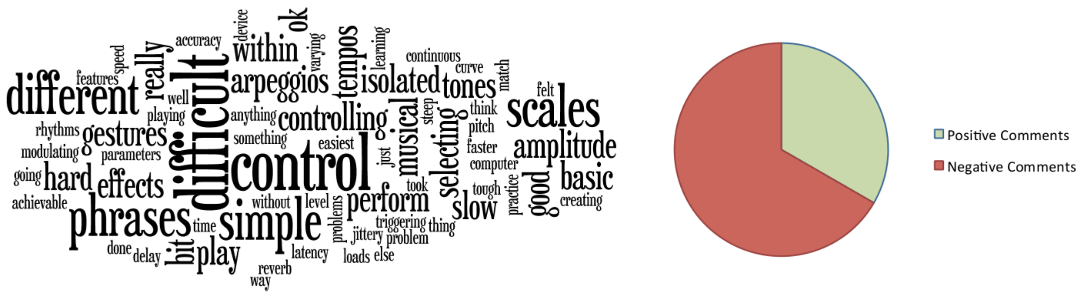


Figure 5.26: Frequency word cloud and total positive and negative comments for no feedback

Table 5.20: Percentage of positive and negative comments for the pilot study.

Feedback Stage	Positive Comments (%)	Negative Comments (%)	Total Number of Comments
Haptic	62.50	37.50	24
Force	54.55	45.45	22
Tactile	42.31	57.69	26
No feedback	33.33	66.67	21
Total	48.39	51.61	93

5.7.6 Usability Results

The SEQ for all case studies can be seen combined in Table 5.21 and Figure 29. The overall rating of haptic feedback was seen to be *somewhat easy* to use, with an interquartile range (IQR) of 3. Following this, the force feedback stage was assessed as being *neither difficult nor hard,* (IQR = 3). The tactile feedback stage followed, evaluated as being *somewhat difficult,* (IQR = 0.5). Finally, the no feedback stage was judged as being *mostly difficult* to use, (IQR = 1). Although the effect of feedback cannot be statistically tested, a practical assessment of the data can be made based upon the comprehensive testing undertaken. Therefore, in this study, the perceived difficulty of the tasks can be seen to increase as feedback was removed. However, the differences between the individual feedback stages are somewhat small.

Table 5.21: Combined SEQ Results for the pilot study.

Feedback	Median		IQR
Haptic	5	*Somewhat Easy*	3
Force	4	*Neither Difficult nor Hard*	3
Tactile	3	*Somewhat Difficult*	0.5
No Feedback	2	*Mostly Difficult*	1

The results of the SMEQ in the explorative experiment can be seen in Table 5.22 and Figure 5.27. In the pilot study, haptic feedback was considered to require *some* to *a reasonable amount of effort* in the completion of musical tasks, with a standard deviation of 11.03 between participants. Following this, force feedback was evaluated as requiring a *reasonable* to *fair amount of effort,* (SD = 7.12). Next, tactile feedback was appraised as demanding a *fair amount of effort* to *a lot of effort,* (SD = 12.62). Finally, the no feedback stage was perceived as requiring *very much effort,* (SD = 2.59). As was seen in the SEQ analysis, the perception of *mental effort* required to undertake musical tasks was observed as increasing as feedback was removed, with the individual scoring of each feedback stage differing slightly between participants. Additionally, with the inclusion of tactile feedback, the participants' perception of mental effort was seen to deviate much more than with force and no feedback.

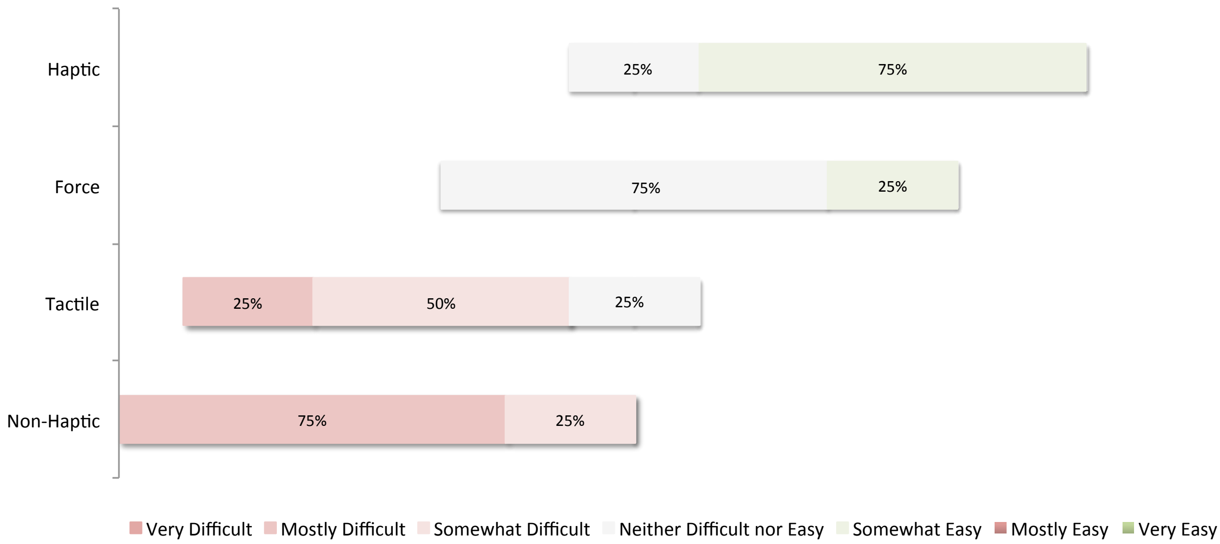


Figure 5.27: Combined SEQ Results for the pilot study.

Table 5.22: Combined SMEQ Results for the pilot study.

Feedback	Average		SD
Haptic	47.25	*Some to Reasonable Amount of Effort*	11.03
Force	55.25	*Reasonable to Fair Amount of Effort*	7.12
Tactile	75.75	*Fair to A Lot of Effort*	12.62
No feedback	90.75	*Very Much Effort*	2.59

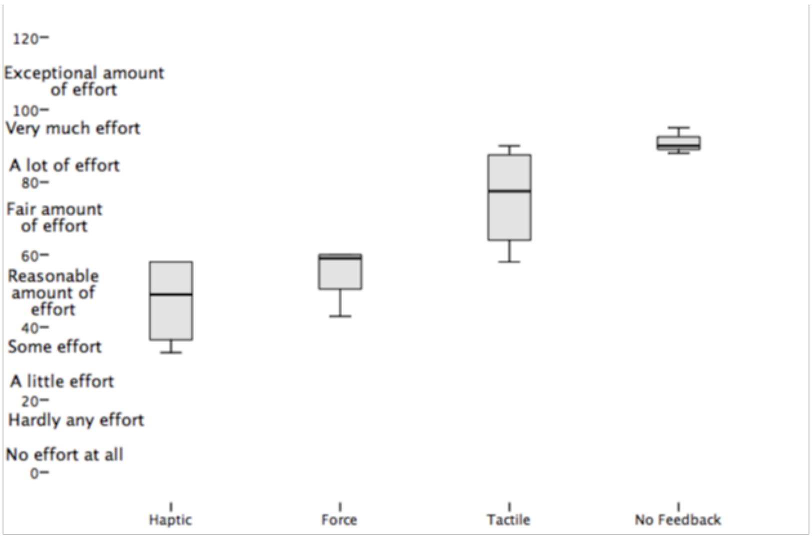


Figure 5.28: Combined SMEQ Results for the pilot study

Table 5.23: Combined NASA-TLX Usability Results for the pilot study.

NASA-TLX Category	Haptic	Force	Tactile	No feedback
Mental Demand	33.25	43.25	57.50	66.75
Physical Demand	34.00	38.00	36.25	38.75
Temporal Demand	28.00	25.75	37.75	36.50
Performance	26.75	28.00	60.25	55.75
Effort	34.25	36.00	57.50	60.25
Frustration	26.50	29.25	40.75	42.75
Raw TLX Score	33.79	38.37	45.91	50.96

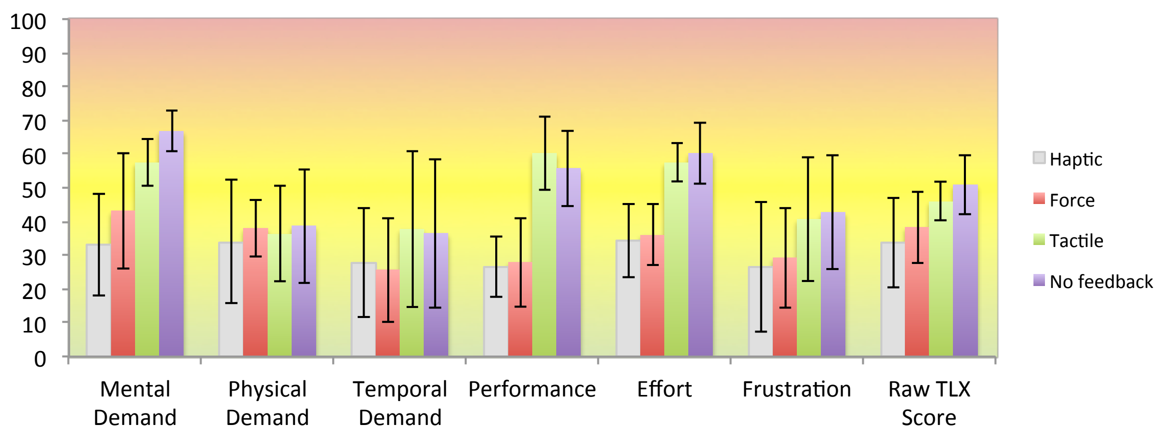


Figure 5.29: Combined NASA-TLX Usability Results for pilot study.

In the results of the NASA-TLX questionnaire a number of subcategories were observed as invariable between feedback stages, see Table 5.23 and Figure 5.28. However, some categories of the TLX displayed noticeable differences in explorative exercises.

The first category where visual difference could be inferred was in the evaluation of Mental Demand. The haptic feedback stage was evaluated as requiring the least amount of *mental effort* in explorative tasks (M = 33.25, SD = 15.22). This was followed by force (M= 43.25, SD = 17.15), tactile (M = 57.5, SD = 7.02), and no feedback (M = 66.75, SD = 6.06) respectively. Haptic feedback received a positive to neutral rating, and as feedback was removed in the order given, the user's rating was observed changing to a neutral to negative rating for no feedback. This result denotes that the user's *perception* of mental demand increased as feedback was removed in music-orientated tasks.

Following this, the category of Performance was seen to alter between feedback stages. The evaluation of device *performance* was reacted to positively for haptic feedback (M = 26.75, SD = 9.04) and force (M = 28.00, SD = 13.21), the user rating fell considerably when force feedback was removed for tactile (M = 60.25, SD = 11.12), and finally no feedback (M = 55.75, SD = 11.14). These results indicated that in the perception of *performance*, the participant were reliant upon force feedback. That is to say, tactile feedback did not positively affect the perception of the participants' *performance* when applied with or without force feedback. This is supported as no definite differences were observed between haptic and force feedback ratings, as well as tactile and no feedback ratings also.

The same observations could be made in the user's perception of Effort. For this TLX category, the user's assessment of *work exercised* in the application of feedback was seen to increase as feedback was removed. This was observed in the order of haptic (M = 34.25, SD = 10.99), force (M = 36.00, SD = 9.14), tactile (M = 57.50, SD = 5.59), and no feedback (M = 60.25, SD = 9.01) respectively. In the execution of music-orientated tasks, force feedback was seen to reduce the amount of *perceived effort* the participant had exerted. Further to this, the application of tactile feedback had no positive or negative effect upon effort when applied with no additional feedback. Furthermore, it did not present with a negative effect upon force feedback either.

Finally, the TLX category for Frustration presented with a visual trend over the four feedback stages. The haptic feedback stage had the lowest level of perceived *frustration* in use (M = 26.5, SD = 19.11), followed by force (M = 29.25, SD = 14.89), tactile (M = 40.75, SD = 18.35), and no feedback (M = 42.75, SD = 16.89) respectively. Although these changes appear only slightly different, they indicate that the participants were *stressed* more for no feedback than they were for haptic feedback. Both tactile and force feedback reduced the levels of *annoyance* the participants experienced.

