Musical vibrotactile feedback

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October 2007

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of Master of the Arts in Music Technology.

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2007/10/01

Abstract

This thesis discusses the prospect of integrating vibrotactile feedback into digital musical instruments. A holistic approach is taken, considering the role of new instruments in electronic music, as well as the concept of touch in culture and experience. Research about the human biological systems that enable vibrotactile perception is reviewed, with a special focus on its relevance to music. Out of this review, an approach to vibration synthesis is developed that integrates the current understanding of human vibrotactile perception. An account of musical vibrotactile interaction design is presented, which includes the implementation of a vibrotactile feedback synthesizer and the construction of two hardware prototypes that display musical vibration.

Abrégé

Cette thèse étudie la possibilité d'intégrer la rétroaction vibrotactile dans les instruments de musique numériques. Une approche holistique est adoptée, considérant à la fois le contexte de la musique électronique et le concept du toucher aussi bien sur le plan philosophique que linguistique. On passe en revue la recherche portant sur les systèmes biologiques humains permettant la perception vibrotactile, et tout particulièrement sur sa pertinence en musique. Grâce à cette revue de la littérature, on propose une approche de la synthèse de vibrations qui intègre la compréhension actuelle de la perception vibrotactile. Une méthode de conception d'intéraction vibrotactile musicale est présentée, incluant la mise en oeuvre d'un synthétiseur à rétroaction vibrotactile et la construction de deux prototypes qui reproduisent la vibration musicale.

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List of Acronyms

a/d	analog-to-digital
adsr	attack-decay-sustain-release
dmi	digital musical instrument
FA	fast afferent
ffr	frequency following response
hci	human-computer interaction
jnd	just-noticeable difference
ldr	light-dependent resistor
mft	multi-function transducer
midi	musical instrument digital interface
mm	millimeters
ms	milliseconds
NP	non-Pacinian
P	Pacinian
rms	root mean square
RA	rapidly adapting
SA	slow afferent
USB	Universal Serial Bus

Chapter 1

Introduction

The sense of touch has been vital to the development of musical skill for millennia, yet the recent dominance of digital technology in composition and sound production techniques has separated experiences of playing and listening from the body [5]. Now, in the early twenty-first century, electronic music finds itself amidst a revival of the tactile values that are built into the very word “music” — the original meaning of which applied simultaneously to organized sound and organized body movement [6]. Electronic music culture has compensated for the missing element of touch in various ways, but the advent of advanced and affordable computer interfacing technology means that the haptic channel may be re-engaged by new digital musical instrument designs. It is well known that acoustic vibrations are utilized for self-monitoring in acoustic performance [7, 8, 9], and that vibrotactile feedback can greatly improve touch perception during interaction without significantly adding complexity or cost to an interface [10]. This combination of circumstances suggests the re-tactualization of music, already underway with the emergence of gestural control systems, will be accelerated in no small part by the integration of vibrotactile feedback into digital musical instruments. Musical vibrotaction is a high-resolution, high-bandwidth perceptual system that promises nothing less than the reestablishment of embodied experience in electronic musical discourse.

1.1 Structure of this thesis

This introductory chapter describes some of the issues relevant to new musical interface design and to this project in particular, as well as an explanation of how making musical interfaces vibrate is a step towards solving some of the problems associated with electronic music performance. Previous research that inspired and guided this project, from the areas of audio-haptic correlation and digital flute design, is reviewed.

During the initial effort to define the terminology necessary for this writing, it became clear that touch is itself a multifaceted and complex subject in its own right. In the contemporary literature on interface design, touch tends to take on radically different meanings depending on its context. What is meant by the word "haptic" or "tactile" is often not consistent. In order to help establish a firm understanding of these issues, Chapter 2 is dedicated to an investigation of the definition and the history of touch, as well as its role in everyday language. In Chapter 3, psychophysiological literature relevant to vibrotactile interface design is reviewed. Chapter 4 details the vibration synthesis software developed out of this research. Prototypes of vibrating flute interfaces are presented in Chapter 5. Chapter 6 consists of a discussion of vibrotactile feedback as an integrated component of gestural control. Finally, concluding remarks about this research are made in Chapter 7.

1.2 Instrumentality and mapping

Using a computer as a component part of a musical performance system challenges the traditional understanding of music and musical instruments. The **Breakflute**, the final prototype constructed as a part of this research, is an interface that captures the instrumental gestures of a player with sensors and translates them into musical feedback, as both sound and vibration, using a parameter mapping scheme. Thus there are non-physical components of the instrument — namely, an *analog-to-digital* (*a/d*) conversion scheme and a software synthesizer. If all of these components were not tightly integrated and static in their behavior, the instrument would constantly change in fundamental ways. This is what Wanderley and Depalle observed when they defined a *digital musical instrument* (or *dmi*) as consisting of a particular gestural interface, mapping scheme, and sound synthesis process [4]. The key instrumentality of the *dmi* definition is its adaptability to innovative gestural acquisition and sensing technologies, networking protocols, and digital signal processing techniques. At the same time, it ensures that those properties remain predictable, allowing for interactions that preserve the fundamental behavioral and cultural traditions of musicality: replicable feedback response, affordance of training and pedagogy, and the attainment of the status of "virtuoso" — a highly-skilled musical instrument control expert.

The Breakflute does indeed meet the criteria for the definition of a *dmi*. To what extent it is a viable performance instrument is left for its players to decide. This thesis will not deliberate about whether the Breakflute is or is not expressive, whether it requires effort to learn or to play, whether it is intimate, nuanced, easy to learn, difficult to master, or potentially virtuostic. However, what is certain is that the Breakflute exhibits similarities to other instruments which promote skill-based musical performance behaviors, because it provides multi-modal feedback with a mapping scheme that is psychophysically informed.[1]

Mapping refers to the assigned relationship between the parameters of gestural acquisition and musical feedback. In traditional instrumental interaction, feedback necessarily contains information because it is a product of the instrument's behavior.[2] In a sense, acoustic instruments provide vibration feedback that is tightly coupled to the musical output "for free" because the same resonant system excited by the performer determines both the sound and the vibration properties of the instrument. The resonator of the instrument, whether a hollow bore, chamber, soundboard, or shell, radiates a sound that can be perceived by the ear, and a vibration that can be perceived by touch, at exactly the same time and as a result of the same mechanical

[1] For more on the semiotics of musical performance behavior, see [11].

[2] The meaning of the term "traditional instrument" is subjective and dynamic. In this thesis, it should evoke images of an expert musician who plays a program of repertoire on a stage for an actively listening audience, with a physical device that retains a constant structure and means of interaction.

process [12]. With a *dmi*, however, the input and output are held together by a mapping scheme that *must* be designed intentionally, because the digitization of gesture and feedback results in a layer of abstraction that has no physically-based properties. In fact, the only strictly physical component of a *dmi*, the material structure of its gestural interface, is not derived from the necessity of exciting an acoustic resonance but rather from interaction with a human. Sound may be synthesized in any fashion, and projected from any location in the performance space. Feedback is also defined by the instrument's design. While there is some creative freedom in mapping, creativity is limited by the rigid constraints imposed by the player's cognitive faculties. Some mappings are more intuitive than others, and an intuitive interface is one that will more readily produce meaningful music.[3]

Representing music as vibration necessitates a *cross-modal mapping*, or a mapping of parameters from one mode of perception into another. This thesis explores the possibility of using the entire range of vibrotactile sensations to present useful feedback about a musical performance, rather than to simulate the properties of acoustic instrument vibration. This presents a special challenge that is not present in teletaction or virtual touch applications, where the primary concern is simulation of real-world sensations [16]. In order to explore the *plasticity* of a cross-modal mapping from sound to vibration, the musical output of the Breakflute has been chosen to consist of breakbeat sequences [17]. The breakbeat idiom involves repetition of rhythmic phrasing, a sound spectrum saturated with a wide range of frequencies and partials, and a mix of distinct parts or voices. It is important to note that the counterintuitive idea of a flute playing breakbeat music was conceived in two stages: the physical system was designed to maximize vibration sensation, and the vibrotactile feedback was programmed to facilitate perception of separable rhythmic elements. The aim of the Breakflute is not to simulate acoustic vibration, but rather to map sound to vibration in a way that makes performing drum loops with a flute seem

[3]This is treacherous ground indeed. There continues to be a lively debate about the nature of an interface's "expressivity" [13], "effectiveness" [14], "controllability" [15], and a host of other descriptors. These formulations will be avoided in this thesis. Instead, feedback will be viewed as the defining characteristic of musical interaction. This topic will be addressed in more depth in Chapter 6.

natural.

1.3 Related work

Research topics that have influenced this thesis directly include the translation of gestural data and sound feedback into touch stimuli, and the development of flute-like digital interfaces.

1.3.1 Audio-haptic correlation

Cross-modal feedback coupling is a well established problem in interface design. An early example of vibrotactile feedback based on audio manipulation was a rhythm display for deaf music students where real-time sound output was processed to display musical vibration [18]. Actuators in the players' chairs were driven by a filtered version of the musical output of their instruments. The students reported a higher amount of "enjoyment" and "appreciation" for music when vibrotactile sensations supplemented their playing experience.[4]

In another project, haptic perception was utilized to communicate performance nuance, allowing a haptic observer (akin to a listener) to use muscle memory to differentiate multiple performances of the same piece [8]. "Performance nuance" (also called "musical feeling") was defined with an equation relating velocity to duration between note onsets. Data extracted using this relationship were translated to both force and vibration signal for use with the *moose*, a force feedback mouse. The difference in dynamic phrasing and effort between two performances was perceivable as the changing stiffness and position of a virtual wall, and demonstrated that musical performance gestural data could effectively be represented with a continuous force signal.

Crossing modes in the opposite direction, a translation scheme from force to sound

[4]It is not hard to imagine that this heightening of sensory experience would also be preferred by musicians that are hearing. In an informal inquiry, there were consistent reports from the users of the Touch Flute that the vibrating instrument felt more "alive" and "engaging" than non-vibrating controllers (see Section 5.1).

for use in an audio-haptic device was created [19]. Sound was produced by convolving the impulse response of the virtual surface with the force profile generated when a user interacts with the surface. The *Audio and Haptic Interface* utilized modal synthesis to generate audio signal from contact interactions with virtual objects, coupling aural and haptic events with minimal decision-making or mapping on the part of the designers. The result was a physically-based, continuous cross-modal correlation with low latency. This approach set a precedent for the sort of “inherent” cross-modal mapping presented in this thesis (see Chapter 4).

One area of tactile interface research that has recently received considerable attention is mobile applications. A crude notification device, the pager vibrator, is perhaps the most familiar and commonplace use of artificial vibrotactile feedback in modern life. Improving on these blunt instruments, systems have recently been developed that are capable of a more nuanced display of vibration. For example, a mobile device that provides a background (or “ambient”) channel of information, dubbed a “peripheral awareness display”, was implemented with the *TouchEngine* system. It was shown that the *TouchEngine*’s piezoceramic vibrotactile actuator improved task completion time for several mobile interactions [20]. Another use for mobile vibrotactile feedback is to display “tactile icons” alongside musical ringtones [21]. For this purpose, a vibrotactile stimulation method has been proposed for mobile devices that utilizes a specialized electronic voice coil component called a *multi-function transducer* (*mft*), designed to operate in the frequency and amplitude ranges of both sound and vibration [22]. The *mft* is a functioning loudspeaker, but also exhibits a strong resonance in the lower frequencies that are within the range of tactile sensitivity. In order to display a ringtone both auditorally and vibrationally, a sound file is processed and separated into audio and haptic “components”. The audio signal is output by the acoustic range of the *mft* in its original form, but is also redirected to be conditioned by a lowpass filter and amplifier. If the tactile range of the *mft* is not sufficiently activated by this extracted vibration signal, additional signal in this range is synthesized and mixed with the original.