5.7.7 User Experience Results

In the pilot study, the UEQ categories of Attractiveness, Perspicuity, Efficiency, and Dependability presented with noticeable differences between feedback stages, seen in Table 5.24 and Figure 5.29. The categories of Stimulation and Novelty were inconclusive, with large standard deviations and similar mean scores noted for each category and feedback stage.

The category of Attractiveness in the UEQ operated as an independent indication of the *intrinsic desirability* of the different feedback stages; also reflected in the Preference of Use question presented later. The UEQ categories of Perspicuity, Efficiency and Dependability were applied as *goal-directed* aspects of evaluation, resulting in a more *pragmatic* evaluation of feedback. These qualities related directly to the evaluation of *practicality* and *functionality* of each user's experiences of feedback and ultimately reflected the evaluation of the users' *satisfaction* in achieving their goals. Although some deviations in participant answers were observed, the overall trend within pragmatic qualities was that haptic feedback was the most preferred feedback type, followed by force, tactile, and finally no feedback. Each category will now be discussed individually.

From analysing the Attractiveness category's data, the participants' *overall impression* of the different feedback stages appeared to reduce as feedback was removed: haptic (M = 1.63, SD = 1.17), force (M = 1.58, SD = 0.84), tactile (M = 0.83, SD = 0.96), and no feedback (M = 0.33, SD = 0.92). These results indicated that the overall *desirability* of a DMI directly related to the amount of feedback received by the user. Additionally, the users perceived force feedback as more desirable than tactile. Furthermore, the addition of tactile feedback to force was seen to increase the standard deviation between participant ratings, meaning that the participants' opinions diverged in their estimations.

For the category of Perspicuity, the four case studies revealed that it was easier for the participants to become *familiar* with the haptic feedback stage than when they were provided with no feedback at all. Although the deviations between user ratings were somewhat noticeable, the trend was visually apparent and expressed as influential in the user interviews conducted after each feedback analysis. The user's' rating of *learnability* in the interview section of the analysis further strengthens this observation.

In the Efficiency category, the *effectiveness* of feedback in the completion of musical tasks was considered equal for both haptic and force feedback. However, the addition of tactile feedback to force increased the deviations observed between participant answers. Furthermore, tactile feedback was seen to improve upon the amount of unnecessary effort required to complete tasks over no feedback. This indicated that tactile feedback had a positive influence upon the user's perception of device efficiency when no feedback was present and that tactile feedback influenced the participants' ratings when combined with force feedback.

Finally, the participants' perception of interaction *dependability* appeared to increase as feedback was applied. This implied that tactile and force feedback increased the user's impression of sound control. However, there was no improvement observed between haptic and force feedback; although an increase in deviation was apparent for haptic feedback. These results indicated that the users felt more in control of the interaction when feedback was present. However, the addition of tactile feedback to force feedback had a variable effect upon the users.

In the UEQ categories of Stimulation and Novelty, the qualities of feedback that were not goal-directed, there appeared to be an indication that feedback had little or no effect upon the *psychological needs* and *emotional* experiences of the user. However, when expanded upon in the usability interviews (of both Part 3 and the explorative study), the evocation of previous experiences appeared to be quite influential. In addition to this, the different feedback types appeared to stimulate each user differently, indicating that subjective experience was highly influential in the analysis of these categories.

Table 5.24: Combined UEQ Results for the pilot study.

UEQ Category	Feedback	Mean	SD
Attractiveness	Haptic	1.63	1.17
	Force	1.58	0.84
	Tactile	0.83	0.96
	No Feedback	0.33	0.92
Perspicuity	Haptic	1.25	0.88
	Force	1.06	0.60
	Tactile	0.38	0.51
	No Feedback	-0.25	0.77
Efficiency	Haptic	1.06	1.12
	Force	1.06	0.62
	Tactile	0.19	0.89
	No Feedback	-0.38	1.08
Dependability	Haptic	1.06	1.08
	Force	1.06	0.27
	Tactile	0.06	1.10
	No Feedback	-1.19	0.89
Stimulation	Haptic	2.00	0.73
	Force	1.88	0.45
	Tactile	1.00	1.51
	No Feedback	1.31	1.65
Novelty	Haptic	2.06	0.89
	Force	1.81	0.60
	Tactile	1.75	1.03
	No Feedback	1.56	1.22

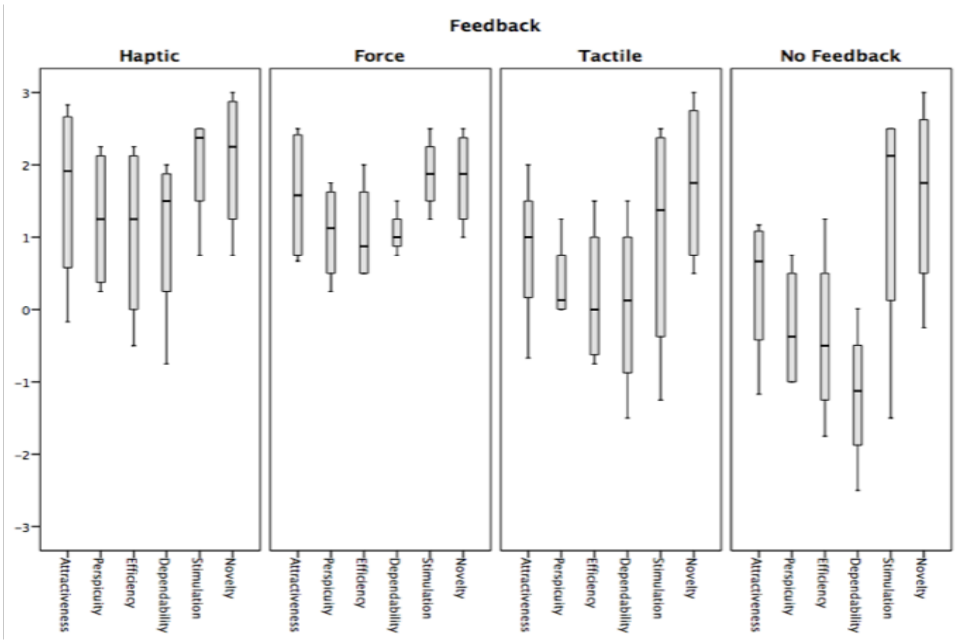


Figure 5.30: Combined UEQ Results for the pilot study.

5.7.8 User Experience Questionnaire and Interviews

The preference of use results of the pilot study can be seen in Table 5.25 and Figure 5.30. In this category, the participants were asked how likely they would choose the different feedback stages to perform with. All participants considered the haptic (Md = 5.5, IQR = 1.25) feedback stage to be the most *desirable* to use in this scenario, followed by force (Md = 5, IQR = 0.25), tactile (Md = 3.5, IQR = 1.25), and no feedback (Md = 3, IQR = 0.5). Participants expressed a likelihood of performing with the haptic feedback stage as *somewhat to most often*, *somewhat often* for force feedback, *occasionally to neither often nor occasionally* for tactile feedback, and finally *occasionally* for no feedback. These findings illustrate how artists prefer haptic feedback in interactions with the digital mediums with which they perform. Additionally, these findings also support the Attractiveness category of the UEQ.

Table 5.25: Preference of Use for the pilot study.

Feedback	Median		IQR
Haptic	5.5	*Somewhat to Most Often*	1.25
Force	5	*Somewhat Often*	0.25
Tactile	3.5	*Occasionally to Neither Often nor Occasionally*	1.25
No feedback	3	*Occasionally*	0.5

5.7.9 Interview Data Analysis.

The final part of the explorative analysis was to interview the participants to expand further upon their responses to the different feedback stages. Qualitative data was gathered via open-ended questioning and subjected to a CIT analysis, as was seen in Part 3 of the analysis. The categories of the content analysis were predetermined from the exploration of existing DMI analysis techniques outlined in Chapter 4.

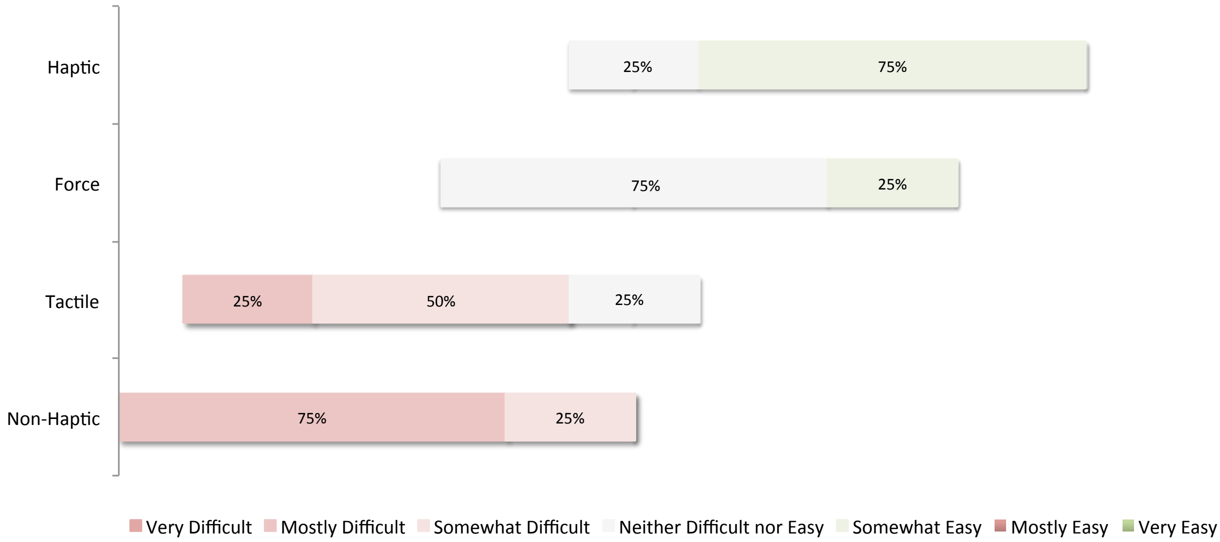


Figure 5.31: Preference of Use for the pilot study.

5.7.9.1 Haptic Feedback

For haptic feedback, the participants were generally pleased with the level of feedback they received, with 23 positive comments and only 9 negative. Participants considered the categories of Timing and Feature Controllability as the most important areas of concern for haptic feedback; this was followed by Learnability and Explorability respectively. The results of the CIT can be seen in Table 5.26 and Figure 5.31. Interest in these two categories highlights the participants' concerns with the application of feedback in a musical context. These two categories in particular related to the performance of complex gestures involved in controlling the PD patch, highlighting important issues in feedback implementation in musical tasks.

The Timing Controllability category of the haptic feedback stage was evaluated positively, but was not without issues. Exercises that required temporal precision were difficult, but it was felt that these difficulties could be overcome with training and time. With this feedback stage, participants were able to control the patch and implement the

DMI in musical tasks. This highlighted the practical applications of haptic feedback in this context. For example:

Positive:

- “I feel with more practice they’d be achievable”
- “Timing was easy; it wasn’t glitchy or noticeably lagging”
- “I had a lot of fun, it was like dancing whilst playing the guitar”

For the category of Feature Controllability, the participants’ perception of accuracy in the manipulation of pitch, volume, and envelope shape was considered acceptable. However, there were perceived difficulties in movement and calibration. The participants were able to successfully operate the device and control the patch, but some aspects of the feedback stage were not to their liking. These points were expressed as follows:

Positive:

- “The control of pitch, volume, and the envelope shapes gave me enough control to create musical phrases accurately”

Negative:

- “…could still be a little difficult at times”
- “[The device was] …difficult to get around, it needed calibrating to fit my needs and my gestures”

Table 5.26: CIT Results for haptic feedback.

Content Analysis Categories	Positive Comments	Negative Comments	Total
Timing Controllability	9	1	10
Feature Controllability	6	4	10
Learnability	3	3	6
Explorability	5	1	6
Total	23	9	32

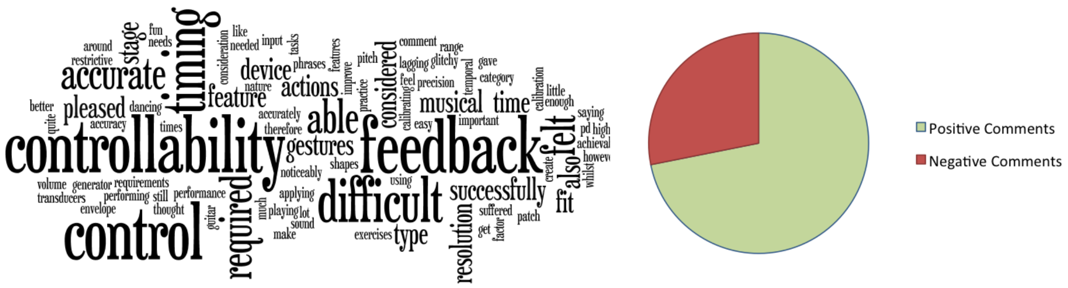


Figure 5.32: Frequency word cloud and total positive and negative comments for haptic feedback

5.7.9.2 Force Feedback

For the force feedback stage, there were 19 positive comments and 7 negative. The content analysis categories of Explorability and Feature controllability were commented upon the most. These two categories indicated that the participants were interested in exploring the application of the device in a creative context and developing the appropriate skills to control the patch effectively. These results can be seen in Table 5.27 and Figure 5.32.

For Explorability, the participants expressed a desire to apply the device in a number of different and creative ways. The potential abilities of the force feedback stage were perceived as being large, encouraging the participants to explore different gestures in the control of the sounds being generated. This was expressed in the following ways:

Positive:

- “[It’s] great fun and creative”
- “There are a lot of different ways I could think of using this device”

In control of the different features of the patch, the participants were both equally positive and negative. Although the accuracy and range of movements were appraised positively, the participants were also concerned about the calibration of the device to fit their own unique movement range. For example:

Positive:

- “…once it was set up for my needs it was better”

Negative:

- “It wasn’t so good before calibration…”

Table 5.27: CIT Results for force feedback

Content Analysis Categories	Positive Comments	Negative Comments	Total
Explorability	8	1	9
Feature Controllability	4	4	8
Learnability	4	1	5
Timing Controllability	3	1	4
Totals	19	7	26

Figure 5.33: Frequency word cloud and total positive and negative comments for force feedback

5.7.9.3 Tactile Feedback

The CIT for tactile feedback revealed that participants were concerned about the *control* of sound generator features and the *explorative* aspects of their interaction; see Table 5.29 and Figure 5.34. Overall, there were an equal number of positive and negative comments made.

In terms of Feature controllability, the participants felt that controlling the different parameters of the patch was difficult, but the addition of tactile feedback was considered useful in controlling pitch and potentially timbre. With the removal of force feedback, participants were unsatisfied with the precision of their movements. Interestingly, as was seen in the functionality experiment, the tactile feedback stage of the experiment displayed similar control measures to that of force feedback, in terms of move time and precision. However, participants were convinced that the device was not mapping their movements precisely and that the controls were “glitchy” and unreliable. Some of the comments made were:

Positive:

- “…the tactile feedback helped”

- "… the tactile feedback helped a little with pitch control"

Negative:

- **"**It's not too good"
- "It's not very easy to control…"
- "Control is non-existent"

The Explorability aspect of the tactile feedback stage received an equal number of positive and negative remarks. The overall opinions expressed related to the input parameters being considered as having a high number of potential of uses and being fun to explore. However, they were also considered as limited due to the perceived reduction of accuracy. Comments relating this were as follows:

Positive:

- "Loads of combinations are made possible with this device"
- "The capabilities are greater within the programming aspect of its application"

Negative:

- "It's not easy to explore on account of it changing parameters randomly"
- "…it was tricky to make it reliable"

Table 5.28: CIT Results for tactile feedback.

Content Analysis Categories	Positive Comments	Negative Comments	Total
Feature Controllability	7	7	14
Explorability	4	4	8
Learnability	4	2	6
Timing Controllability	1	3	4
Totals	16	16	32

Figure 5.34: Frequency word cloud and total positive and negative comments for tactile feedback.

5.7.9.4 No Feedback

The no feedback stage of the experiment was rated negatively by all participants and thought to be overall the hardest feedback type to perform musical tasks with, see Table 5.30 and Figure 5.35. The participants thought that the *learnability* of the device was complex and somewhat comparable to that of learning a new acoustic instrument. This was thought to be due to the time it took to judge distances and the positioning of their hands around the device. Due to the complications in *learning* how to control the input parameters, the *explorative* aspects of the feedback stage were also judged negatively as more time was needed to analyse the device.

For Learnability, the perception of accuracy was lacking for all participants. However, this was also seen as a positive aspect for one participant. The evaluation of time needed to learn how to control the device varied slightly by participant, but remained overall the longest in comparison to the other feedback stages. For example:

Positive:

- “I understand how it works…”
- “With the input controls attached to origin/width of Gaussian blur on the two videos, one per sensor, the results were fun and interesting anyway”

Negative:

- “… but it feels glitchy nonetheless”
- “It’s difficult to understand how it’s working”

The Explorative aspects of this feedback stage were judged unfavourably, but were also seen in a positive light when MOCAP was fully realised. With the difficulties experienced in Learnability and the limited time for exploration that resulted, a complicated review of Exploration was experienced. For example:

Positive:

- "The combination of motion sensing and distance detection allows for a good amount of gestures"
- "It's good…"

Negative:

- "It was difficult to explore all of the elements…"
- "… although also limited in other ways"

Table 5.29: CIT Results for no feedback.

Content Analysis Categories	Positive Comments	Negative Comments	Total
Learnability	7	8	15
Explorability	5	4	9
Feature Controllability	2	5	7
Timing Controllability	2	5	7
Totals	16	22	38

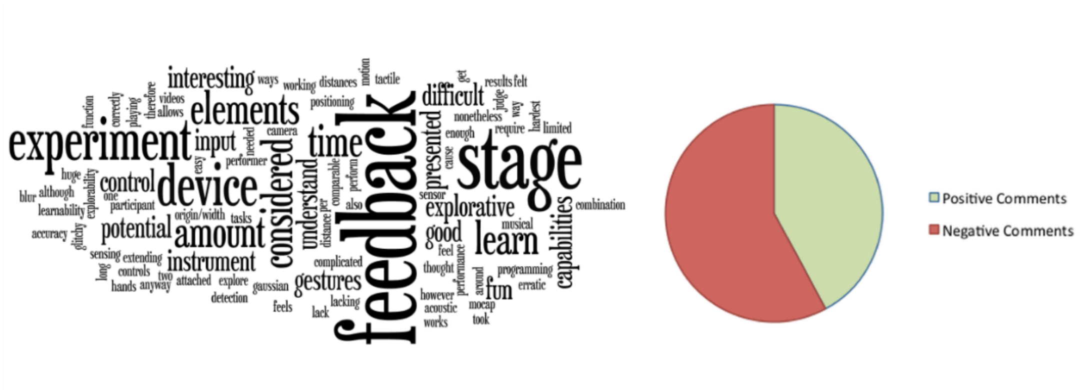


Figure 5.35: Frequency word cloud and total positive and negative comments for no feedback.

Table 5.30: Percentage of positive and negative comments for the pilot study.

Feedback Stage	Positive Comments (%)	Negative Comments (%)	Total Number of Comments
Haptic	71.88	28.13	32
Force	73.08	26.92	26
Tactile	50.00	50.00	32
No feedback	42.11	57.89	38
Total	57.81	42.19	128

5.8 Chapter Conclusions

From the analysis of feedback in musical interactions, it has been demonstrated how a HCI informed framework can be applied to evaluate a DMI [58]. Specifically, it was observed how a device's analysis could be informed by HCI techniques that are applied in the evaluation of general computing and computing for unique applications. With reference to the experimental results presented here, the functional capacity of haptic, force, tactile, and no feedback afforded to users in tasks that require the selection of specific frequencies was quantified and evaluated. Further to this, these same aspects were also evaluated in the execution of musical tasks.

In the functional analysis, participants were capable of selecting specific frequencies (with relative pitches) with observable increases in mean move time across the four stages of feedback. However, a statistical analysis of mean move time variance between each feedback stage presented with no significant effect for feedback at $p < 0.05$ levels. This indicated that although there was evidence of practical differences in move time, haptic feedback and its derivatives had no significant effect upon mean move times in frequency selection tasks. This finding supports the argument that haptic, force, and tactile feedback have no significant effect upon a device's performance of functional pitch selection exercises.

The accuracy of pitch selection of participants across the different feedback stages varied with frequency. Standard deviation from the target frequency did so over three distinct bandwidths, for frequencies including and below 261.6 Hz, for frequencies above 261.6 Hz up to and including 523.25 Hz, and for frequencies above 523.25 Hz. For sine waves below 500 Hz the predetermined physiological constant was maintained

(SD = 3 Hz), with frequencies above this threshold increasing their standard deviation by approximately 0.6%. The mean accuracy figures for each feedback stage presented with no significant differences at the $p < 0.05$ levels. This indicated that although there was again evidence of practical differences in accuracy, haptic feedback and its derivatives had no statistically significant effect upon frequency selection in this task. These results also reflected those results found in the audio-tactile experiment presented in the physiological studies of Chapter 3. This finding also support the argument that feedback may have no significant quantitative effect upon a device's performance in audio-based exercises.

In contrast to this, the application of feedback in musical tasks presented with an observable advantage over no feedback. The CIT analysis of participant responses to the different feedback stages revealed that although there was no measurable difference in feedback function, there was a perceived qualitative difference between them in the execution of musical exercises. However, the reduced number of participants who presented for this analysis raises questions of its significance. In response, it is argued these participants were afforded a much longer period of exploration and freedom of application than was seen in the functional experiment. Additionally, the analysis focussed on the performance of the feedback type and not the performance of the individual, compensating somewhat for subjectivity in analysis.

As there is no specific questionnaire designed for musical task analysis, the CIT was used as a precursor to the design and creation of one. The categories of importance were constructed from existing DMI analysis materials, outlined in Chapter 4, and varied in importance between feedback stages. Overall, in the execution of musical tasks, the haptic feedback stage received the least amount of critical comments (37.5%) and the most positive comments (62.5%). This was followed by force feedback, 54.55% positive and 45% negative. The tactile feedback stage received 42.31% positive comments and 57.69% negative. Finally, the no feedback stage received 66.67% negative comments and only 33.33% positive comments. For haptic feedback, the topic of simple triggering and control of the different sound generator characteristics was focused upon, with 20.85% of the overall comments being made coming from this category. This category was also considered important for force (18.18%), tactile (19.23), and no feedback (19.05). However, it was not the most critical category for all feedback stages. For example, the continuous control of feature modulation was the most important category for force feedback (27.27%), this was also true for the no feedback stage (33.33%). For tactile feedback, the creation of phrases with different contours gathered the most comments (23.08%). Although there was some variation in the number of comments made, there was a clear preference for haptic feedback over the other feedback stages in the musical exercises analysed. In addition to this, force feedback was rated more favourably than tactile. However, these conclusions are based on a small number of participants and are somewhat reminiscent of the observable differences in functional data. Therefore, care must be taken not to elaborate beyond the data presented as a whole.

For the SEQ, it was found that when participants were given the opportunity to evaluate their own performance in frequency selection tasks, they rated themselves differently for each device. Participants evaluated the difficulty of the task with tactile and no feedback as being more difficult than with haptic and force feedback. There was no significant difference between the haptic and force feedback stages or the tactile and no feedback stages, indicating that tactile feedback had no influence upon the perception of ease of use. The quantitative measures of performance indicated that there was no significant difference in move time and accuracy, yet participants were inclined to be more self-critical of their performance than necessary when feedback was altered or removed. Many participants indicated that although they found the task difficult across all stages, their level of engagement varied, as it would if they were performing for the first time with a new acoustic instrument.

In explorative tasks, the participants expressed a SEQ preference of feedback in the order of haptic, force, tactile, and no feedback. This order of feedback preference deviates slightly from the functionality analysis as clear differences were observed between all feedback stages. In the functionality analysis, the participants considered the effort required to complete the task as equal for both haptic and force feedback. In the explorative tasks, the haptic stage was rated more favourably than force feedback. In addition to this, the IQR remained the same between experimental stages. These results indicated that there was some effect of context between experiments.