The *ComTouch* system was a bidirectional remote mobile vibrotactile communication device, by which finger pressure exerted on a sensor by a sender was translated to vibration intensity on the receiving end [23]. The sensing and vibration systems were relatively uncomplicated, yet the system was found to be useful for communication in several interaction scenarios, once again affirming the effectiveness of vibrotactile feedback for interaction design.

Skinscape used a music composition model to develop an approach to artistic tactile composition [24]. The system was not interactive; vibration was programmed offline and played back as a presentation to an actively feeling audience. Although primarily concerned with aesthetics, *Skinscape* is similar to this project insofar as low-level synthesis was utilized to create an evolving vibration signal with similarities to music.

A system for audio editing has been developed where a touch interface was used to provide cues during audio scrubbing tasks, with the goal of making audio editing tasks quicker and more intuitive [25]. The audio file being edited was low-passed and the resulting signal was used to drive a vibrotactile mouse, so that the user could feel changes in amplitude by scrubbing through the file in the time domain. In a later iteration of the project, a haptic knob replaced the mouse, providing force feedback as well [26].

The *VR/TX* system is an excellent example of psychophysics applied to guide a cross-modal mapping [27]. *VR/TX* (pronounced "vortex") utilized spatiotemporal classification criteria for encoding feedback. A typology of "tactile sound" was developed using research on texture perception, in which time-dependent and space-dependent sound variables were correlated to gesture. Discrete tactile "notes" called *tactile stimulation events* were then synthesized in response to gesture. Intended to improve control of open-air gestural controllers, a graphical interface was provided for programming a unique vibrotactile feedback scheme specific to individual gestural controllers.

1.3.2 Other uses for vibrotaction

Not all vibrotactile devices display vibrations as events or simulate resonance. Texture perception is afforded by the vibrotactile system as well, and thus many vibrotactile devices have been designed for surface texture and friction simulation.[5] Additionally, *tactile vocoders* employ vibrotaction for speech perception [32, 33]. In most of these systems, speech signal is processed by a bank of bandpass filters modeling the critical bands of auditory perception, which is used to modulate an actuator control signal. It could be very interesting to use a tactile vocoder to display musical signal. Vocoders differ from the core research presented in this thesis, however, because they aspire to communicate symbolic information with pure sensory substitution. In contrast, the synthesizer created for this thesis is based on psychoacoustical parameter extraction (see Chapter 5).

1.3.3 Flutes

Vibration perception during musical performance is limited to the parts of the body that are in contact with the vibrating elements of the instrument and the frequency range of the musical content. Although there are more points of bodily contact while playing other instruments such as the cello [34], the glabrous (hairless) skin of the hand and mouth engaged in pre-Böhm flute performance are the areas of the human body most sensitive to vibration [35]. A flutist's vibrotactile experience thus proposes design criteria for a digital feedback system because these instrumentalists are in the unique position of having their highly sensitive fingertips and lips in direct contact with their instrument's resonator (a vibrating air column). A brief review and evaluation of flute designs is presented here to place the flute prototypes presented in Chapter 5 in context.

Perhaps the most well known and widely available woodwind controller is the Yamaha *WX5* [36]. The *WX5* utilizes binary switches to sense key position, a technique that does not accurately capture the fingering gestures used to play acoustic woodwinds.[6] A bite pressure sensor in the mouthpiece is included to account for

[5] These parameters may be grouped by the term *passivity* when describing device functionality. For texture see [28, 29, 30]; for friction, [31].

[6] In acoustic open-tonehole flutes, holing gestures (covering toneholes with the fingertips) control pitch continuously, not discretely, depending on the amount of the hole that is covered and whether an airtight seal is formed around its edge [37]. Accidentals may be played on the flute by "half-holing", and in fact glissando can also be played by slowly rolling the fingertip over successive

the dimension of reed bend control familiar to woodwind players. To acquire blowing gestures, a sensor is provided that responds to air pressure changes but is not specifically sensitive to air flow.[7]

The *MIDI flute* is an acoustic Böhm flute that has been equipped with sensors [39]. It is classified as a *hyperinstrument* because it is a functional acoustic instrument but uses electronic technology to control a synthesizer at the same time [40]. Key position and velocity are sensed with Hall effect sensors paired with permanent magnets. Air pressure inside the instrument is sensed with an electrodynamic microphone. A software envelope detector is then used to send *midi*[8] note-on and note-off messages to a synthesizer.

The *Hyper-flute* is also a hyperinstrument, and uses a variety of sensors such as tilt switches, Hall effect, pressure, and light sensors [42]. An ultrasonic sensor is utilized to detect proximity to an external point in the performance space. Blowing gestures are not acquired. Note that the designers of the *MIDI flute* were concerned with digitizing natural acoustic flute playing gestures, but the *Hyper-flute* extends flute performance practice with extra degrees of freedom (e.g., tilt and position).

The *Epipe* is a gestural controller that preserves the physical characteristics of an open-tonehole flute body and boasts accurate tonehole coverage sensing [43]. Each hole is surrounded with 16 binary capacitive switches that are used together to sense how much of a hole is covered. The instrument's size, shape, and other attributes are based on a specific acoustic instrument. The *Epipe* was intended as a prototype for a tonehole sensing interface, and so there is not any respiratory interface at all. Instead, an analog input is provided so that any analog sensor may be interfaced for sound excitation.

Table 1.3.3 provides a glance at some of the differences among these flutes. Note that the Breakflute is the only instrument in the table that has no acoustic resonator but does provide vibrotactile feedback.

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holes.

[7]In acoustic flutes, a resonance is excited by exhaling air *through* a tube [37]. Thus a breath sensor that does not directly sense air flow is responding to a different control parameter than the one to which acoustic flutists are accustomed [38].

[8]Musical Instrument Digital Interface (for details see [41]).

Table 1.1 Flute interfaces.

Device	Recorder	Böhm flute	WX5	Hyper-flute	MIDI flute	Epipe	Breakflute
Type	Acoustic	Acoustic	Digital	Hyper	Hyper	Digital	Digital
Fingering interface	Hole	Key	Key	Key	Key	Hole	Hole
Tonehole sensing	Air impedance	Air impedance	Switch	Various	Hall effect	Switch array	Light
Tonehole sensor type	—	—	Binary	Various	Continuous	Continuous[a]	Continuous
Respiratory sensing	Air flow	Air flow	Air pressure	Air flow	Acoustic pressure	None[b]	Air pressure
Vibrotactile feedback	Yes	Yes	No	Yes	Yes	No	Yes

[a] 16 binary switch sensors per hole.
[b] An analog "energy" input is provided and can be used with many different sensors.

1.4 Methodology

Designers of new *dmi*s must choose their own methodology for creating musical instruments that are fun to play and sound good. There are many theories that have been applied for this task — some are complementary and some are incompatible with each other. My own approach was to draw from an understanding of how invented (rather than evolved) instruments have entered the world of musical performance.

The design of most musical instruments is the product of centuries, if not millennia, of evolution through trial-and-error experience [44]. In some cases, however, technological advancements have enabled new instruments to emerge spontaneously. The saxophone (1846) is one case; the obvious electronic example is the theremin (1919) [37]. Hugh le Caine (1914–1977) contributed many breakthrough new instruments, including the *electronic sackbut* (the first keyboard-controlled synthesizer), the first filterbank, the first polyphonic synthesizer, and the *multi-track*, the ancestor of the modern sampler [45] (see Figure 1.1). While all of these inventions relied on innovation to provide musicians with a new expressive tool, they also incorporated an awareness of contemporaneous musical practices — they were designed to play known musical idioms in a new way. This contrasts with the approaches taken by composers such as Edgar Varèse (1883–1965) and Luigi Russolo (1885–1947), who utilized electronic technology to produce unfamiliar sound for the purpose of creating a new form of musical expression [46]. These composers continue to have great influence on modern music and electronic art music in particular, but their use of novel instrumentation was primarily compositional rather than organological in nature.

Decades of experimentation must elapse before the artistic potential of invented instruments can be realized. The saxophone was designed for loudness, so that it could be used outdoors by parades and military bands, but it would later play a central role in the birth of jazz. The theremin was first used to play classical string and vocal repertoire, but its distinct sound became synonymous with 1950s futurism. It has been and continues to be widely used by pop musicians. The Linn *LM-1* (1982), the first programmable digital drum machine, was designed to mimic the timbres and timings of a session drummer (Figure 1.2), but its limitations

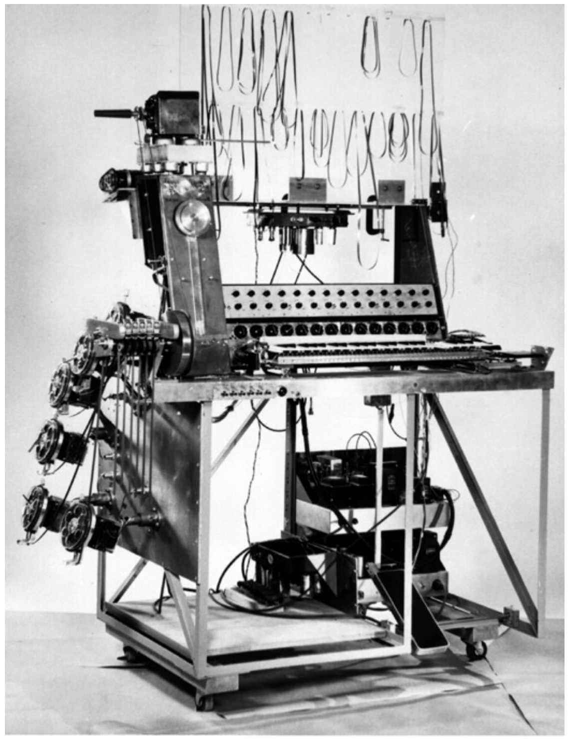


Figure 1.1 The *multi-track*, ancestor of the sampler. Photograph courtesy of the Canada Science and Technology Museum.

as such would later be exploited to develop hip-hop and electronic dance music. Roland's analog *TB-303* (1982) was, incredibly, intended to provide guitarists with a realistic electric bass accompaniment, but its sequencer and real-time controllable filters effectively invented the genre of acid house music [47] (Figure 1.3). Perhaps the quintessential example of these metamorphoses is the radical shift in the role of the phonographic turntable (1892), which began as a sound playback appliance and became a performance instrument almost a century later.

For these reasons, working within known musical styles may be more likely to generate instruments that invigorate widespread creative movements than design theories that seek to subsume the "expressive" characteristics of acoustic instruments with digital technology. Rather than starting with the goal of creating a new kind of

Figure 1.2 The *LM-1*. Photograph courtesy of Der Moogulator. [1]

Figure 1.3 The *TB-303*. Photograph courtesy of Kevin Lightner. [2]

music, new instrument design can reasonably be guided by enabling existing music to be played in a new way. Instead of limiting expressive potential, this approach may even enhance it. Therefore the methodology for the design of the vibrotactile interfaces presented in this thesis relies on a known form of instrumental interaction (flute playing) to play existing musical idioms (breakbeat loops).

1.5 Research contributions

As a new musical instrument, the Breakflute will complement the growing repository of capable gestural controllers for music performance research. Even as electronic music has become exceedingly popular, and is now even well accepted in the classical world, the list of novel electronic instruments that can be readily practiced and performed is very short.[9] The most important contribution of this thesis is that of a vibrotactile flute that has been systematically designed. Just as audio feedback is more effective if it integrates psychoacoustical models, vibrotactile feedback stands to be improved if based on a comprehensive understanding of vibrotactile perception. Another principal aim of this research is thus to integrate the so-called *four-channel model of mechanoreception* into a musical vibration display (see Chapter 3). It would seem as if this approach has not yet been tried in musical vibrotactile interface design, and so this particular implementation cannot be considered fully mature; however, it is a thoroughly researched first attempt. A software vibration synthesizer called **FA/SA** has been programmed to explore musical vibrotactile feedback synthesis, and two vibrating musical interface prototypes have been constructed. The **Touch Flute** was the first proof-of-concept for a wind controller providing vibrotactile feedback. It sensed basic keying and blowing gestures and responded with sound, as well as vibrotactile feedback in the mouthpiece and keys. The Breakflute improves upon this design with refined actuation and gestural acquisition systems, and provides a more musical playing experience.