The SMEQ in the functional analysis confirmed and supported the findings of the SEQ, with a varied rating indicating that *some amount of effort* to *a fair amount of effort* was required to perform the tasks. However, the SMEQ was different in focus from the SEQ as it measured the amount of mental effort exorcised during the task. The results indicated that the amount of mental effort required to perform increased as feedback was removed, although the actual quantified performance of the different feedback stages did not significantly differ. These differences were significant between the haptic and force feedback stages and the no feedback stage. The tactile feedback stage did not differ significantly from any other stage. The perception of increased mental effort was also indicated as being a significant effector during the user experience analysis.

The same trend was also observed in the SMEQ results of the pilot study. However, the user ratings of feedback presented with clearer differences. In addition to this, the feedback stages appeared to be analysed overall more critically than in the functional analysis. These results implied that there was more opportunity afforded to the participants to analyse the amount of mental effort required in the completion of musical tasks. In addition, due to the observed deviations in SMEQ scores observed in Experiment 1, there may also be some indication of variations of mental effort required due to the changes in experiment context.

Usability testing in the functionality experiment revealed no significant effect of feedback across all feedback stages. However, the data collected revealed some interesting results. For example, the self-measure of *performance* in this usability scale was found to be reasonably poor for all feedback types. This indicated that participants were equally negative about how *successful* and *satisfied* they were with their performance across for all feedback types. The combination of TLX, SEQ, and SMEQ results further supported participant dissatisfaction with the perception of device performance.

The TLX scores for the explorative study presented with observable variations in the user's evaluation of feedback. The categories of Mental Demand, Performance, Effort, and Frustration all presented with practical differences between feedback stages. In the perception of *mental demand* the explorative tasks required, the participants had indicated in the SMEQ questionnaire that feedback had some effect upon the levels of mental effort. In the participants' evaluation of performance and effort, there presented variation between haptic and force feedback and tactile and no feedback. This indicated that force feedback had a positive effect upon these factors and that tactile feedback had very little influence. Further to this, the introduction of both tactile and force in DMI design reduced the level of *annoyance* the participants experienced. The variation in results seen in both functional and explorative studies indicated that general usability can be ascertained from a functional analysis alone, but in depth data can be only be extracted from an explorative study. Therefore, it can be stated that a DMI's usability must be measured in an applied musical context for a complete investigation to be carried out.

The UEQ data from the functionality study highlighted a significant difference between the users' experience of *efficiency* and *dependability* across the four feedback stages. For efficiency ratings, significant differences were observed between haptic / force feedback and tactile / no feedback ratings. This indicated that the evaluation of the participants' experience of work performed to total effort expended was not affected by tactile feedback, but by force feedback alone. Similarly, the participants' appraisal of dependability displayed the same evaluation characteristics. The participants' experience and assessment of device reliability showed that they *felt* that the tactile and no feedback stages were less *reliable* than the haptic and force stages, regardless of there being no measurable effect of feedback in their accuracy and move time.

The user experience data from the explorative study presented with noticeable differences between feedback stages in the following categories: Attractiveness, Perspicuity, Efficiency, and Dependability. The categories of Stimulation and Novelty did not noticeably vary, presenting with large standard deviations and no discernible differences between mean scores for each feedback type. The participants considered haptic feedback as the most *desirable* feedback type, followed by force, tactile, and finally no feedback. The time in which the participants became *familiar* with the different feedback types also followed this trend. This was also apparent for the perception of device *dependability*. Finally, the *effectiveness* of the DMI was improved with the application of force feedback only. That is to say, no noticeable differences were observed between haptic and force feedback or tactile and no feedback. These results indicated that although a significant effect of feedback was observed and verified between feedback stages, in the exploration and application of feedback in a creative context feedback was more influential across the different TLX categories.

Following each feedback stage of the functional and explorative studies, content analysis was used to measure critical incidents for each feedback stage. Overall, the CIT analysis revealed some interesting trends. The most obvious of these was the decrease in positive comments and the increase in negative comments made as feedback was removed from the interaction. Additionally, participants were particularly more vocal about their *personal preferences* when interacting with each DMI feedback stage. This trend highlighted the importance of performer individuality and prior experiences when designing and applying a DMI device with feedback. In comparison, fewer comments were made about *explorability* in the musical context analysis. This underlined the restrictive nature of the functionality experiment and the overall reduction of expressivity it enforced. This also supported the requirement for a more explorative investigation in the evaluation of *experience*. The *explorability* of the devices was expanded upon in the user case studies and involved the further consideration of musical application in its analysis.

In the explorative study, it was observed that the level of feedback supplied from a DMI to its user increased the user's perception of positive attributes in the execution of music-based tasks. The haptic feedback stage received the highest number of positive comments in creative applications; this was followed by force, tactile, and no feedback respectively. The tactile feedback stage received the highest number of negative comments; followed by no feedback, force, and finally haptic feedback. Interestingly, the tactile feedback stage also received the highest number of total comments; followed by haptic, force, and no feedback. The participant's appraisal of feedback in a musical context was important to this study as a traditional HCI evaluation of performance could not be performed as was in the functional study. In the execution of musical tasks, the CIT analysis was performed to quantify this aspect of the analysis.

With the specific matching and categorisation of the devices and the quantitative and qualitative data recorded during functionality testing, the results of the first experiment showed that the effect of haptic feedback and its derivatives were able to be measured in the operation of a DMI, with accurate data measures. These findings denoted interesting results for the different types of feedback displayed to the user and although there was no direct affect upon the quantitative performance of a DMI, feedback positively influenced the user's perceptual experience when applying them in note-level-control metaphors, musical exercises, and explorative creative studies.

In conclusion, the application of a HCI inspired evaluation was successfully executed in the analysis of DMI feedback. The accumulation of differences observed within this analysis revealed influential factors of information feedback on the user's experiences in both functional and musical DMI application contexts. From the data gathered, DMI feedback appeared to be influential on a number of context dependant levels. In the functional study, there was found to be no significant effect of feedback upon the quantifiable performance capacities of the tested feedback stages. However, when questioning the user further, there was discovered to be important inequalities in the user group's perception of *usability* and their *experiences* completing the task. Within these areas, the musician's perception of performance was found to be more favourable with the presence of both tactile and force feedback. In the explorative study, the participants were able to complete the musical exercises with all feedback stages; however, the individual's self-evaluation of success varied depending on the level of feedback applied. Therefore, it can be concluded from these experiments that haptic feedback has a significant effect upon a DMI user's experience in the creative application of technology.

Chapter 6: User Experience of Haptics in DMI Interaction Design

Within this chapter, the results of the previous experiments will be examined and their effects upon user experience in the performance of musical interactions will be expounded upon to formulate a set of recommendations for the design of new haptic interfaces for musical expression.

6.1 Implications of Research Findings

Within the field of Computer Music, audio-visual interface devices dominate commercial markets and haptic feedback is neglected or delivered as a novel feature in a device's interaction methodology. Examples of this can be seen in USB piano keyboards, basic slider and button controllers, and many of the digital renditions of interactive instruments and sequencers that are available as downloadable applications on touch-screen mobile devices. The results of the analyses presented in this thesis have suggested that there is a potential to improve upon a user's experience and increase the capacity of information that can be physiologically communicated in interactions that include haptic feedback. In addition to this, the results of the experiments also suggest that neglecting feedback in a DMI's design has a negative effect upon aspects of a device's perceived usability.

From the investigations presented within Chapter 2, it was observed how the human senses are presented with multimodal information in interactions with acoustic musical interfaces. Moreover, it was discussed in Chapter 3 how the sense of touch in this context is capable of capturing and presenting complex information that the other senses cannot. Further to this, from the experiments conducted in Chapter 5, it was observed how interactions with haptic DMI devices present data that is rich in not only physiological meaning, but psychological too. Considering each of these individual findings, a number of interesting conclusions can be made.

Throughout this thesis an assessment of how enjoyable and engaging interactive devices are to use has been presented, analysed, and discussed. The validated systems of analysis that were applied throughout have attempted to resolve *usability* aspects of

DMI feedback methodologies through the application of robust, objective, and reliable metrics from the fields of Psychophysics and Human-Computer Interaction. Through the application of specific evaluation principles from these subjects, it was possible to gain a quantifiable insight into the effects of feedback on a device's perceived *usability*. In the evaluation of functionality, it was observed that all feedback types were perceived to be equally usable. Moreover, in Parts 3 and 4 of Chapter 5 it could be observed how the traditional application of device functionality in usability context testing ignores the important differences that can occur in a device's evaluation when the broader concepts of cognitive, affective and the other social aspects of an interaction are ignored. This highlights the disparities that exist between the actualities of device interaction in functional and explorative studies and how they fail to consider the subjective ideals of the user. This aspect was also seen to be overlooked in many of the previous DMI evaluations that were presented and discussed in Chapter 2. However, this does not discredit the application of usability methods in a device's functional evaluation, but highlights how the application of usability methods in isolation ignores the context of device applications in real-world artistic endeavours.

With reference to the findings of Chapter 3, the physiological and psychological effects of tactile feedback were seen to have a negligible influence on the quantifiable function and usability evaluations of feedback, seen also in Part 3 of Chapter 5. The value of usability testing was not diminished, as both the basic functionality evaluations and usability data gathered were used as objective comparatives for the assessment of the devices studied. Similarly, the user experience data of Part 4 would have yielded a more significant effect of feedback without being able to compare results to the quantified parameters of the functionality experiment. Comparisons between functionality testing and the explorative case studies also highlighted important factors of consideration in evaluating the successful completion of a musical task versus a much less constrained creative endeavour, as a DMI cannot simply be determined as *usable* without context. Instead, it was observed how a DMI applied as a tool and the experiences of creativity can be used as the composite of several qualities that are heuristically discovered and determined by the artist. Therefore, it can be concluded that the *usability* of a DMI should not be analysed alone or outside of the context of a specific application.

Usability can instead be better understood as a factor of user experience that emphasises the importance of the context of an evaluation, whereas the overall user experience should serve to quantify the factors that influence a user's application of specific technologies. Particularly to the findings presented within this thesis, regard to the senses involved in a musical interaction can be considered as a highly influential factor on user experience. However, it should also be acknowledged that touch is understandably reduced in importance below that of aural in the musical interactions witnessed.

It is traditionally understood that touching, holding, and physically interacting with an acoustic musical instrument is required to effectively quantify its suitability. In contrast, for digital technology, an objective assessment of *efficiency*, *effectiveness*, and *user satisfaction* when interacting with a device is used to raise potential usability issues before mass production and commercialisation takes place [144]. In HCI, a usability analysis seeks to quantify an interaction between a user and a device in a specific way to ascertain if the device is proficient in undertaking the tasks it was designed for. For musical instruments, musicians perform a similar evaluation when appraising the potential of an instrument before composing for or performing with it. Further parallels can also be observed between qualitative and quantitative usability evaluations between both acoustic instruments and digital devices. It has been observed how a person's previous experiences can influence their attitude towards a device before testing; with three distinctive processes being attributed to induce pre-use relationships between a device's aesthetics and perceived usability [145].

The first of these influences is the role of popular stereotyping; attributing the successful design of one instrument with the same, or similar, design implemented on another. Secondly, a "bleeding" effect can occur where the aesthetic design perceptions of one instrument are applied to similar features on another. Finally, an effective response to a design's aesthetics may improve a user's attitude and therefore their overall evaluation of an instrument. Preconceptions are often formulated before interacting with a device and the physiological, psychological, and philosophical aspects of being human are applied to bring meaning to them. These intricacies can reveal themselves without the actual use of a device occurring [146], placing importance of previous experience over the material or functional properties of an instrument's usability.