[9] Groups such as McGill University's Digital Orchestra are addressing this issue by coordinating instrument designers, composers, and classically trained performers to develop credible repertoire and skilled players for novel instruments [48].

This chapter has reviewed some of the previous work related to this research and presented a design methodology based on other invented musical instruments. In the next chapter, a brief survey of the enduring and pervading role of touch in human life will outline the cultural context of touch interface research.

Chapter 2

Tactility

> *My body as given to me by sight is broken at the height of the shoulders and terminates in a tactile-muscular object.* [49]

The concept of touch is tangled, thorny, sticky, and at times may even feel impenetrable. The inspiration for this chapter was the observation that, at the same time that active touch interfaces are exploding in popularity and applicability, most of the newer literature uses the word "touch" liberally, as if its meaning is already familiar. However, a comprehensive understanding of what is meant by the word would contribute much to interface design efforts. To my surprise, developing this understanding has proven an exceedingly difficult task — I quickly discovered that there is an immense amount of writing dealing with this single definition. Touch seems easy enough to conceptualize on a macroscopic level, but upon close examination the term breaks down and becomes startlingly complex. This chapter introduces some of the broad concepts and themes in tactility studies. First, a list of modern touch-related terminology is presented along with definitions that have been compiled from various disciplines. Next, a brief history illustrates how touch migrated from its place in religion and philosophy to a sensory phenomenon subject to scientific inquiry. Finally, the use of this terminology and other touch metaphors in modern language is presented in its original context, to further demonstrate the permeating relevance of tactility and make a convincing argument that touch indicates the most fundamental and visceral quality of lived experience.

2.1 Terminology

The entry for “touch” has been said to be the longest in the Oxford English Dictionary.[1] Many contemporary definitions and variants of touch terminology persist, even within the interface design community. The following collection of terms was compiled from literature on perception, physiology, and humanities. It is not intended to be authoritative.

`haptic` Derived from the Greek αφή (“haphe”), meaning “pertaining to the sense of touch” [52]. Specifically refers to physical object or event perception external to the body, effectuated by a combination of active, exploratory kinesthetic perception and passive cutaneous sensation [53]. Vibrotaction is thus a vital component of haptic perception. The primary haptic sense organ is the hand [54, 55].

`taction, tactual` Refers to all perception mediated by cutaneous and kinesthetic sensibility [53], as *visual* refers to eyesight and *aural* to hearing.

`tactility` The experience of tangibility [56]; the touch counterpart to visibility.

`cutaneous sensation` Sense modalities arising from stimulation of cutaneous (skin) receptors, e.g., texture, temperature, wetness, and skin deformation [57].

`tactile sensation` Cutaneous sensation resulting from mechanical stimuli. Tactile sensation is specifically passive and qualitative rather than active and exploratory. It is often said that mechanoreceptors

[1] In [50] it was claimed to be the longest entry; the 2006 edition of the OED includes 64 definitions [51].

in the skin enable tactile sensation, and proprioceptors in joints, muscles, and ligaments give rise to kinesthesia.[2]

`kinesthesia` The sensation of the position and movement of the limbs and other body parts, activated chiefly by mechanoreceptors in joints and muscle tissue [60].

`mechanoreception` The sensation of mechanical displacement of the skin or body tissue [57].

`proprioception` The most common usage refers to perception of limb position [57]. Also used to generally indicate the obtaining of information about one's own actions in relation to an ambient environment, causing confusion about the meaning of the term. In this second definition, posture, orientation, and equilibrioception are included; it would also apply to hearing one's own voice, seeing one's own hands, or touching a part of one's own body [61]. While proprioception is now commonly used as a synonym for kinesthesia, it lacks a precise definition [60], and for this reason should perhaps be avoided when possible.

`interoception` The sense of the physiological condition of all body tissues, including emotional arousal, metabolic functioning, and pain. It has recently been shown that these and other components of interoception are represented by an afferent pathway entirely distinct from that of mechanoreception [62].

`feeling` A feeling can be a unitary sensation (akin to a "sound" or a "vision"), but also a mental state or event (such as an emotion or a hunch). It is also used to refer to the mind-sensation of desire or

[2] In terms of stimulus characterization, it has been shown that these two modes are not distinct [53] and instead comprise a "kinesthetic-cutaneous continuum" where low frequency, high amplitude stimuli that move parts of the body relative to each other constitute "forces" activating kinesthesia, and higher frequency, lower amplitude stimuli fall under the "vibration" category and activate cutaneous mechanoreceptors [58]. Recent research has further revised this model by showing that cutaneous mechanoreceptors contribute to kinesthesia by responding to internal vibrations and skin stretch [59].

aversion [63]. It should be noted that these latter meanings conflate activities of the mind with activities of the body.

`tact` Just the *right* touch [56].

2.2 Origins

Touch was philosophical before it was biological, and has been often associated with primodiality, contagion, and forbidden eroticism. Even today in our culture there remains a reluctance to touch or be touched, yet throughout our history touch has been known as gateway to authoritative knowledge in the sciences, medicine, and religion [56]. The contributions of several thinkers that regularly surface in tactility studies are very briefly summarized in this section; the intention is not to provide an exhaustive history but rather to track how touch has journeyed from a place of moral contemptibility to being studied in today's laboratories as the primary sense.

The etymology of the word *haptic* may suggest that Platonic touch is still alive in the modern touch lexicon. While Platonists acknowledged that all animals possess a sense of touch, acute visual discrimination was credited with affording a contemplative intellect. Touch was thought to be uninvolved with, and even a hinderance to, spirituality and higher thinking, as evidenced by the assertion that there is "no sense further from the intelligence" [64]. The sharp division between mind and touch has been disproved scientifically, but Aristotle's contention that "the loss of this one sense alone must bring about the death of an animal" [56] has been largely confirmed by modern biological research as a universal rule of life. Aristotle had a profound effect on the typology of senses in the West — so profound in fact that the Aristotelian division of the senses into the five hierarchical categories of sight, hearing, taste, smell, and touch is still the prevailing model of perception held by virtually everyone outside a perceptual psychology laboratory [65].

Vision became increasingly relied upon for transference and preservation of intellectual information in the medieval period, as scholars and theologians shifted from an oral tradition to visual media for expression and communication [66]. At the same time that this newly expanded role of vision fostered the dissemination of ideas, the vulgarity of touch held fast as evidenced by a widespread prohibition against transcriptions pertaining to the skin [54]. The connection between the sense of touch and corporeality was not lost on Thomas Aquinas (1225?–1274), who observed that a touch sensation signals a bodily change: "Touch and taste involve physical change in the organ itself; the hand touching something hot gets hot" [64].

Attitudes began to shift with the advent of Renaissance humanism, which advocated a renewed role for sensory experience in worldly knowledge. The breakthroughs in human anatomy made by Andreas Vesalius (1514–1564) were not the result of theological or philosophical insight but instead emerged out of the very tactile practice of human dissection [56] (see Figure 2.1). At the same time, the Reformation movement brimmed with tactile metaphors, promoting a direct and immediate connection with the divine using a touch lexicon, which challenged the reign of visual imagery promoted by a Catholic church with Platonic underpinnings [64]. While artwork during this period continued to be dominated by depiction of Platonic themes, the growing importance of tactility was implicit in the development of techniques that appealed to the viewer's corporeal senses of motion, force, and texture. These qualities have been controversially (but nonetheless significantly) termed *tactile values* — textural and kinetic realism that is experienced as the translation of visual qualities to the body percept [67] (see Figure 2.2).

Later, in a period when Enlightenment thought was once again making much of visual metaphors for knowledge (e.g., "bright", "brilliant" [68]), Denis Diderot (1713–1784) called particular attention to the profound influence of sensory experience on perception and the formation of ideas. His remarks on the interplay of touch and vision were prescient of several present day theories of perception. For example, he described the notion of *sensory substitution* when he suggested the blind may be taught to read using touch, and he discovered *sensory compensation* when he made an empirical argument for the blind having a heightened capacity for touch perception. He also observed that perception of form depends upon the short-term memory of component sensations, a central part of haptic theory [69].

The science of *psychophysics*, established in the nineteenth century, is concerned with qualitative measurement of the relationship between stimulus properties and

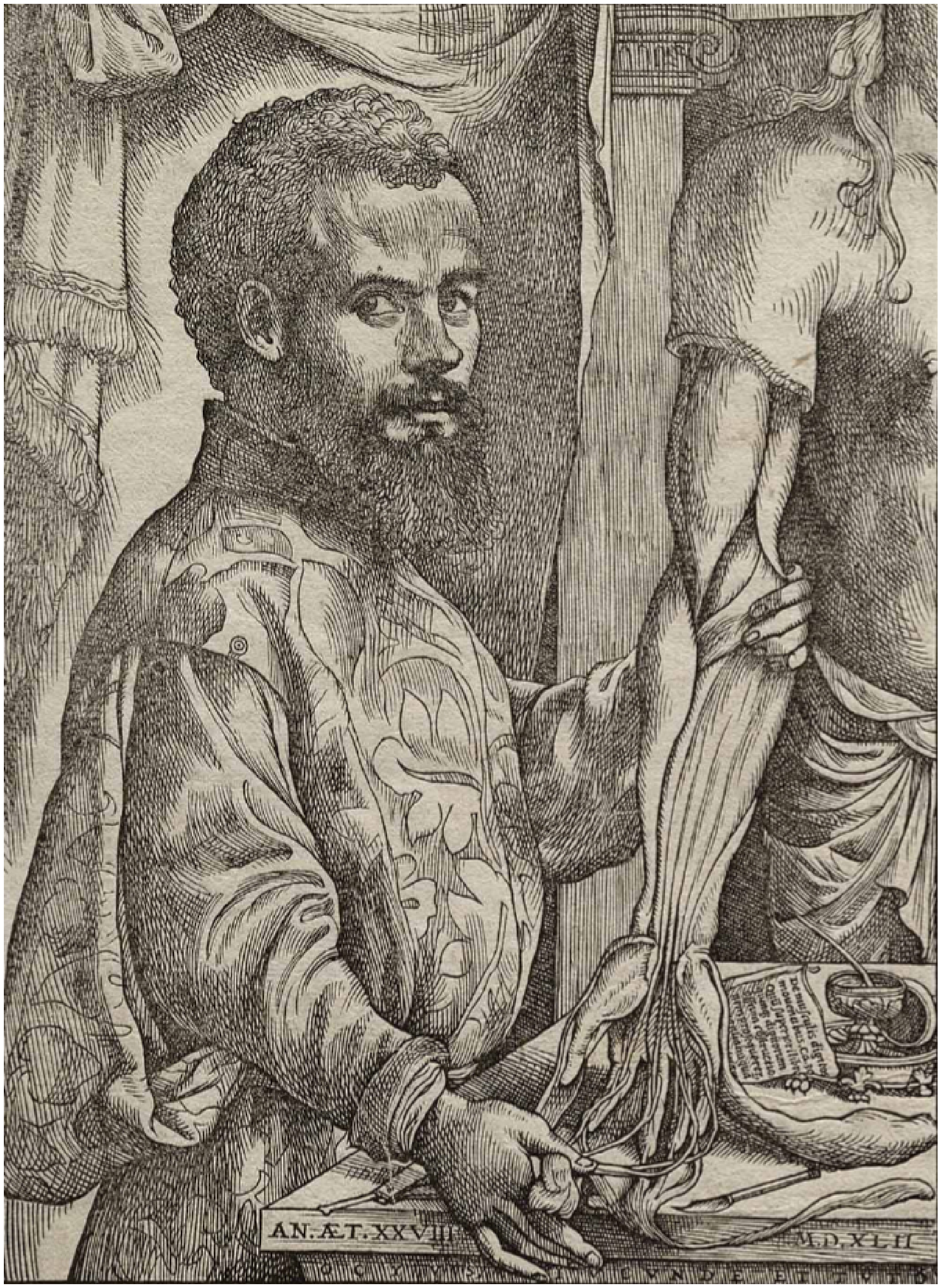


Figure 2.1 Vesalius touches to know. Portrait of Andreas Vesalius. In *De humani corporis fabrica libri septem.* Basel, 1543. Original image and photographic reproduction are in the public domain.

Figure 2.2 Giotto's painting style has been said to portray tactile values. Can you feel it? Giotto di Bondone. *Noli Me Tangere.* ca. 1305. Cappella Scrovegni, Padova. Original image and photographic reproduction are in the public domain.

a subject's sensory experience [57]. Ernst Heinrich Weber (1795–1878) helped develop what has become known as *Weber's Law*, which states that one's ability to discriminate a difference in magnitude between primary and comparison stimuli is a function of the magnitude of the primary stimulus [69]. Weber also offered scientific evidence that Aristotilian touch is actually a combination of separable perceptual modes including body locus, weight, and temperature. Johannes Müller (1801–1858) contributed the theory of specific nerve energies (or *specificity theory*), which stated that each nerve elicits a specific sensation associated with it, regardless of how it is stimulated. This paradigm would last until twentieth century, when perceptual psychologists would develop *pattern theory*, which states that a sensory experience is the aggregate effect of many simpler nervous events [65].

As pattern theory matured and evidence mounted in its favor, psychologists and physiologists began examining sensory phenomena in terms of *haptic perception* rather than the qualities of passive stimulation. David Katz (1884–1953) asserted that "haptics is rooted in phenomenology", and emphasized the role of activity in touch as well as the importance of vision on guiding touch [70]. His work also signaled a final shift away from the Aristotelian division of senses into a well-defined hierarchy, instead individuating sensory modalities according to their role in developing a belief in the reality of an external world [54]. In particular, his experiments made a strong case for a sharp separation between vibration and pressure sensation.[3] He also noted that touch sensations may be either proximal or distal. While skin contact is the obvious mode of proximal touch, Katz noted that vibrotaction also enables perception of vibration sources originating far beyond body's surface, such as the approach of a distant train. Moreover, by probing a distal surface with a manual tool, texture and material substance can be perceived through the properties of the tool's vibration. Distal probing may also give rise to a perceptual illusion of proximity, as if the tool is an extension of the body. Following in these footsteps, James Gibson's (1904–1979) *perceptual system* denoted the holistic quality of perception in time as well as in space. Gibson asserted that the integration of separable

[3] Katz's studies were mostly limited to vibration that occurs incident to texture perception rather than actively vibrating stimuli.

sensory modalities leads to the perception of higher-order invariants, and that these invariants, as opposed to sensory qualia, define our perceptual experiences [71].

2.3 Touch in language

Our touch senses are much more than a mode of data input for a computational mind. It may be argued that touch represents the overriding quality of experience. In many ways, touch is the crucible of modern epistemology. Like a frame that delineates the boundaries of a painting from the wall behind it, existence is framed by sensations of touch. The separation of self from other arises in large part from this capability [63]. When we realize that touch tells us who we are and our place in the world, we cannot but marvel at its infinite relevance. Our most extreme experiences are touch sensations, leading us to the height of sexual pleasure and the depths of physical pain. Touch guided us before we had a conscious mind, and was our first sensation [72]. Even in the throes of death, it is not hard to imagine that the final sensation could also be described as a *feeling* — suggesting that tactility frames our existence not only spatially but also temporally.

The following quote from Bertrand Russell is found on the website for the European Union's *TOUCH-HapSys* research initiative [73]:

> *It is touch that gives our sense of 'reality'... Not only our geometry and physics, but our whole conception of what exists outside us, is based upon the sense of touch.* [74]

The entire human body is infused with touch receptors, which is perhaps what causes somatic, mind, and touch concepts to be associated and often entangled. Because of the extraordinary role of touch in human experience, its vocabulary has developed an abundance of metaphorical uses. Stephen Thayer provides a particularly colorful collection in *Tactual Perception: A Sourcebook*:

> *Our language is filled with expressions that underline the importance of the sense of touch in communicating important subtleties of feeling and attitude. Consider the following expressions: keep in touch; a touching experience; he's touchy; a gripping experience; handle with kid gloves; deeply touched; be tactful or tactless; someone is a soft touch or has a soft touch; a clinging personality; how does that grab you?; a pat on the back; to press or push someone; a hands-off policy; get a grip or hold on; holding my own; the personal touch; put on the finishing touches; the Midas touch; make contact with; rub someone the wrong way; to feel edgy; be on your toes; tickles my fancy; touched in the head; palpable lie; solid reputation; a rough character; rubbing shoulders with; cheek to jowl; nose to nose; makes my skin crawl; a slimy character; itching to go; touch and go; only scratched the surface; stretch the imagination; grasp an idea; get a handle on; able to handle something; only skin deep; like a slap in the face; a mere slap on the wrist; give elbow room; in a pinch; got by the short hairs; on pins and needles; walking on egg shells; like a kick in the teeth.* [70]

Touch is so primeval that the language of tactility is commonly used to signify the deepest possible level of intimacy. To *keep in touch* is to preserve a relationship with another person; to *grasp* a concept means to absorb it so thoroughly as to have gained the ability to manipulate it freely; when we *have a feeling [deep down]* about something, though it may contradict what we *see right in front of us* or what we have *heard*, we are often told that the *feeling* is usually right. Touch is also used to indicate change — when something has been *touched* it has been transformed, and often corrupted. Considering that recent research on the role of metaphor in cognition has suggested that these primary metaphors are not "dead" but rather that they may utilize the same cognitive structures as haptic processes [75], it is not a stretch to hypothesize that our haptic sensorimotor system actually is utilized for determining what is most real, even in abstract reasoning.

Although computer technology has come to exert far-reaching influence on daily experience, computers may often feel “impersonal”, “cold”, or “distant”, perhaps arising from the fact that they do not engage our touch senses to a significant degree. Writes Constance Classen in the introduction to *The Book of Touch*:

> *…[W]e live in a society of the image, a markedly visual culture, in which, while there may be many representations of touch, there is often nothing actually there to feel. The attractions of advertising, television, or the Internet, are designed to be consumed by the eyes and the ears. The endless appeal to the sense of touch one finds in contemporary visual imagery, unaccompanied as it is by the actual tactile gratification, may have helped make touch the hungriest sense of postmodernity. The inability to touch the subject matter of the images that surround us, even though these have a tremendous impact on our lives, produces a sense of alienation, the feeling of being out of touch with one's society, one's environment and one's cosmos — an isolated fragment in an indifferent universe.* [68]

It may be the case that the perceived disconnect between digitally produced sensations and real-world material interaction is temporary, a latency lasting only a few decades while active touch technology matures. In the near future, prehensile avatars will extend our somatosensorimotor system across computer networks, and the isolation and alienation associated with today's information technology will be reduced to an undesirable digital artifact that may be eliminated by elegant solutions to engineering problems.

In this chapter, the unique role of tactility has been outlined and a case has been made for development of technologies that engage the touch senses. The following chapter reviews some of the psychophysiological literature most pertinent to vibrotactile interface design.

Chapter 3

Vibrotactile perception

Modern research on vibrotaction has focused on mechanoreceptive nerve fiber response, the cortical entry stage of neural signals, and subjective judgments of perceptual characteristics such as threshold of detection, magnitude, and frequency [76]. Because a primary aim of this thesis is to generate musical vibrotactile feedback for a vibrating digital musical instrument, the capabilities of the human vibrotactile system must be understood. This chapter outlines the neurophysiology of vibration reception. It also reviews some basic psychophysical phenomena and the current understanding of tactile sensory coding. In this overview, vibrotaction will occasionally be compared to audition, because many readers of this thesis will likely have some background in psychoacoustics.

3.1 Neurophysiology

The neural mechanisms of tactile perception have recently become fairly well understood [77]. The four known mechanoreceptive afferent units in glabrous skin are the FA2 (*Fast Afferent type 2*, also called the *Pacinian* or *PC* afferent), FA1 (*Fast Afferent type 1*, or *RA* afferent), SA1 (*Slow Afferent type 1*), and SA2 (*Slow Afferent type 2*). The "fast" and "slow" nomenclature refers to the unit's adaptational property. Whereas fast afferents quickly stop firing when a stimulus is applied, a slow afferent continues firing long after the skin has been indented (see Section 3.2.3). Other ways that they may be differentiated are according to their receptive field size (the area of skin that, when mechanically deformed, excites the receptor), the specialized cellular structure that surrounds the axon ending, and innervation density in the hand [78]. It has been shown empirically that the functionality of each mechanoreceptor is specialized to respond to a different type of stimulus. Each of these four afferent unit types correspond to sensory channels which, when stimulated independently in a laboratory setting, produce "unitary" sensations (see Section 3.3). Mechanical skin disturbances usually activate all receptor types in some ratio to each other, depending on the properties of the stimulus. Thus everyday suprathreshold sensations are the result of the combination of neural activity across the four channels. The fact that each of these afferent units give rise to distinct sensations is what makes delineating the components of tactile perception exceedingly more complex than audition. Rather than two copies of the same sense organ (as is the case with the ear), we have four organ types infused with varying density all over the body, sensitive to multiple modes of skin disturbance, firing in distinctive patterns.

Each mechanoreceptor terminates in one of four unique cellular structures (Figure 3.1). The Pacinian corpuscle encases the ending of the FA2 afferent. Pacinian organs are located in the deeper layers of subcutaneous skin and can be found in tissues throughout the body [57]. They are large, onion-like balls comprised of layers of cells which function as an "extremely selective cascade of high-pass filters" [77] in order to protect the nerve ending from the high-amplitude, low-frequency forces of everyday manual interaction. It is especially worth noting that the neural firing pattern of FA2 fibers represent stimulus waveform in much the same way as do auditory afferents, and it is thought that they are also primarily responsible for the perception of vibrations originating from distal sources [77]. Thus the Pacinian contribution to vibrotactile perception exhibits at least two similar properties to auditory perception, evidence for the hypothesis that the FA2 is the most active neural mediator of musical vibrotactile perception.

FA1 afferents end in Meissner corpuscules. These receptor structures are ovoid fluid-filled bulbs nestled between the ridges of the boundary between the cutaneous and subcutaneous tissue layers. They have low spatial resolution, but are especially

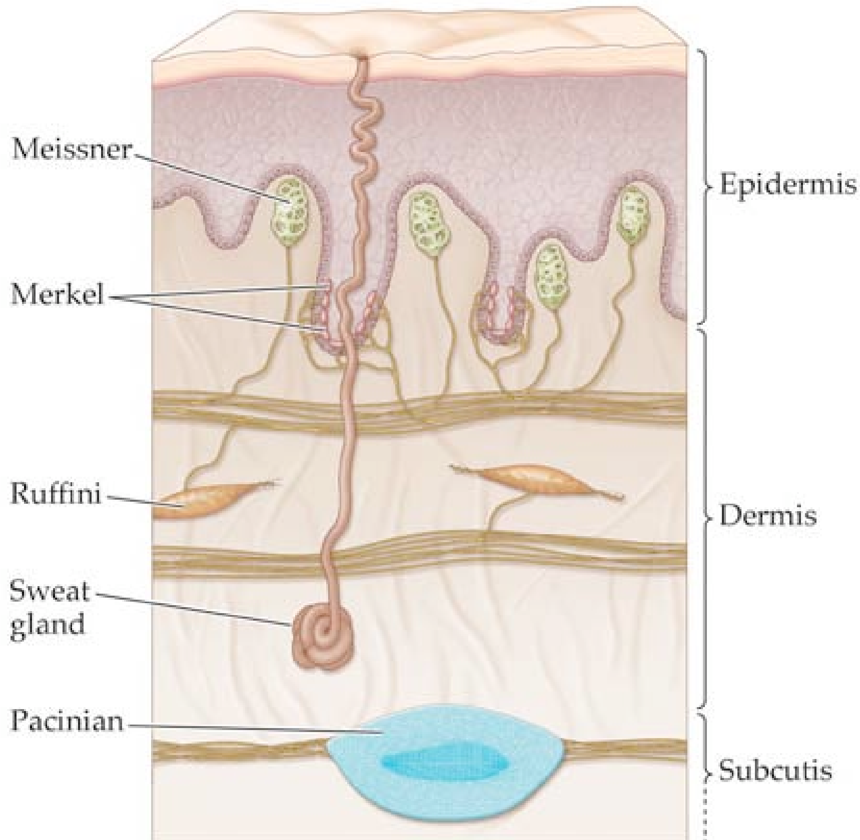


Figure 3.1 A cross-section of glabrous skin illustrating the four mechanoreceptors. From Wolfe et al., *Sensation and Perception*, fig. 12.2. Sunderland, MA, USA: Sinauer Associates, 2006. Reproduced with permission from Sinauer Associates. Copyright 2006, Sinauer Associates.

well suited to represent skin motion and low frequency vibration. It has been shown that the Meissner-FA1 system is highly responsive to low frequency forces exerted on objects held in the hand. This and other evidence suggests its primary function is to assist in grip control [77].