It is therefore understandable that commercial many DMI devices are not necessarily designed with developing new interactive *experiences* in mind. That is to say, why create a device that is pleasing or evocative to touch if it is not necessarily influential in creating preconceptions or early impressions of a new device's usability. However, new interdisciplinary approaches to design are being conceived that integrate methodologies that apply an understanding of bodily perception, performance, and presentation of information sympathetic to the user's somatic experience. The field of *Somaesthetics* is one such design approach that is gaining popularity [147]. This approach to design applies the philosophies of *thinking through the body* and *designing for interactive experience* to achieve embodied interactions with technology in an attempt to provide pleasurable interactions through the exploration of experience. The applied methods of DMI design and testing that were discussed in Chapter 2 present an interestingly similar approach. Here, the primacies of previous musical practices were applied in the construction and testing of DMIs. This provided a familiar language, quantitative and qualitative data, and examples of practical application with design testing methodologies. It is therefore suggested in this thesis that the inclusion of multiple factors should be a fundamental aspect of any rigorous device analysis.

Understandably, other attributes in music take president before touch, most importantly being the quality of the sound being produced. Additionally, many popular instruments have developed an iconic audio-visual standing in the music community by being associated with certain popular performers and musical genres, for example Jimi Hendrix and the Fender Stratocaster. As early DMI devices were modelled upon acoustic devices, they were inevitably evaluated in comparison to them without musicians ever interacting with them. An example for electronic musical instruments would be the keyboard mechanism of the early synthesisers, discussed in Chapter 2. This type of interface is recognisable to many musicians, allowing for the development of a pre-use relationship and permitting subjective conclusions to be drawn. When measuring a user's experience with a musical device, researchers are now equipped with validated methods of analysis and evaluation that focus on the more philosophical relationships that a musician has developed towards an instrument over time. This type of measure is sympathetic with a user's emotional state in relation to a device, for example, how the user feels about their experiences when interacting with them and if it has met their preconceived expectations.

6.2 The Intimacy of Music

Further examples of how digital technology has manipulated and augmented experience can be seen in other areas of the music industry. For example, while the number of live performances has been steadily increasing since the year 2000, the number of hard copy sales of music has dwindled in comparison. Music consumption has moved away from a materialistic ownership of various music formats (such as CD, vinyl, or tape) towards a shared communal experience that is brief and momentary. For an audience, a musical performance is experienced in the moment and this experience is difficult to reproduce via copies of the same performance without context. Digital technology is capable of capturing the audio-visual element without question, but it is not capable of capturing the feeling or intimacy of an individual member of the same audience.

Interacting with musical instruments displays a similar augmented form of physical intimacy that involves close and informal contact with the body; consider again the example in Chapter 3 of the intimate playing style of stringed instruments such as the violin, viola, and cello. Physiologically, touch is a modality that results in the combination of information gathered from the receptors in the skin, as discussed in Chapter 3. In addition to this, from the data gathered in Chapter 5, it must also be acknowledged that touch can evoke an emotional response. When regarding technology in the creation of music as evocative or representational of an emotional state, it should also be observed as something that is poignant to all senses, including the internal emotional representations of the interaction. Therefore, investigating the effect of haptic stimulation in this context has allowed for a better understanding of the internalised experiences of the user. Through the combining of the physiological and psychophysiological analyses presented in Chapter 3 and the human-computer interaction methodologies discussed in Chapter 4, it has been observed that an evaluation of the sympathetic, pervious, and expressive exterior organ in relation to the emotive perceptual experiences of the user can be achieved. Understanding the conveyance of physiological information, regarding the different elements of haptics, can perhaps in turn lead to a more supportive measure of a device's potential to convey psychological detail and potentially achieve embodiment [147] [3].

Acknowledging that users are capable of feeling more than physical stimulation allows for the measurement of an interior perception of the device being interacted with. Through the analysis of haptically enabled devices that are capable of communicating similar information as acoustic instruments, insight is gained into how an interaction with creative technology is experienced on an emotional level. Haptic feedback may prove to bring psychologically passive and uninspiring objects into a personal or emotional proximity, and in doing so, enable users to gain a greater understanding of them.

6.3 Previous Experience

Digital music and the technology used to create it is as ubiquitous and evocative of emotion as older, more traditional, music forms. That is to say, digital music, and the tools used in its creation, can be considered as being proficient in invoking emotions that in turn create emotional bonds between the physiological and psychological experiences of the user. Relationships with music are established through personal tastes that are developed through experience, listening habits, and time, all of which serve to bring meaning to a musical interaction. These relationships, which are developed by users of music technology, can be observed throughout history and location.

As some consider certain forms of music atrocious or unpleasant, others hold them in high regard. Sound art can be whatever the beholder bestows upon it, and the same concept can be applied to the objects used in the creation of this art by the artists. Through decisions made in the creative process, an artist will make choices about medium, style, and expressionism. The personal choices, skills, and experiences of the artist can lead to a classical orchestration or a composition of noise music. There are many artistic movements throughout history that have seen fit to engage the observer on a multitude of levels, but they cannot all be categorised or justified easily. Therefore, when a piece of technology is evaluated in its application in the arts, it must be considered how it is applied and how it specifically relates to the end user or artist.

Through the study of a musician’s experience with music technology, it can be observed that musicians not only use technology to make music easier, they use it to live with. Interacting with technology involves the user on an emotional, intellectual, and sensual level [68]. The research and analysis theories discussed in Chapter 4 bestow upon investigators the tools to explore how users apply technology in tasks that extend the reach of their internal empathy or compassion by assisting in the internalisation of the external world around them [148]. This is particularly pertinent in evaluating technology applied in the creation of art, as it is the artist who is attempting to create a physical representation of an internalised concept.

In music, it can be observed how musicians choose certain musical instruments and compositional styles over others. It can be argued that some instrumentation is capable of evoking stronger emotional responses in both performer and observer than others evoke. Musicians have often expressed their relationship with their instrument as something that is emotional and subjective that has been developed over time. It has been found that this kinship is usually unique to the artist, arousing the individual through various means. Below, are extracts of a study undertaken by S. Turkle [149]. Within this text, there are interviews and writings of musicians expressing how they feel about their instruments and what it was that initially interested them.

... I can feel the instrument vibrate from head to foot as I draw my bow across its strings, a throbbing through my chest, a buzzing through my legs and feet, a tingling to my fingertips.

- Tod Machover, talking about his cello.

When I learned to play the piano, my mother sat next to me nearly every day. I feel an association between the piano keyboard and family love.

- Howard Gardner, on his association of family, love, and the piano.

It was the sound that first drew me in. What was a police siren doing in a university common room during [the] Fresher's fair?

-Trevor Pinch, his first attraction to the synthesizer.

What can be summarised from these brief accounts is that the emotional state of a performer and their relationship with their instrument is more than a measure of efficiency and accuracy in realising musical intentions or that the instruments discussed are just physiologically pleasing for the artist to use. Further emotive senses are involved in the choices made by the artist. However, it is often the subjective experiences of the artist that are used to hold certain sound qualities in higher regard than others, which may explain why audiences empathise with musicians when they observe their performances. These relational differences are the result of many influences that include prior experiences, personal attitudes, and many other internal and external effectors. Therefore, a person's emotional response to a musical instrument is a function of both the design of the instrument and the individual's previous experiences. McCarthy and Wright surmise this requirement for receptiveness to experience by highlighting that experience is not something that comes readymade [68]. Furthermore, it is the individual's responsibility to become ready and receptive to an experience in the present, as it may manifest itself in the future. That is to say, the meaning of an experience in the future depends heavily on the individual's own history, character, and idiosyncrasies in both the present and in the past.

In addition to this, the emotional response of an individual when listening to music is also the result of a multifaceted sequence of interconnecting factors. Furthermore, factors such as current mood, prior memories, and the level of engagement have been recorded as having some effect upon a listener [150]. In addition to this, the emotional response of an individual listening to music can be predicted when combining electroencephalogram (EEG) and acoustic features derived from music [151]. Daly et al. suggested that emotional responses to music are the result of processes that are internal to the listener and the acoustic properties of music being listened to, which is to say, the stimuli presented to the listener. It can therefore be observed that prior experience and the stimuli delivered are influential in the relationships that are developed between instruments and musicians.

6.4 Beyond the Physical

The study of touch is highly complex and in the studies presented within Chapter 3 the physiological and psychophysiological responses of the body were measured and discussed. In Chapter 5 it was observed that the user's *experiences* of the different feedback stages were the most significant effector in the operation and application of feedback. From these two chapters, it was observed that when interacting with the various feedback types the devices displayed information to the exteroceptive senses to be processed and used in conjunction with the interoceptive senses. Furthermore, it was the sense of touch that gave an immediate indication of what is happening during the DMI's interaction with the performer. The body translated the information presented and it made the user spatially aware of their surroundings from an inward orientated or interoceptive sense of position, movement, and balance. To differentiate the internal and external senses, consider how the texture of a device is affirmed via touch or an interaction with a touch-screen is determinate versus the emotional avowal or pleasure response evoked when touching an animate object, such as a pet, child, or loved one. This second type of interaction holds an immediacy of sensation that is both affirmative and comforting to the person experiencing it [146]. Therefore, it can be seen that the use of a DMI is encompassed by the many divisions of the human condition and should, therefore, be considered more than just the externalisation of an inward sensation.

Also of consideration to this discussion is the role of multimodal interaction with the multiple feedback types that were applied in the context of the analyses carried out in this thesis. To demonstrate, consider the popular saying "*Seeing is believing*" and how it was originally written as "*Seeing is believing, but feeling is the truth*". With regard to technology, the final part is often neglected and visual representations of data are rarely surpassed by the other senses. However, musicians instinctively know that this form of interaction is not always the most affirmative and although visual data is the most prominent and quickest way to convey information to a DMI user, it is notably distant, easily manipulated, and altogether inaccessible for some users. That is not to say that musicians are discouraged from using visual devices, but that they are aware of the removal and separation of the relationships formed between these feedback types; as they have often experienced these in acoustic interactions. The link between physical and virtual interactions via combined tactile and visual interactions are definite and give affirmation of input actions, but they are neglected in most audio technology designs. The removal of tactile feedback from interaction with technology is prominent in almost all touchscreen devices today. Additionally, the sense of touch is the sense that is least susceptible to deception and is therefore the one in which the most trust is put [149].

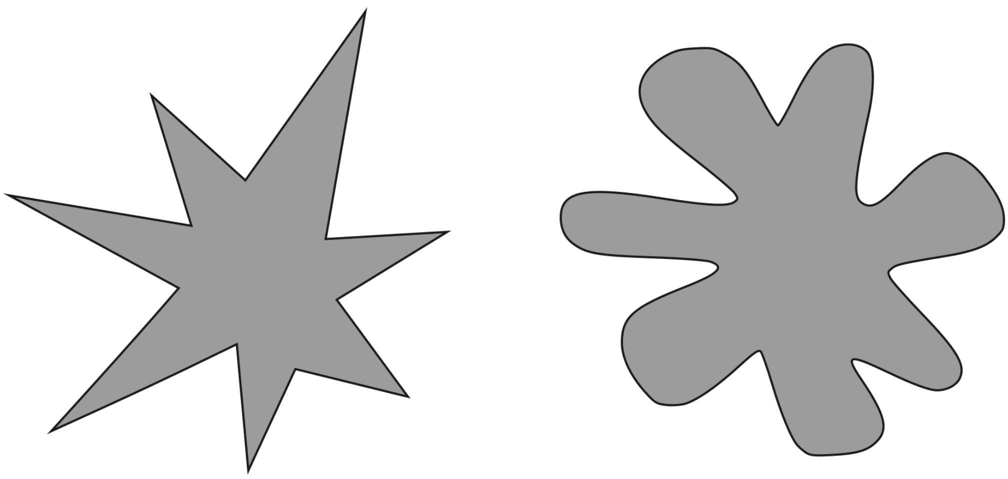


Figure 6.1: An example of the Bouba / Kiki Effect [156].

The sense of touch brings visually distant information near. It can also be used to reassure that an interaction has been successfully undertaken. The combined senses of sight and touch contain a vast wealth of information for a person to process. However, as with the preconceptions of usability discussed earlier, indirect tactile experiences are capable of reaching a user before they physically interact with a device, if indeed physical touch is experienced at all. This concept of *virtual touch* is similar to the observations made by Kohler during the bouba/kiki experiments of 1929, Figure 6.1

[152], where a non-arbitrary mapping between a sound and the shape of an object was observed. As discussed earlier in this chapter, as with perceived usability, physical sensations are capable of reaching the inner senses via visual stimulation. Therefore, when a user browses a selection of music apps, they are not solely evaluating aesthetic design qualities or functionality; they are perhaps also formulating a virtual tactile sensation. Discrimination between a *virtual touch* and actual touch is only realised when the user interacts with a device to ascertain its true usability.