Merkel discs are the smallest of the four structures, grouped in bundles just underneath the outer skin layer. The small, well-defined receptive fields of the SA1 nerve endings make them highly sensitive to surface features such as curvature, edge, and texture. The firing patterns of Merkel-SA1 afferents effectively create an accurate spatial neural image of a stimulus [77].

Ruffini spindles, the putative receptor structures for the SA2 afferents, are comparable in size to the Pacinian corpuscules. Like Pacinian endings, they are also located deeper inside skin tissue and have large receptive fields [78]. However the primary function of the SA2 seems to be to respond to lateral skin stretch. This particular sensitivity has two hypothesized functions. The first is detection of direction of motion of objects gripped in the hand, which may contribute to grip and manipulation feedback. The second is perception of hand shape: the functional properties of the SA2 suggest that the static posture of the hand may be detected primarily through sensations of skin stretch in the palm and fingers [77].

3.2 Psychophysics

Psychophysics is concerned with investigating the relationship between physical stimuli and sensations in the psychological domain [79]. Psychophysical research has yielded much knowledge about the human ability to perceive vibration. One common approach has been to determine the lowest threshold for some perceptual parameter. We live in a suprathreshold world however, and so testing has also been carried out to determine the functioning of everyday vibrotactile sensations. This is vital consideration for interface design, as vibrotactile feedback will be effective only if it is within the boundaries of thresholds of perception, comfort, detectable changes over time, and other factors. This section will briefly summarize findings in the literature regarding some of the most studied metrics of vibrotactile perception.

3.2.1 Location and size

Cutaneous sensitivity varies across different regions of the body. Location and size comprise the somatotopic dimension of vibrotactile perception, dealing with where and how much of the human body is stimulated.

The location of a contactor on the body contributes to the number and combination of afferent receptors recruited, as well as an interoceptive localization component. Proximity of separately discriminable stimuli is called the *two-point limen*, and is subject to spatial masking effects [80]. Spatial acuity is affected by location, frequency, and indentation energy, and has been related to receptor innervation density [81]. It is an especially important measure for the design of whole-body stimulators with multiple sites of stimulation, and for *tactor arrays*, tiny matrices of pin contactors used for texture display and letter reading [82].

The size of a stimulus is determined by physiological properties such as skin impedance and the receptive field size of the activated receptor systems, as well as perceptual variables such as spatiotemporal masking effects. Because each mechanoreceptor type has a particular receptive field size, the mix of afferents recruited by the stimulus will also play a role in perceived size.[1]

3.2.2 Threshold of detection

The threshold of detection is the lowest amplitude of periodic displacement that can be sensed. It is contingent on several factors including frequency of the stimulus, contactor geometry, and skin impedance. The dynamic properties of the vibration signal such as its envelope, duration, and the presence of masking stimuli may also affect the threshold level. Threshold is reached when a single rapidly adapting afferent unit (either FA1 or FA2) fires a single impulse [85]. Within the range of about 20–40 Hz, threshold is independent of frequency; between roughly 40 and 500 Hz, however, sensitivity peaks at about 250 Hz [78]. For small contactor sizes, threshold is also independent of frequency [86].[2]

The mechanical impedance of the skin area being tested also affects absolute threshold. Skin impedance determines the output force necessary to drive a vibrotactile actuator at a given frequency to produce sensations. Impedance has been

[1]This thesis deals with stimulation of glabrous skin, and so concerns with other body sites will be omitted; for a review of vibrotactile perception on other body locations, see [70, 65, 83, 84]

[2]The prototypes in this project use fingertip stimulators no larger than 1 cm in diameter, classifying them as "small" contactors.

found to be strongly affected by the area of stimulation site and the static pressure applied by the contactor [81].

A non-vibrating element around a contactor, called a *surround*, isolates an area of skin with a sharp impedance gradient [87]. The presence of a surround decreases the threshold in the lower range of frequencies and increases it in the higher range [88]. This is an important consideration for this research because the body of a flute around a tonehole is in essence a surround.

The interplay of multiple stimuli may also have an effect on threshold. *Masking* may occur if the presence of a "background" stimulus causes a primary stimulus to go undetected. A masking stimulus may be present at the same time as the primary stimulus (*simultaneous* masking), or immediately preceding or following the primary (*forward* or *backward* masking) [65]. There is some evidence that masking only occurs when both stimuli activate the same receptor system [89, 90].

3.2.3 Sensation magnitude

Sensation magnitude (or "loudness") is tied to stimulus intensity, but also to many other factors, including stimulus frequency. Above threshold, equal-sensation magnitude varies across vibratory frequencies. Suprathreshold equal-sensation contours illustrate that as sensation magnitude increases, it becomes somewhat less dependent on stimulus frequency, although not nearly to the same extent as the Fletcher-Munsen equal-loudness contours for audition (see Figure 3.2.3).

The *just-noticeable difference* (or *jnd*) of sensation magnitude is smallest change in stimulus intensity that causes a perceived change in magnitude. As it will be recalled, Weber's Law states that the perceived intensity increment or decrement from a primary stimulus to a comparison stimulus is a function of the intensity of the primary [69]. Differences in methodology have led to many different reported *jnd*s, ranging from 0.4 dB to 2.3 dB[3] [78]. It is suggested in [91] that up to four levels of vibration amplitude are easily discriminated.

[3] $dB = 20\log(D_1/D_{ref})$ where D_1 is the skin displacement produced by the stimulus and D_{ref} is a reference value, usually 1.0 μm peak displacement [78].

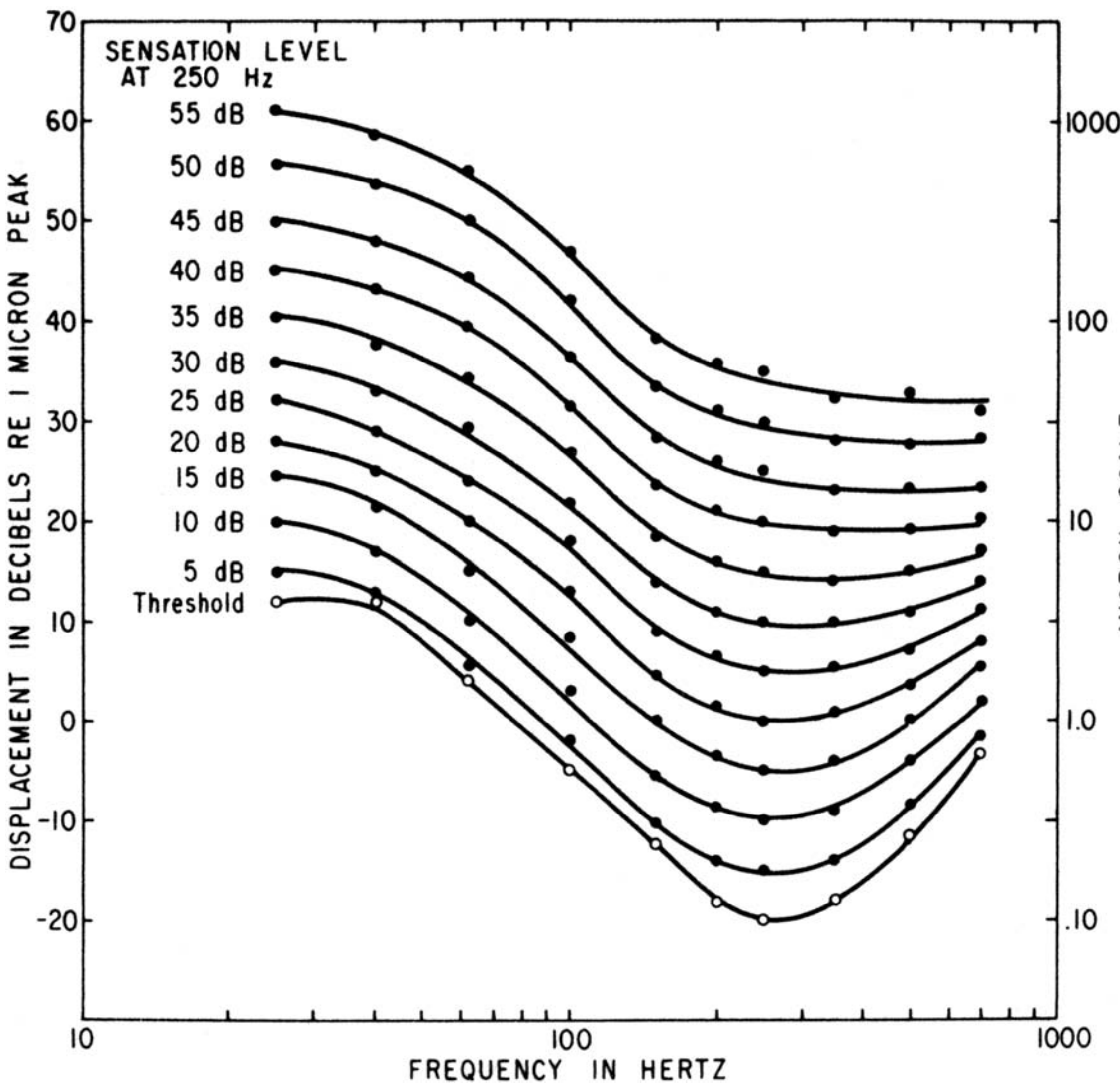


Figure 3.2 Equal-loudness contours of vibrotaction. Note that the curves do not flatten as intensity increases as do the Fletcher-Munsen curves of auditory perception. From Verrillo et al., *Perception & Psychophysics*, vol. 6, p. 371, 1969. Reproduced with permission from the Psychonomic Society. Copyright 1969, Psychonomic Society.

Vibrotactile *adaptation* occurs when exposure to a vibrotactile stimulus decreases sensitivity to properties of subsequent stimuli. Most psychophysical investigations of adaptation have focused on increases in the threshold of detection or decreases in the perceived magnitude of suprathreshold sensations, but a desensitization to other properties such as waveform or frequency would also fall under the category of adaptation. It should be noted that differentiating between adaptation and forward masking depends on experiment design [65]. A neurophysiological basis for adaptation exists, as it has been shown that high-intensity vibration causes mechanoreceptors to become less excitable, leading to an acute impairment of the sensitivity of skin [92].

Enhancement and *summation* are phenomena that may occur when two stimuli are presented sequentially in time (temporal enhancement or summation), or simultaneously at different loci (spatial enhancement or summation), whereby the presence of a second stimulus affects the perceived magnitude of the primary stimulus [65, 93]. Enhancement occurs when the second stimulus causes the first to increase in magnitude, and summation occurs when the sensations produced by two stimuli have been integrated without an increase in magnitude. Summation is exclusively a property of the Pacinian system, which integrates energy over both space and time [94].

3.2.4 Pitch

Pitch perception is such a fundamental aspect of musical experience that it seems to naturally command a dominant role in feedback, in both auditory and vibrotactile modes. Vibrotactile "pitch" is a term that highlights sensitivity to the rate of periodic stimuli, as it does in psychoacoustics [95]. The skin is sensitive to frequencies ranging between 0 Hz (an *indentation stimulus*) and about 500 Hz, and is maximally sensitive at about 250 Hz [96]. Unfortunately, the neural coding mechanisms for signaling information about the frequency of vibrotactile stimuli are not well understood. In audition, pitch is almost exclusively dependent on stimulus frequency; amplitude and waveform have comparatively little effect on the perception of tones [97]. In contrast, vibrotactile pitch is complicated by several factors, such as the multichannel nature of cutaneous mechanoreception [98], amplitude of skin displacement [99], stimulus duration [100], and body locus [101]. A detailed theory of vibrotactile pitch would be very useful for interaction design, but attempts at developing such a theory have fallen short of proposing a comprehensive translation scheme from auditory pitch.

The first biological system studied as a candidate for the mediator of vibrotactile pitch perception was the peripheral nervous system. The *frequency following response* (*ffr*) of an afferent unit refers to the fidelity of the entrained neural firing pattern to a periodic stimulus [76]. Indeed, afferents that are presented a periodic stimulus fire in a pattern that is also periodic as well as phase-locked to the stimulus, meaning that peripheral nerves represent vibration with an electrical signal of the same frequency [98]. The fact that the frequency following response of peripheral nerves seem to mirror periodic stimuli suggests that the skin is quite sensitive to vibration frequency. However the limited ability to perceive vibrotactile pitch implies that a process is going on "downstream" that does not preserve this signal. Recent research on brain activity has shown that the number of cortical firings during vibrotactile stimulation is the result of the product of the frequency and amplitude of the periodic stimulus, which also corresponds to the *root mean square* (*rms*) of the velocity of the vibration [99]. This finding is quite significant because it quantifies the relationship between vibration frequency and amplitude.

Vibrotactile frequency discrimination, concerned with the *jnd* between pitches and the number of discriminable pitches in the vibrotactile range, is complicated by several other factors. The *jnd* has been shown to increase with frequency [35], leading to the logical design guideline that the higher frequency range should use wider pitch bands than the lower range. In hearing, the size of the *jnd* for frequency discrimination within the range of musical sound is very small [97]. With vibrotaction, however, the *jnd* is comparatively large and varies substantially through different frequency ranges. At about 20 Hz, the *jnd* is only 4 Hz, but at 300 Hz, it is roughly 60–75 Hz. Moreover, if frequency is held constant while intensity is varied, a noticeable shift in pitch may also be perceived [65]. As stated above, sensory magnitude also shifts as frequency is changed. However, when subjective magnitude is made equal, the number of discriminable pitches is still dependent on whether pitch is considered as relative or absolute [102]. In [91] it is alleged that up to nine discrete pitches should be used for symbolic information, and [27] hypothesizes between eight and ten discriminable pitches, but neither of these guidelines seem to be based on formal studies. It was shown in [103] that three or four vibrotactile pitches could be differentiated, with wide variability among subjects.

Several researchers have thus proposed that the high interdependency of frequency and amplitude suggests they be considered a single vibrotactile stimulus parameter [102]. Specifically for musical applications, it has been claimed that the only musical parameters representable by vibration are timing, amplitude, and spectral weighting (relative amount of harmonic content), because frequency discrimination is so complex that it confounds a straightforward approach to defining vibrotactile pitch [34]. Yet vibrotactile pitch exhibits an important similarity to auditory pitch: within certain ranges, frequency discrimination fits a critical band model [104]. Most significantly, it has been shown that certain frequency ranges give rise to distinct subjective sensations (see Section 3.3). This seems to imply that, while vibration frequency does not directly correlate to vibrotactile pitch, it nevertheless can be exploited for musical feedback as long as it is understood that pitch must be considered as dependent on intensity and that sensory quality varies dramatically with frequency.

3.2.5 Waveform

It might be tempting to correlate the waveform of a vibrotactile stimulus to the "timbre" of a musical tone or event. However, complex waveforms are not distinguishable by vibrotaction in the same way as they are in audition — waveform plays an important role in texture perception, but sensitivity to complex periodic vibration stimuli is considerably limited. Still, there are vibration signal waveform attributes that can be distinguished, viz. amount of harmonic content, periodicity, and modulation in certain ranges [105]. It has been reported that the progression from sine wave (periodic, no partials) to square wave (periodic, many partials) to noise (non-periodic) is subjectively sensed as a spectrum ranging from "smoothness" to "roughness" [27].

This suggests that there may be a sensation of vibrotactile "brightness" that can be targeted by varying periodicity and harmonic content in a vibration. In addition, there is a sensitivity to amplitude modulation, or "warble tones", suggesting there is an ability to perceive the vibrotactile equivalent of vibrato [24].

3.3 Tactile sensory coding

Vibration display is limited by the capability of the vibrotactile system to pick up information presented to it (its "bandwidth"). It has been claimed that the rate of receiving information through cutaneous sensation is about one percent of that of audition [106, 18]. Although newer research is pointing to the possibility of augmenting communication rates using multichannel vibration displays and pattern learning [90], a coarser frequency response and limited sensitivity to harmonic content do suggest that skin has a lower bandwidth than audition. An accurate model of vibration perception is the key to designing a vibrotactile display that uses bandwidth effectively.

Cutaneous sensitivity differs from hearing because there are several more channels that mediate sensory stimuli at the afferent level. The four-channel model of vibrotactile perception asserts that there are four perceptually independent vibration channels, separable by several of the qualities of a vibration stimulus (for example, frequency) [107]. The P (*Pacinian*), NP1 (*non-Pacinian 1*), NP2 (*non-Pacinian 2*), and NP3 (*non-Pacinian 3*) channels are mediated by the FA2, FA1, SA2, and SA1 afferents, respectively (see Table 3.1). Due to the multichannel nature of mechanoreception, certain ranges of frequency are subjectively described as having distinct qualities from one another. In qualitative studies, subjects have reported stimulation of the P channel as "vibration", NP1 as "flutter", NP2 as "buzz", and NP3 as "pressure" [78]. It is important to note that, while all of these channels may be activated by a vibration stimulus, they are not necessarily specialized for that purpose. For example, the perception of a rough surface when the fingertip is moved along it is facilitated by complex microvibrations of afferent nerve fibers. However, some of these nerve fibers would not fire in the presence of an actual vibration stimulus. Vibrations are perceived and recognized specifically as such by the population response and firing patterns of the activated mechanoreceptors.

The human vibrotactile system involves a complex interplay between a vast number of perceptual variables, making it difficult to unravel the mechanisms involved in musical vibrotaction. This chapter has reviewed some of the neurophysiological and psychophysical issues relevant to vibrotactile interface design. The following chapter presents a software synthesizer based on this research.

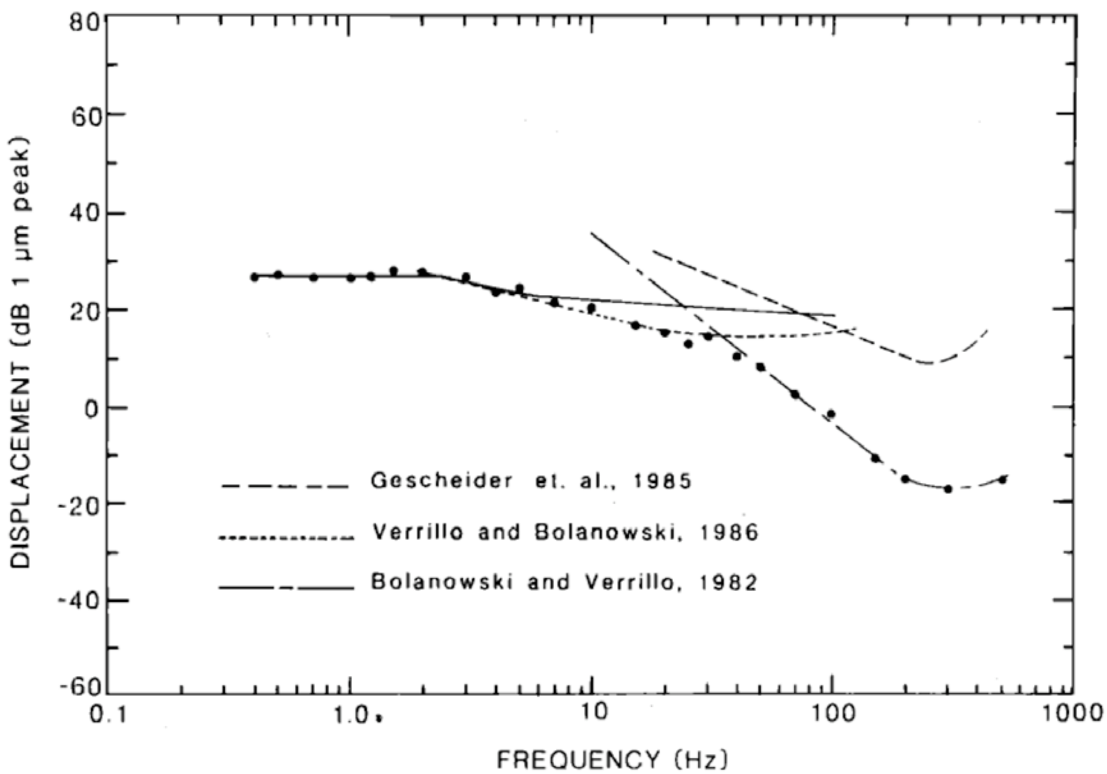


Figure 3.3 The threshold-frequency characteristic across the four channels of mechanical touch sensation, with each line representing a different channel. The data points indicate the absolute threshold for detection at the base of the thumb using a large contactor. Reproduced with permission from Bolanowski et al., *Journal of the Acoustical Society of America*, vol. 84, no. 5, p. 1691, 1988. Copyright 1988, Acoustical Society of America.

Table 3.1 Psychophysical vibration channel characteristics

Psychophysically defined channel	**P**	**NP1**	**NP2**	**NP3**
Full name	Pacinian	Non-Pacinian 1	Non-Pacinian 2	Non-Pacinian 3
Physiological type[a]	FA2	FA1	SA2	SA1
Adaptational property[a]	Rapid	Rapid	Slow	Slow
Receptive field size[a]	Large	Small	Large	Small
Putative receptor structure[a]	Pacinian	Meissner	Ruffini	Merkel
Fiber innervation density (per cm^2)[b]	21	140	49	70
Subjective sensation[a]	“Vibration”	“Flutter”	“Buzz”	“Pressure”
Spatial resolution[c]	Very poor	Fair	Poor	Good
Frequency range (Hz)[a]	35–500	3–35	80–500	0.4–3.0
Prime sensitivity range (Hz)[a, d]	250–300	25–40	150–400	0.4–1.0
Shape of frequency response function[a]	U-shape	Flat[e]	U-shape	Flat

[a] [78]
[b] [108]
[c] [109]
[d] Defined as best frequencies to lower threshold of perception
[e] Includes a notch at 30 Hz

Chapter 4

Software implementation

A key contribution of this research is a software synthesizer that models the four channels of mechanoreception (see Section 3.3). This chapter begins by applying psychophysiology to outline the necessary components of a vibrotactile synthesis framework, after which a description of the audio feature extraction process and vibration signal conditioning is described.

4.1 Modeling mechanical touch

The psychophysical basis of vibrotactile perception can be used to develop a methodology for vibrotactile feedback synthesis. Because the vibration feedback signal will be divided into component sensations amongst the four channels of mechanoreception, an investigation into the role of each channel can yield design guidelines for vibrotactile feedback tailored for cutaneous display.