The human body also contains a sense specific tactile spatial memory [147], an example being the ability to recognise letters when drawn on the back. This type of memory is acquired through experience, another example being the ability to feel through a familiar environment in the dark. Although this knowledge is often passively processed, it is made use of in every moment. This knowledge acquisition is not simply an interaction between the senses that develops into an understanding of what is happening in the direct vicinity, but is developed through correlations between the internal somatic systems and the perceptual processes of the brain. This system is constructed through processing a combination of the three internal interoceptive senses: the proprioceptive, kinaesthetic, and vestibular senses. In this context, proprioception can be defined as the body's position felt as muscular tension, kinaesthesia is the sense of movement from within our body, and the vestibular sense is derived from the inner ear controlling the balance mechanisms. The combined applications of these interoceptive senses correlates to the earlier definition given for *haptic* interactions, and any somatic response a user has to an environment or device is also perceived this way.

The experiences of individuals are accumulated over many years and the development of the senses used to perceive external stimuli have taken millenniums to evolve. Therefore, it can be argued that both elements are in a constant state of slow-moving flux, altering on a species-by-species and subject-by-subject basis over time and that these changes are the result of external spatiotemporal influences upon the body of the individual. Initially, these changes were evolutionary requirements of survival; whereas nowadays, these changes are arguably more psychosomatic responses influenced by social constructs and individual ideals. Traditionally, musicians have been playing acoustic instruments developed to create sound in a way that incorporate all of the senses together. However, as was discussed in Chapter 2, the manner in which sound is now being generated is no longer restricted by the physical constraints of acoustic sound generation. Therefore, the changes that have taken many years to accomplish, will ultimately result in the musical process being slowly altered and eventually altogether changed.

6.5 Changes in Experience

The fields of HCI and Interaction Design are constantly changing to keep pace with advancements and developments in technology. Although there are still concerns with the usability aspects of computing, there is also now an interest in experience [68]. Currently, a developing trend in the field of HCI is the growing interest in experienced-focussed HCI that emphasises the experience of using technology, rather than focussing on the task being completed with it [153]. Similarly, in Chapter 5, it was observed that consideration had to be given to the context in which the DMI was applied, in terms of the functionality and explorative exercises completed. Along with context, many emerging technologies are easily defined as consumer products rather than professional; as they were once seen to be in the past. Technology is no longer limited, but available to all. This direction of study is leading to a new design ethos where aesthetic experience is being applied to integrate technology into creative media industries.

Many advances in music technology have been implemented in the form of devices that make music production easier. In doing so, these developments have achieved the speeding up of the methods in which something is created or accomplished. By means of compensation, the human element has also had to speed up. Technology is applied in many areas to increase the completion times of any given task, and in response, users have had to adapt themselves to this increase in pace [149]. As technology speeds up, users have had to adapt their senses to this increase in pace. This has improved lifestyles in many ways, and yet, has degraded them in terms of shortening the time in which users have to experience them.

Regarding technology and its application to music, many instances of this phenomenon exist. For example, the increase in *home produced* music is a by-product of the fast-paced technological revolution that many more musicians have accessed. The historic technological requirements of a recording studio and the other high cost technologies have in the past restricted most people from self-producing music. Nowadays, most home computers can handle this task without having to spend much more than the cost of the actual computer. This freedom of creation has overwhelmed digital markets with endless musical experiences, and has augmented the relationship consumers and creators develop towards musical interfaces.

Current market consumptions of analogue equipment are favourable and this market has in turn created digital devices that introduce imperfections directly modelled upon old analogue technology. This reintroduction of the imperfections of dated technology addresses the audible requirements of an analogue experience. However, the role of a DAW in replicating the audible effects of older technology neglects to incorporate a sense of touch, both physiologically and psychologically. Haptic interfaces that expand input gesture capabilities enable the meaningful manipulation of virtual sound objects. This technology has long been available in video game consoles and musical interfaces, but its influence on the user's experience has yet to find an accurate measure.

As discussed in Chapter 2, haptic devices are becoming increasingly prominent in commercial markets with the recently renewed interest in VR. The commercialisation of VR technologies allows for prolonged user exposure to digital renditions of physical interactions. While the rhetoric of VR technology has ebbed and flowed, technologies that integrate touch have been proliferating [154]. Commercial examples of this include medical and military training, such as remote keyhole surgery, mine clearance, and undersea and interplanetary exploration. Further examples can be seen in Fujitsu's prototype haptic sensory tablet, ViviTouch's Electroactive Polymer technology in Mad Catz gaming headsets, Tactus Technology mobile phone layers, and Immersion's TouchSense. Technology of this type is being integrated into a vast array of commercial mobile devices and haptically enabled technologies are slowly substituting everyday passive devices that operate purely on an audio-visual level. It is predicted that the proliferation of haptic technology will expand into three distinct forms of device:

- Basic haptic feedback devices (such as video game controllers).
- Haptic displays (capable of simulating shape and texture).
- Exoskeleton external devices (which exert force and pressure directly onto the skin).

6.6 From Experience Evaluation to Design

The discipline of HCI has developed a wide-range of tools for the appraisal of computer technology applied in the accomplishment of specific tasks. This includes evaluation techniques that are designed to discover issues that arise in unique applications of technology, such as in haptic DMIs. For the appraisal of complex devices, the field of HCI can be called upon for the evaluation of usability and user experience. In addition to this, the subject of Human Computing (or Human-Centred Computing) can also be called upon to evaluate the user's intentions and motivations in the application of technology in creative contexts. An appraisal of function, or a task-focused approach, presents metrics that are easy to measure and quantify. However, in the creation of music, the application of technology relies upon the user's previous experiences to accurately express the artist's inner thoughts or intentions. Therefore, it is proposed that although DMIs require functional testing to highlight potential usability issues, a comprehensive analysis should also include the evaluation of real-world situations to accurately capture and evaluate all aspects of an interaction. Thus, to expand an investigation of a device into the real world, an experience-focused analysis should also be undertaken. This idea emphasises the "third paradigm" concept discussed earlier, which includes the gathering of information relating to culture, emotion, and previous experience. It is strongly evident from the analysis of data gathered in Chapter 5 that task-focussed evaluations are a necessary precursor to an experience-focussed evaluation, but they do not present sufficient information about the real world application of such technology when carried out alone.

Information about real-world devices and how they operate can be measured and applied to their virtual equivalent. In the case of DMIs, much of this information exists as an acoustic musical instrument. Therefore, data can be measured and applied to provide a sense of realism and embodiment to virtual or augmented instruments or expanded upon to fit new types of devices. Digital artists are renowned for their creativity, innovation, and adaptation in the design and construction of digital musical instruments; however, these digital representations are often devoid of haptic feedback. It is possible to reconstruct the operating principles of acoustic instruments and apply this to DMIs, as is seen in augmented instruments and DMIs that replicate the playing style of an acoustic instrument. However, for most commercial DMI interfaces, the emptiness of *button bashing* can be seen as a significantly negative aspect of their use. DMIs offer freedoms to musicians that are near endless, but computer music performers often also play traditional instruments. This highlights the need to experience the creation of music with all the senses incorporated.

If aural, visual, and haptic collocations are possible within DMI design, it should therefore be possible to simulate the *feel* of an acoustic experience within it. Sound can be created electronically with the freedoms afforded through digital sound generation and with the combined information of the interaction response being fed back with the same meaning as an acoustic instrument. Sound can be digitally created and manipulated by the artist and a deeper sense of craft can potentially be realised. Computer musicians need to be able to experience consistency, adaptability, musicality, and touch-related sensations that are induced by touch to experience the physiological and psychological occurrences outlined within each of the research conclusions of this dissertation.

6.7 Emergent and Future DMI Designs and their Evaluation

Traditional musical instruments allow musicians to create sound through explicit gestures that are specific to the generation of sound that a particular instrument employs (Figure 1.3). Many of these instruments are consistent in that they are unambiguous in their operation. Conventionally, they are designed for single users, are single-sound orientated or sound specific in their design, and the context in which they are used is largely determined by the user; that is to say, solo or within an ensemble and so on. This has facilitated instrument designers by predefining the composition and arrangement of the sound generating modules within an instrument to suit the specific style of interaction required. As the input and the output of the instrument are physically inseparable, an explicit dialogue has been formed between the musician and the instrument, one that has been established through extended practice and performance. This relationship is further facilitated when the user can apply interactions learned from one instrument to another of similar design.

As was discussed in Chapter 1, these relationships are not as apparent in many DMI designs. New interfaces for musical expression are becoming multi-modal and embedded, allowing musicians to interact with digital sound generating modules in a multitude of novel and innovative ways. In many instances, haptic DMIs allow a natural interaction to take place between computers and musicians, bridging the physical-digital divide with an interaction paradigm that is familiar to the user. Furthermore, instead of creating computer interfaces for musicians, DMI designers now have the potential to provide musician interfaces for computers. That is to say, the nature of the interaction is changing beyond traditional concepts of a musical interaction, yet there is the possibility to stimulate the user in an evocative and familiar way. However, if future DMI designs continue to neglect the potential of feedback to tap into the deeper philosophical potential of haptics, the metaphysical distance between the user and the systems in use will continue to increase and the *disconnect* felt between the digital and physical worlds will increase.

Accordingly, the *disconnect* or *physical-digital divide* will continue to present interface designers with issues beyond basic interaction metaphors unless DMIs are developed to fully stimulate a user. To measure the effects of stimulation and for an accurate evaluation and appraisal of new DMI designs, the tools and techniques applied must also be assessed for their suitability. In this thesis, it has been suggested that HCI evaluation tools can be augmented for the assessment of DMI designs in a Computer Music context. However, within HCI the concept of a device *evaluation* is broad. Furthermore, current evaluation methods have been identified as being inappropriate for emerging HCI applications [155]. Poppe et al. have highlighted failings in traditional HCI evaluation methods. From their findings, it is apparent that further consideration of potential design paradigms is required and future developments in DMI design must be discussed in a musical context.

6.8 Considering Previous Experience in New DMI designs

From the findings made in this thesis, specific principles of interface design for DMIs have been developed and investigated. It is suggested that consideration of the following points should be made in the creation of new haptically enabled DMIs:

- **Transparent in use:** it must be possible to determine a DMI's function, this must be clear to both the musician and the observing audience, as it is easier to recognise an action than to recall one.
- **Reactive and communicative to as many of the user's senses as possible:** in relation to a device's *transparency*, information must be presented to as many of the user's senses as is possible in a timely and logical manner to emphasise the effect of the input interaction upon the system in use.
- **Present a meaningful set of tangible interactions:** all information related to the system's *reaction* should be presented to the musician clearly and they should also be able to interpret meaning easily, this will serve to enhance discoverability and improve the musician's overall understanding of the device.
- **Clarity of affordances delivered via the sensors types used:** a DMI that is designed with familiar features should be done so with clarity in how these features react and should therefore respond in a recognisable and familiar way.
- **Consistency in the information displayed to the user:** the location, appearance, significance, and behaviour of an interface must be consistent for it

to be effectively learned. In achieving this, when errors are made the interface will allow musicians to recover and continue without any additional mental or physical strain.

- **Clear and stable mapping of user gestures in the interaction model:** the mapping of gestures in a spatial context and the systems temporal responses should be clear and stable.
- **Consistent device constraints for the interpretation of gestures:** physical, logical, and clear limitations upon an interaction will prevent errors and assist in interaction interpretation by both the musician and the system in use.

By following these guidelines, new haptic DMI designs will be fully communicative to all senses and present computer musicians with an array of carefully designed tools for their own artistic endeavours. In addition to this, the audience's experience will also be improved upon as clarity between the musician's actions and the system's response will be achieved. In addition to these guidelines, the concepts applied in the design of "Tangible User Interfaces" [156] and the paradigm of "enaction" [157] should be considered to further overcome the issues presented in Chapter 1.

6.9 Chapter Conclusion

The use of haptic feedback may go beyond the singular, subjective, or artistic experience to convey data that is evocative of the past experiences of a musician, an ensemble, or an audience. Embracing haptic technology will assist in collaborations between artists, making the sharing of musical interactions and mutual touch experiences easier. In this way, one user may virtually feel another, creating an ideal context for collaborative work [148]. Musicians will be enabled in the communication of performance information, expressing their mutual playing experience and creating a shared touch between musicians and audience members. This technology can also be applied for training purposes, impromptu solo performances, and improvisation. The production of a tangible presence around a digital musical instrument will result in the wider acceptance of them among traditional musicians. Which will make them "*literally manipulable or graspable*" [148].

Haptic technology can be applied to bring physicality to virtual objects. However, it can also allow for the introduction of intimacy of touch to these devices. The future development and inclusion of such interfaces in music will rely on the acceptance of these devices by musicians, but also on the audience's ability to virtually touch them. This will serve to complete the broken feedback loop that is present in modern electronic musical instruments. If the tactile needs of the exteroceptive senses can be addressed, it is proposed that the interoceptive will be enriched. It is not yet fully possible to stimulate the inner workings of the human condition through digital means, but it should be an endeavour of all new digital objects.

Chapter 7: Conclusions and Future Work

The research presented in thesis has explored the role of haptic feedback in digital musical instrument design applied in the field of Computer Music. To achieve this, HCI methodologies were investigated and augmented in the construction of a DMI evaluation framework applied in the evaluation of haptic feedback. As described in Chapter 1, haptic feedback plays an important role in interactions with acoustic musical instruments, but most contemporary DMI designers often overlook its application in Computer Music. In addition, there has been a recognized need for structured analysis techniques in the evaluation of these devices, such as those applied in the field of HCI. Therefore, this thesis has focused upon the analysis of haptic feedback and the development of a rigorous testing framework. The primary contributions of this thesis to the field of Computer Music research were outlined in Chapter 1. In this final chapter, each of these contributions will be summarised.

7.1 Original Contributions

"The design and construction of an analytical tool for the investigation of physiological and psychophysiological parameters of vibrotactile feedback."

In Chapter 3, the Audio-Tactile glove was designed, constructed, and successfully applied in the investigation and validation of applications of vibrotactile theory. It was proposed that this research tool could be useful for researchers and designers of new musical interfaces who wished to explore audio related tactile feedback in their instrument designs, allowing the end user to experience passive or active tactile feedback depending upon the designer's application. The experiments presented in Chapter 3 proved that the Audio-Tactile glove could be successfully applied in the evaluation of vibrotactile feedback. The measurement of perception information being delivered concurrently with sonic events allowed for the exploration of appropriate feedback techniques in DMI design.

"Validated vibrotactile feedback in signal detection tasks, in terms of vibrotactile amplitude, frequency, and timbre."

Also in Chapter 3, the relationship between stimulus and sensation were investigated and previous psychological findings were validated. Specifically, the psychophysical concept of a sensory threshold was examined for pure and complex waveforms across a frequency range of 10 to 1000 Hz. In addition to this, signal detection theory was applied to quantify the sensory magnitudes of tactile feedback and its potential application in DMI interactions. Although a number of psychophysiological studies have already been undertaken to quantify these aspects of stimulus detection, in this thesis they have been further validated in a computer music context. It was found that the absolute threshold of detection varied from person to person and that it was also dependent on the frequency, amplitude, and harmonic content of the applied signal. In addition to this, it was found that musicians do not display any increase in sensitivity through experience.

"Established the significance of concurrent aural and tactile signals in pitch/frequency detection tasks."

In the final experiment of Chapter 3, an investigation was conducted to determine the significance of simultaneous aural and tactile signals in frequency detection tasks. The results of this experiment suggested that combined audio-tactile stimulation had a positive effect upon the participants' ability to discriminate between small changes in frequency. Musical ability did not appear to alter the probability scores in terms of grouping. However, the difference between musicians and non-musicians within the groups appeared to be of some practical significance, as would be expected through training and experience. A psychometric analysis was used to identify the PSE for each waveform type for each group. There were found to be observable differences between the two groups; however, an independent-samples t-test found that significant differences were only present for simple waveforms. Although there was found to be no statistically significant difference, there were practical implications for the differences in PSE frequencies for complex waveforms. Furthermore, in the combined audio-tactile group, a small improvement in JND percentage was observed, but no significant differences were recorded. These results support the theory that simultaneous combinations of tactile and audio stimulation positively influence the perceptual frequency discrimination of our sensory system.

"The development of an analysis framework for the evaluation of interaction with DMIs."

In Chapter 4, it was seen how the field of Human-Computer Interaction concerns itself with research into the design and implementation of systems that allow users to interact with digital technology. This also involves the creation of systems that evaluate explicit and implicit tasks undertaken in a variety of contexts. Several existing methods of device evaluation from HCI were explored. It was highlighted that task-orientated evaluations were not alone suitable for the evaluation of technology applied in a creative context, such as with DMIs. Therefore, it was suggested that for a comprehensive evaluation of this technology, some focus must also be placed upon the evaluation of the user's experience.

From the framework presented in Figure 4.2, it was suggested that the following stages of a device's evaluation should be carried out:

1. The capture of low-level device characteristics, creating a generalized device description. A device should also be reduced to its physical variables in terms of its taxonomy of input.

2. A contextualisation of the evaluation should be made; explicitly clear in terms of stakeholder, questioning who is evaluating the device and why.

3. Functionality testing should be completed; including elements of a usability and user experience analysis. A variety of HCI paradigms exist that can be augmented to best fit the categorisation and contextualisation of the device being analysed.

4. Finally, an explorative study should be carried out in a creative context. Usability and user experience data in a musical context will present more meaningful data as the participants are given more time to evaluate a device in a natural real-world application of the device.

An application of this four-stage evaluation framework was carried out in Chapter 5 and from the analysis of feedback in musical interactions, it was demonstrated how a HCI informed framework could be applied in the evaluation of DMIs.

"The design, construction, and analysis of two new DMIs that incorporate derivatives of haptic feedback."

From the exploration of existing haptic technologies in Chapter 2 and the analysis of tactile feedback presented in Chapter 3 it was possible to design two DMI that were capable of displaying haptic feedback. Specifically, between the two devices, force and tactile feedback could be presented to the user in combination or isolation. The two devices were constructed and then tested by applying the framework of analysis presented in Chapter 4.

In the functional analysis of feedback, participants were able to select specific frequencies with observable increases in mean move time across the four stages of feedback. However, a statistical analysis of variance between each feedback stage presented with no significant effect for feedback, this was also true for frequency selection accuracy measures. This indicated that although there was evidence of practical differences in move time and accuracy, haptic feedback and its derivatives had no significant effect upon performance of frequency selection tasks. In contrast to this, the application of feedback in musical tasks presented with an observable advantage over no feedback. The analysis of participant responses to the different feedback stages revealed that although there was no quantifiable difference between feedback stages in the functionality experiment, there was a perceived qualitative difference between them in the execution of musical exercises.

From the analyses of data gathered from both experiments, it was observed that the different feedback types had a significant effect upon certain aspects of device usability and the user's experience. In the usability testing results, it was seen that the perception of task difficulty and the mental effort required to complete tasks increased as feedback was removed in the order of haptic, force, tactile, and no feedback. Furthermore, in the NASA-TLX usability ratings, the categories of Mental Demand, Performance, Effort, and Frustration all displayed noticeable differences between feedback stages. In terms of User Experience, there were observed some deviations in participant answers; however, the overall trend within pragmatic qualities was that haptic feedback was the most preferred feedback type, followed by force, tactile, and finally no feedback.

"Develop a set of recommendations that considered the role of previous user experience in DMI design."

In Chapter 6, a discussion of these findings was presented. The discussion concluded with the concept of previous experience applied in the design of new instruments for musical expression. Recommendations were made relating to the design of devices with consideration to the following attributes:

- Transparent in use.
- Reactive and communicative to as many of the user's senses as possible.
- A tangible interpretation of the device's reaction must be possible.
- Clarity of affordances delivered via the sensor technologies applied.
- Consistency in the information displayed to the user.
- The application of clear and stable mapping methodologies.
- Clear and consistent constraints for the interpretation of gestures made.

7.1.1 Summary

What can be seen from the findings presented within this thesis is that interactions between musicians and digital instruments are highly complex. That is to say, the relationships developed between musicians and instruments can be highly dynamic in how they effect a musical endeavour. In the process of expressing their musical goals, a musician is attempting to convey some philosophical ideal or concept that has no corporeal form. In Computer Music, the musical intentions of the creator are realised through the application of digital technology. In performances with acoustic instruments, a feedback loop is created as a direct result of the sound generating capabilities of the instrument. For computers, feedback that informs musicians of timing, timbre, or dynamics has to be purposefully and mechanically coupled together as this medium has no such innate communication methodology. However, it has been shown in this thesis that this mode of communication can be realised through the application of haptics. It has been demonstrated that sensory feedback plays an important role in how a musician develops a relationship with and evaluates a DMI interface for the creation of computer music. Providing extra feedback channels for computer-based musical instruments positively benefited the participants of the studies presented here and the results of these studies suggested that in order to bridge the physical-digital divide that has developed in the application of DMIs in Computer Music, instrument designers should incorporate sensory feedback beyond that of audio and visual stimulation. Furthermore, to be of use to a musician, a list of recommendations was presented to ensure that future DMI designs are predictable and stable. In following these recommendations, DMI designers should be able to create two-way isochronously communicative devices that are evocative and communicative to all the senses applied in their use.

7.2 Future Work

It is hoped that through the presentation of the research findings of this thesis that advances in the field of Computer Music have been made. Specifically, it is foreseen that the study of interactions between performers and digital instruments in a variety of contexts will continue to be of interest in this field far beyond the scope presented in this thesis. Further research on digital musical instruments and interfaces for musical expression will continue to explore the role of haptics, previous user experience, and the frameworks that are constructed to quantify the relationship between musical performers and new musical instruments. The complexities of these relationships are further compounded by the skills of musicians and are far more meaningful than a physically stimulating interaction and should therefore be explored further.

It has been seen in this thesis that digital musical instrument design and evaluation methodologies can be applied in the study of interactions between musicians and instruments in a variety of musical contexts. Furthermore, the instrument designer is often the performer and a DMI may take many forms; from concept to performance tool. In a similar vein, in the design processes of computer interfaces, evaluation tools are applied iteratively, in cycles that address the design issues raised within the previous sequence. An example of this can be seen in Norman’s Seven Stages of Action as a design aid in interaction design [158]. Whilst appraising a DMI, the musician constantly questions certain aspects of a design’s usability when applied to specific tasks. For example:

- Can I achieve my goals accurately and effectively?
- Am I working productively and efficiently?
- Is the device functioning as I expect it to?
- At what rate am I acquiring new skills?

Emergent DMI systems require further measures for an accurate appraisal of the user's experience when applying the device in a musical context. In a traditional HCI analysis, a device is evaluated in a specific context and the evaluation methods are expert-based heuristic evaluations or user-based experimental evaluations. Only by determining context is it possible to interpret correctly the data gathered. Therefore, it is suggested that DMI specific functionality, usability, and user experience evaluation methods should be developed.

In the future, it is expected that emerging haptic DMI systems will expand into the following areas and in doing so the tools that are to be applied in their appraisal will have to be augmented to display a thorough understanding of a device's usability and the user's current and previous experiences with musical instruments.

- **Natural Communication:** this relates to the application of multiple sensing technologies that are navigating new DMI designs away from traditional object-oriented approaches. This will in turn influence musical interaction design, as the traditional communication-orientation of an interaction will blend *Actual* and *Symbolic* gestures (Figure 1.2) into less implicit interactions. To realise a more *natural* communication interface, the systems in use will become contextually aware of their application to avoid the user and the system developing different views of gestural applications.