4.1.1 P

The P channel might be said to be the one most relevant to our discussion, because the Pacinian system has several key similarities to audition (see Sections 3.1 and 3.2). Higher frequencies (35–500 Hz) that are felt as a “hum” or “buzz” engage this channel, which is thought to be the system most directly responsible for perception of periodic cutaneous stimuli. There is evidence that this channel integrates stimulus energy over time [105]. It has a U-shaped equal-sensation contour which does not flatten significantly as intensity is increased, and peak sensitivity occurs at about 250 Hz [35]. It may thus be beneficial to filter feedback targeting the range of the P channel to account for its U-shaped frequency response curve. Because the magnitude of the sensory response is directly dependent on the velocity of the stimulus, building an accurate filter would require a translation from sound intensity to a measure of spatial skin velocity. The filter implemented for this project is instead based on informal subjective reports of equal sensation magnitude.

4.1.2 NP1

FA1 receptors are specialized for grip control (see Section 3.1), which plays a very important role in object manipulation, and thus in the playing of a musical instrument. However, the FA1 is also responsive to low frequency vibrations, suggesting its role in musical performance may be twofold. Its frequency response is within the lowest range of musical frequencies, implying the role of the NP1 in musical vibrotactile perception is significant but is probably less prominent than that of the P channel. FA1 afferents innervate the human fingertip with the highest density, causing the NP1 to be twice as "sensitive" as the next most innervated channel, the NP3 (see Table 3.1). If innervation directly affects perceived magnitude, a fingertip stimulus in the NP1 range (between 3–35 Hz) should account for this heightened sensitivity; if all vibration channels are to be engaged equally loudly, average vibration intensity should be de-emphasized in this frequency range. A flattening function is not vital because the response of the NP1 is naturally flat, excluding a "notch" at 30 Hz. For a more accurate model it may be reasonable to include a peak filter at 30 Hz to remove this nonlinearity. In this implementation, a peak filter was not included; rather, a linear negative gain function was applied to the signal in the NP1 range. It should also be noted that the NP1 has been found to be particularly well suited for encoding complex waveform [105], suggesting that modulation might be picked up by this channel as well.

4.1.3 NP2

The NP2, which mediates lateral skin stretch, also responds to vibration. Its frequency following range (80–500 Hz) lies within that of the P channel, but has a high threshold characteristic, making its role in vibrotactile coding difficult to discern [95]. However the four-channel model implies that a vibration program can engage this receptor structure with suprathreshold stimulation, allowing the NP2's unitary subjective sensory quality to serve as a viable mediator of musical feedback. Because mechanical stimulation of the NP2 necessarily activates the P channel well above its threshold, crosstalk is inevitible. This raises some interesting questions about what kind of musical information could be displayed to the NP2. However, the actuators used in this implementation are neither accurate nor powerful enough to directly engage the NP2.

4.1.4 NP3

The NP3, whose primary function is to encode surface features such as shape and edge (see Section 3.1), certainly plays a major role in haptic perception during musical instrument performance. With regards to periodic stimuli, it is chiefly responsive to pressure or very low frequency periodic skin displacement (0.4–3 Hz). It is imaginable that a contactor could be used to display information to the NP3 through the use of "step functions" (multiple levels of sustained pressure), and at the same time display periodic stimuli. However, the actuators used in this project cannot produce a high-amplitude, sustained offset function above the NP3 threshold. A transducer that combines this ability with vibration capabilities would be an excellent tool for vibrotactile feedback design.

4.2 FA/SA

A model of vibration perception dubbed FA/SA ("fasa") has been created in the *Max/MSP* programming environment [110]. Short for "Fast Afferent, Slow Afferent", FA/SA is unique because it performs signal processing for two feedback modalities:

a stereo audio channel and a vibration channel (see Figures 4.1 and 4.2). It includes adjustable parameters that allow an instrument designer to control vibrotactile feedback in a perceptually meaningful way, allowing vibration display to be managed at a higher level than tactile perception modeling.[1]

4.2.1 Audio feature extraction and mapping

FA/SA first synthesizes sound based on gestural input, and then synthesizes vibration based on the sound signal. An audio analysis layer extracts psychoacoustical measures from the audio signal, comprised of *noisiness*, *brightness*, *loudness*, and *onset*. These variables have been mapped to vibrotactile perceptual parameters, consisting of *pitch*, *loudness*, *brightness*, and *envelope trigger*.

External objects presented in [112] are used to extract audio features. The *noisiness*~ object, which outputs a measure of spectral flatness, is mapped to vibrotactile brightness. The brightness of the vibration signal is varied with an equal power crossfade between a sine wave and a square wave. More tonality in the sound is thus represented with a richer harmonic spectrum in the vibrotactile domain.

The *brightness*~ object calculates spectral centroid, a metric that has been shown to act as a determinant of drum part separation in percussion listening [113]. The spectral centroid is scaled between 40 Hz and 400 Hz, with the result that the different drum parts in the breakbeat loop are represented by relative changes in vibrotactile pitch aimed at the P channel. It will be recalled that the *jnd* of vibrotactile pitch is smaller in the lower ranges (see Section 3.2.4); thus a logarithmic frequency scale is applied to assure lower pitches include fewer frequencies than higher ones. Of the drum loops tested, the typical distance between the lowest vibrotactile pitch and the highest is about 100–300 Hz.

[1]There is a choice that must be made regarding the range of vibrotactile sensations to be fed back through the interface. One option is to restrain the sensations to those that are acoustical in nature, drawing from studies on acoustic musical vibrotaction (e.g., [111, 35]). The other option is to utilize the entire comfortable range of vibrotaction above the threshold of detection. As has been stated previously, the prototypes presented in this thesis are not intended to be acoustical vibration simulators; thus the latter option was chosen in order to experiment with using as much vibrotactile bandwidth as possible. See Chapter 6 for a detailed discussion of these issues.

The output of the *loudness*∼ object is mapped directly to the amplitude of the vibration waveform. The narrower dynamic range of vibrotaction was accounted for in the post-processing stage with a peak compressor.

The onset detection external *bonk*∼ [114] is used to drive a simple envelope generator with an adjustable decay to create the sensation of discrete vibrotactile pulses with the above characteristics. Because envelope is time-dependent, adaptation, summation, enhancement, and temporal masking play a significant role in perception; dynamic qualities such as the *adsr* (*attack-decay-sustain-release*) gain function of vibrotactile events should be adjusted to take these into account [115]. Because stimuli in the range of both the P and the NP2 channels may be masked if their duration is less than 200 milliseconds [78], the decay characteristic of the vibrotactile events is lower-limited by 200 ms.

4.2.2 Signal conditioning

After a vibrotactile event is synthesized with the above characteristics, frequencies less than 0.4 Hz and greater than 500 Hz, which are out of the vibrotactile range, are removed with a bandpass filter. The signal then passes through a second filter acting as a frequency flattening function to compensate for the heightened sensitivity to lower frequencies (NP2), and the nonlinear response of the higher frequencies (P). Dynamic range is then reduced using the *omx.peaklim*∼ object so that quieter vibrotactile events are not lost. Extra-vibrotactile frequencies are then filtered out again.

This chapter has presented a software vibration synthesizer that takes into account the psychophysics of vibrotactile perception. The following chapter presents two vibrating digital flutes prototypes.

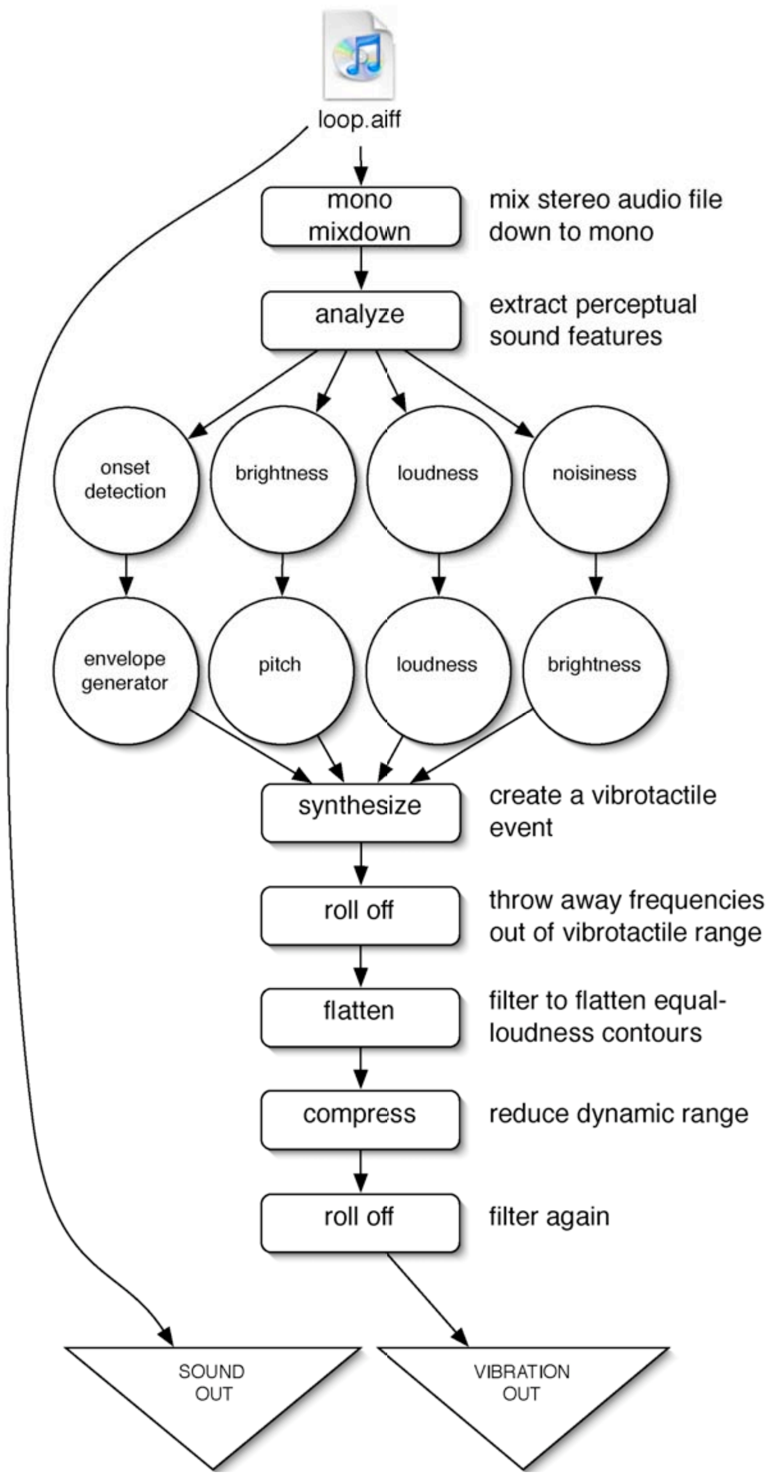


Figure 4.1 Flow chart illustrating audio feature extraction and mapping of the FA/SA synthesizer.

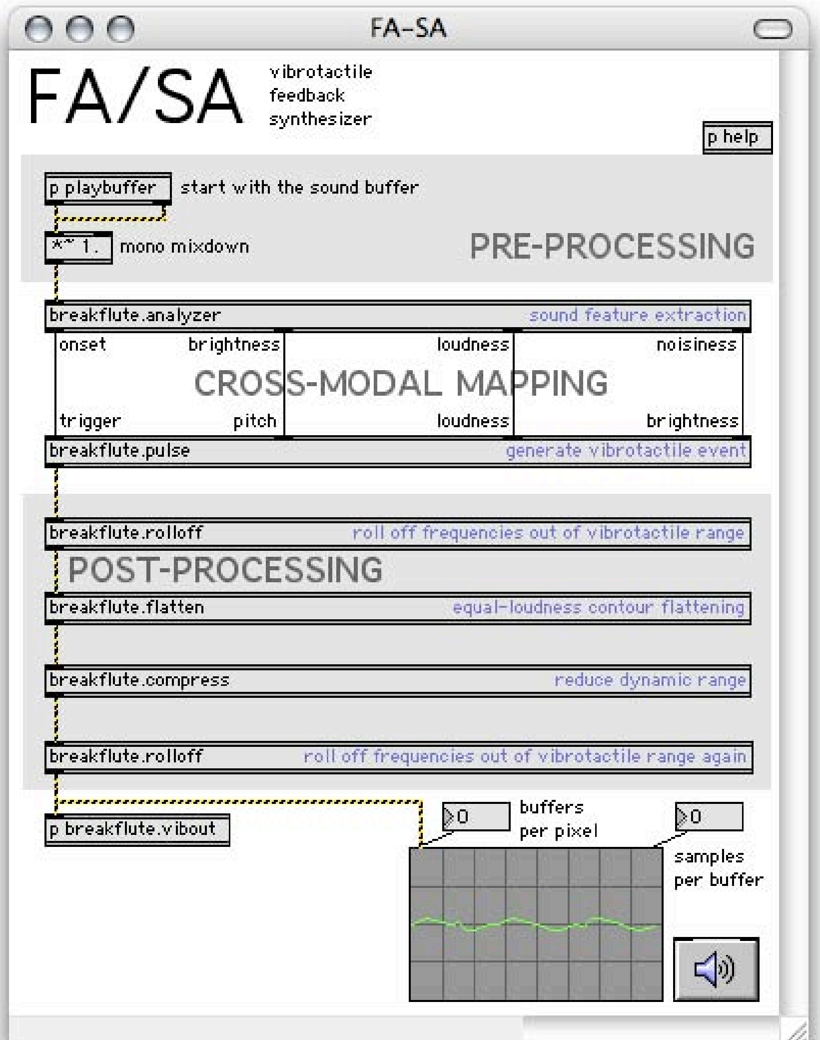


Figure 4.2 The FA/SA patch.

Chapter 5

Hardware prototypes

Two vibrating flute prototypes were constructed. The Touch Flute was the first, with the goal of incorporating a simple two-way sensory feedback loop into a wind controller to experiment with control and vibrotactile feedback. The Breakflute was then constructed to utilize the FA/SA software while also providing a player with musical control. This chapter discusses the process of design and fabrication of these prototypes, as well as findings that could be used to guide future design of similar devices.

5.1 Touch Flute

The Touch Flute was a *dmi* constructed to test a preliminary design approach for a vibrotactile wind instrument. It provided a limited amount of input control, but displayed both sound and vibration. For the input stage, a portion of a key assembly removed from a clarinet was affixed to a plastic pipe, providing a player with two keys. (Note that two keys afford four key positions.) Inside the bore of the instrument, Hall effect sensors were positioned under the keys, a key position sensing technique used previously in the Hyper-flute (see Section 1.3.3). It was found that the vibration actuators on the keys, which contained a permanent magnet, were sufficient to activate the Hall effect sensors, so that a separate magnet was not required. Embouchure gesture was approximated with breath pressure; the mouthpiece contained a plastic tube leading to a Fujikura *XFPN* air pressure transducer [116]. The analog voltage output by the air pressure sensor and the Hall effect sensors were passed to an *a/d* converter called the *AtoMIC Pro* [117], where they were sampled and converted to *midi* messages. The messages were then sent to a computer over a serial port to Max/MSP.

The mouthpiece of the Touch Flute delivered vibrotactile sensation to the player's lips using an Audiological Engineering *Skin Stimulator VBW32* [118]. Designed for sensory substitution applications for vision and hearing impaired people, the *Skin Stimulator* is based on voice coil technology but has been optimized for the vibrotactile frequency range, with a peak resonance of about 250 Hz.

For both sound and vibration feedback, a simple waveform generator was programmed in Max/MSP. One of four pitches could be selected with the keys, and the amplitude of the signal was controlled with breath pressure. The synthesizer allowed for experimentation with sine waves, square waves, noise, and pitch tunings. The sound signal was not processed to differentiate the audio feedback from the vibrotactile feedback; the same signal that produced sound was also sent to the actuators.

The actuators affixed to the clarinet keys were adapted from miniature voice coils designed to be used for in-ear loudspeakers (previously described in [119], to cite one of many examples). Miniature voice coils make convenient actuators because they are low-cost, high resolution, highly efficient, and easy to control. They are, after all, designed for musical applications. However, they are less resistant to interference from external forces exerted by the human body when compared to actuators with more inertia such as unbalanced motors or cylindrical contactors. Sure enough, the voice coils in the keys were found to provide very little sensation when used "out of the box". This was corrected somewhat by increasing the peak displacement and inertia of the diaphragm with the addition of a small mass load (a tiny ball of solder) in its center, a technique mentioned in [120]. In addition, a small audio amplifier was placed inside the bell of the instrument and used to boost the vibration signal. Even with these improvements, the player's fingers tended to dampen the output of the actuators; by pressing down on a key, the force exerted by the player's finger

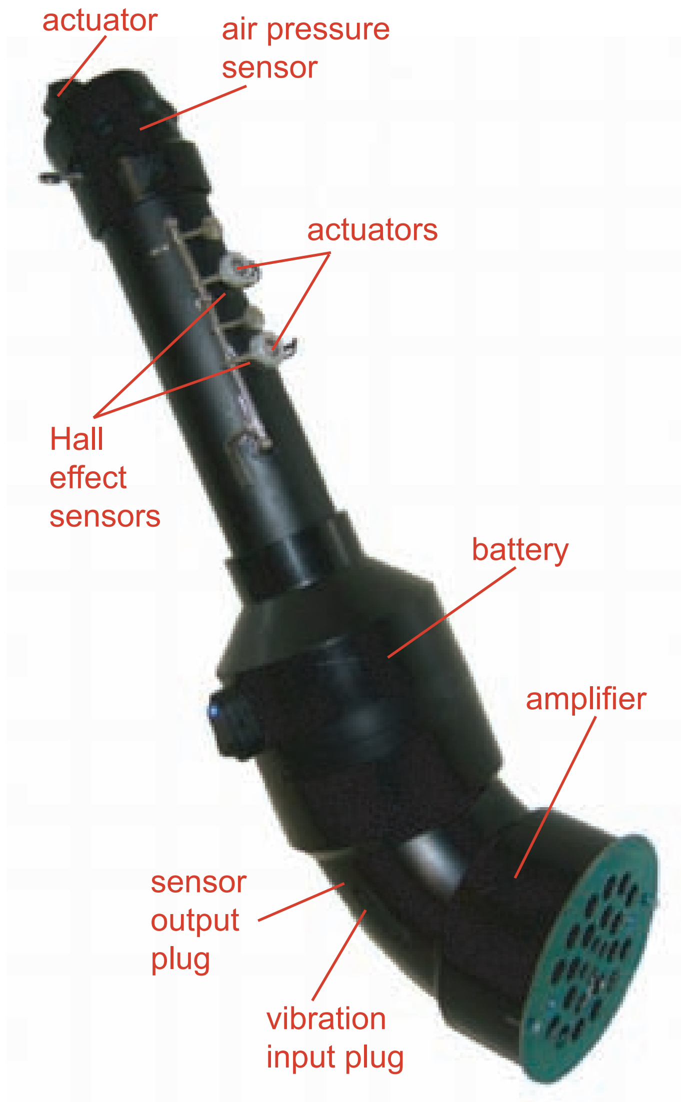


Figure 5.1 The Touch Flute. [3]

would effectively shut off the actuator and no sensation could be felt. The problem was finally resolved by recessing the actuator within a surrounding support. This was one of the most important findings from the Touch Flute and prioritized the optimization of actuator placement in the following prototype.

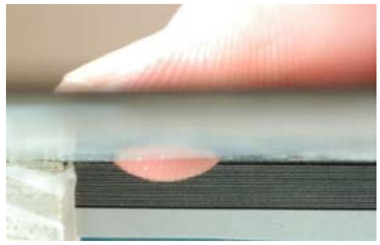
With four discrete pitches and only simple timbres, the Touch Flute was not very musically flexible. However, as a preliminary investigation the interface was quite successful. Though no formal experiments were conducted, people who felt the vibrotactile interface reported that it seemed “alive” and “responsive”. On the contrary, when the vibrotactile feedback was switched off so that only sound feedback remained, there seemed to be no question that the pleasure of feeling a vibrating instrument in the hands and mouth was lost. From a practical perspective, it was clear that loudspeakers held potential as actuators, but were somewhat fussy to work with. The clarinet keys separated the vibration from the bore of the instrument in a way that I found to cause an undesirable disconnect between the vibrations and the kinesthetic feedback from holding the instrument, so an open-tonehole model was used for the next prototype.

Skin extension through a tonehole

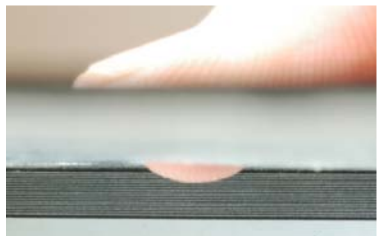
As mentioned above, modifying voice coils designed for loudspeakers for use as actuators is advantageous for several reasons, but poses problems due to the force exerted by fingers on the diaphragms. Voice coils are not backdrivable; contact with fingertips significantly alters their output. Therefore sensation is maximized if the actuator is placed at an optimal distance from the skin’s surface so that the skin is maximally stimulated by the actuator and the actuator is minimally dampened by the skin. The tactile response of a voice coil will be dramatically improved if placed just close enough to the skin to be felt.

Bearing this in mind, the question is raised of how far to position the actuator below the surface of the hole. Because the deformation quality of glabrous skin is similar to that of a fluid-filled sack [78], pressing on a tonehole causes the skin to extend down past the surrounding surface a distance that is determined by the pressure applied and the size of the hole [96]. To maximize the sensation provided by the voice coil actuators in the next prototype, it was necessary to explore the relationship between the size of a tonehole and the length that the skin of a fingertip extends down past the outer surface of the surrounding structure when it is pressed on the hole.

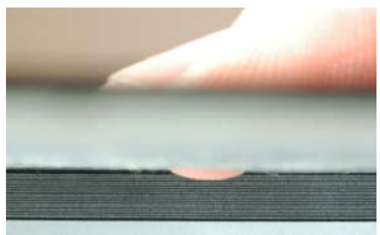
A stimulator with an integrated *non-zero-force indicator* would be necessary to place the actuator against the surface of the skin with the least amount of static pressure, and a *vibrometer* to sense the stimulator's position would allow for tuning of absolute skin displacement [76]. Without such advanced instrumentation available, the actuator system developed here does not account for at-rest static skin pressure, damping, or skin impedance. In an informal setting, three recorder players were asked to press their fingers down on a rigid 1 mm-thick metal surface with five drilled holes, measuring 6, 7, 8, 9, and 10 mm in diameter. Applied pressure was not measured; instead the players were asked to press with the amount of force they would "typically" use to cover a tonehole. Behind the metal surface, a card was placed with horizontal black lines spaced 0.2 mm apart (see Figure 5.2). A high-resolution photograph was taken as the index, middle, and ring fingers were pressed down on each hole. Counting the number of lines obscured by the fingertip gives skin extension past the 1 mm-thick metal surface within 0.2 mm. The importance of considering hole size when placing the actuators is clearly shown in Figure 5.3. Variability across fingertips was significant enough to indicate that actuator placement may be further improved by interface personalization; however, there was less variation amongst players and their individual fingers when the hole size was smaller, suggesting that if an interface is to be used by multiple players and not bias the effectiveness of the feedback to the use of certain fingers over certain toneholes, a smaller tonehole size should be used.



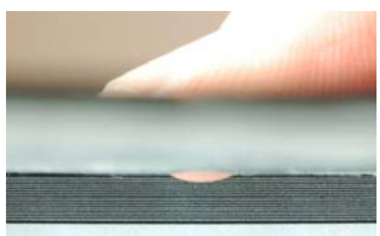