- **Creative Systems:** interactive devices will be developed to be near autonomous or *proactive* in their creation of sound. Traditional instruments are explicit in how they are to be interacted with, the user is the one who initiates the interaction, and they are characteristically responsive in nature. In comparison to this, DMIs can be seen as the opposite, leading to a loss of meaning and transparency in their application. In computer music that applies DMIs, neither of these extremes are appropriate. In their place, a *mixed-initiative* approach to interaction design must be applied to coordinate the musician and the system in use.

- **Diversity of Form:** the physical form a DMI has the potential to take is already quite diverse. The two extremes of this currently span between the following; on the one hand, there are large interfaces, such as immersive displays and interactive spaces, and on the other, there are smaller forms that are wearable or embedded. The diversity of form that DMIs can take in the future will be greatly influenced by technological trends and developments in sensor technology, as has been seen with mobile devices and game controllers. This should serve to replace many familiar or general-purpose interfaces with more purpose-designed or specialised devices.

- **Application Purpose:** where traditional instruments are designed to be task-based, new devices will be designed to be applied in a multitude of contexts. This shifts the design focus away from user experience design to a usability design approach or *multitask-dominant* paradigm. However, creative endeavours are the consequence of a user's internal state (or intention) and in ignoring these, three major problems may arise. Firstly, the user's requirements beyond the physical are ignored. Secondly, affective and emotional aspects of creation are disregarded. Thirdly, the fundamental nature of the experience is disposed of. Therefore, both pragmatic and hedonistic aspects of the interaction being facilitated should be measured and considered.

The work presented in this thesis has only begun to explore the possibilities of haptic feedback in future DMI designs. The experiments presented endeavoured to present evidence of some influence haptic feedback has on a user's perception of functionality, usability, and user experience. Beyond this, future research goals will include the development of laboratory tools that will assist in the creation of a DMI design environment that will allow designers to experiment with different communication paradigms and gestural interface models. Within this space, composers, performers, and DMI designers will be able to explore the affordances of new sensor technologies in the creation of new instruments for musical expression.

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Appendices.

Table of Contents

Early Glove Prototype:

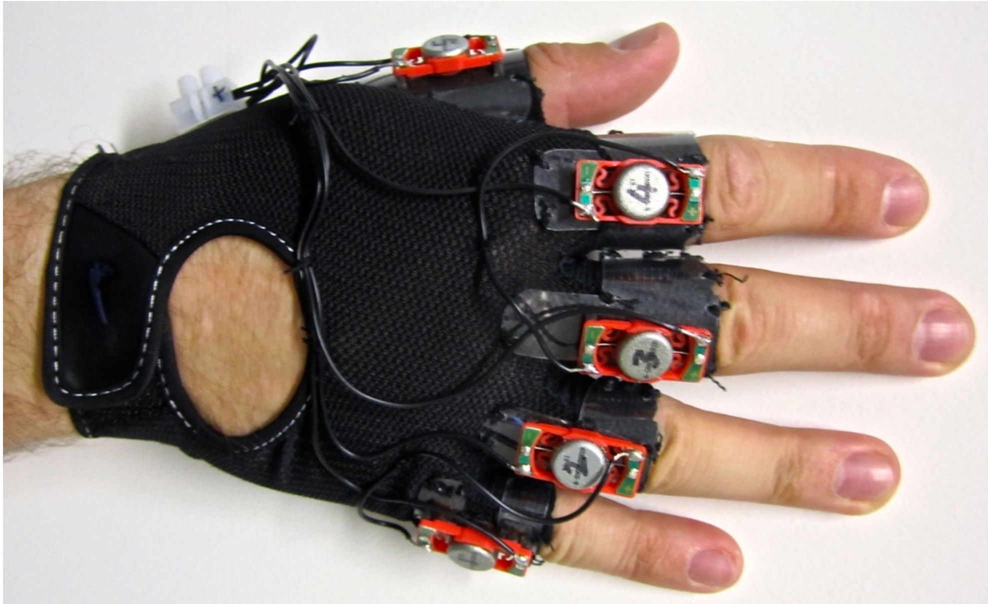


Figure 1: Early Audio-Tactile Glove Prototype.

Concept Development for Musical Tasks and HCI Evaluation:

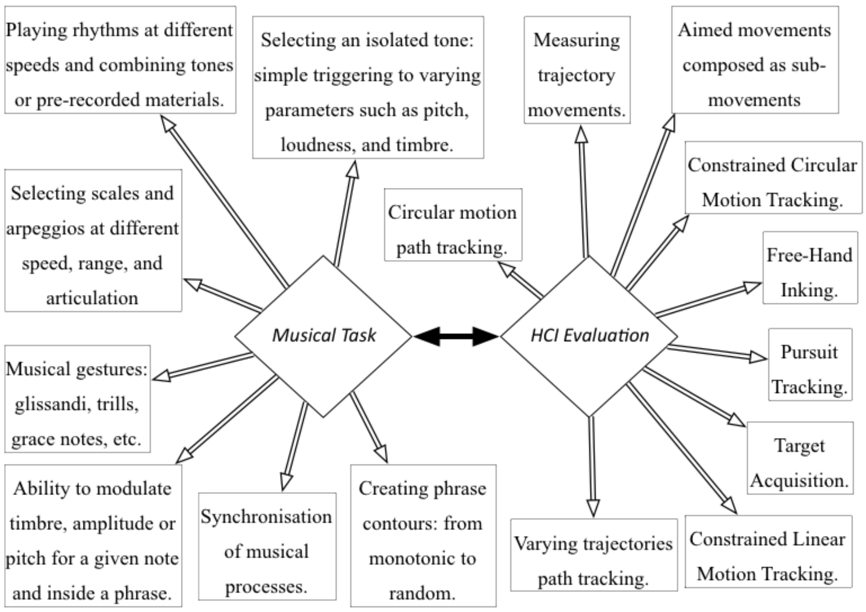


Figure 2: Musical Tasks / HCI Evaluation sketch.

Researcher Questionnaires for Chapter 3:

Experiment Subject Group – A / B (Flip a Coin)

Fixed Questions –

Name: ____

Age: ________   Gender: ____

Profession: ____

Current level of education: ____

Music Experience: ____

Experiment stage 1: Same / Different

√ (correct) or x (incorrect)

160 Hz Practice.

Waveform	Sine	Saw	Square
Sine			
Saw			
Square			

160 Hz Experiment.

Random Frequency Pair	Run 1	Run 2	Run 3
(4) Saw- Sine			
(9) Square-Square			
(3) Sine-Square			
(8) Square-Saw			
(7) Square-Sine			
(6) Saw-Square			
(1) Sine-Sine			
(2) Sine-Saw			
(5) Saw-Saw			

Experiment stage 2.1: Pitch Detection

√ (correct) or x (incorrect)

Sine 160 Hz

Random Frequency Shift	Run 1	Run 2	Run 3
(12) -0.25			
(19) -4			
(6) +2			
(17) -2			
(14) -0.8			
(16) -1.5			
(8) + 1			
(1) +12			
(13) -0.5			
(4) +4			
(9) +0.8			
(18) -3			
(15) -1			
(11) +0.25			
(10) +0.5			
(2) +8			
(22) -12			
(5) +3			
(7) +1.5			
(3) +6			
(21) -8			
(20) -6			

Experiment stage 2.2: Pitch Detection

√ (correct) or x (incorrect)

Saw 160 Hz

Random Frequency Shift	Run 1	Run 2	Run 3
(8) + 1			
(3) +6			
(7) +1.5			
(19) -4			
(22) -12			
(18) -3			
(6) +2			
(14) -0.8			
(9) +0.8			
(11) +0.25			
(13) -0.5			
(5) +3			
(1) +12			
(20) -6			
(16) -1.5			
(10) +0.5			
(15) -1			
(21) -8			
(2) +8			
(12) -0.25			
(4) +4			
(17) -2			

Experiment stage 2.3: Pitch Detection

√ (correct) or x (incorrect)

Square 160 Hz

Random Frequency Shift	Run 1	Run 2	Run 3
(11) +0.25			
(7) +1.5			
(13) -0.5			
(22) -12			
(9) +0.8			
(5) +3			
(17) -2			
(19) -4			
(3) +6			
(15) -1			
(20) -6			
(8) + 1			
(14) -0.8			
(12) -0.25			
(2) +8			
(6) +2			
(1) +12			
(10) +0.5			
(21) -8			
(4) +4			
(18) -3			
(16) -1.5			

Researcher Questionnaires for Chapter 5:

Experiment: Functional / Explorative (Circle One).

Subject #:___ Name:___________________________________ Age:_______

Gender:____________________________

Part 1: Please collect comments on the following topics: (Researcher Interview Data).

Learnability - the time needed to learn how to control my performance with this controller was…

____

Explorability - the exploration of the capabilities of the controller and the number of different gestures and gesture nuances that could be applied were…

____

Feature Controllability - The accuracy, resolution, and range of features when performing musical tasks was…

____

Timing Controllability - musical tasks that required the measuring of temporal precision were…

____

Part 2: Given the previous considerations, please gather comments on the performance of:

• Isolated tones, from simple triggering to varying characteristics of pitch, loudness, and timbre

____

• Musical gestures: glissandi, trills, grace notes, and so on

____

• Simple scales and arpeggios at different speed, range, and articulation

____

• Phrases with different contours, from monotonic to random

____

• Continuous feature modulation (e.g. timbre, amplitude or pitch) both for a given note and inside a phrase

____

• Simple rhythms at different speeds combining tones or pre-recorded material

____

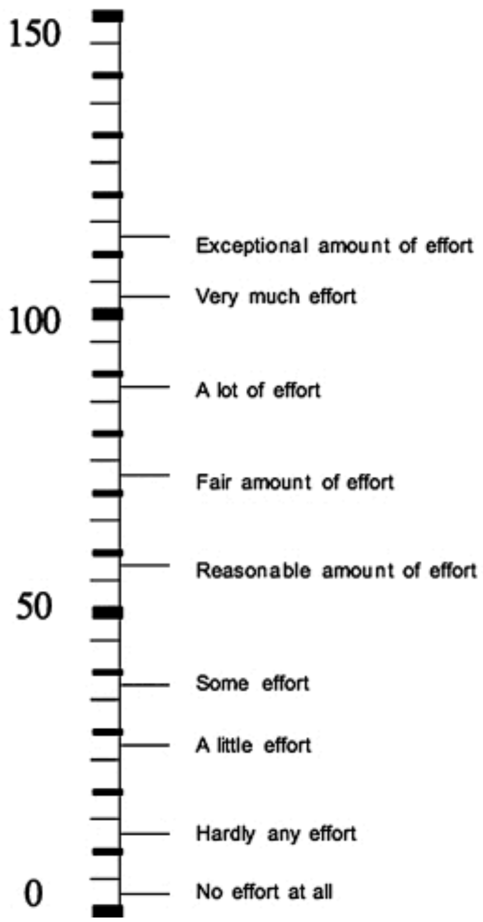
Record Further Comments Here:

Subject Questionnaire for Chapter 5:

Q1: Overall, how difficult or easy did you find this task? (Circle one) [*SEQ*]

1	2	3	4	5	6	7
Very Difficult	Mostly Difficult	Somewhat Difficult	Neither Difficult nor Easy	Somewhat Easy	Mostly Easy	Very Easy

Q2: This graphic displays the amount of effort it took you to execute the task. Please score the amount of effort by marking one of the anchors on the verticle line below. [*SMEQ*]



Please score by marking on the line below [*NASA-TLX*].

Q3: How mentally demanding was the task?

Very Low Very High

Q4: How physically demanding was the task?

Very Low Very High

Q5: How hurried or rushed was the pace of the task?

Very Low Very High

Q6: How successful were you in accomplishing what you were asked to do?

Perfect Failure

Q7: How hard did you have to work to accomplish your level of performance?

Very Low Very High

Q8: How insecure, discouraged, irritated, stressed, or annoyed were you?

Very Low Very High

Q9: How often do you think you would use a device like this to perform with? [Use]

Very Often Not Very Often

Please assess the device by ticking one circle per line. [*UEQ*]

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26

For researcher use only [Subject #:________].

Simple Melodies Used in Explorative Studies:

1.


2.


3.


4.


5.


6.


7.


8.


9.


10. 

11. 

12. 

13. 

14. 

15. 

16. 

17. 

18. 

OSC Receive Pure Data: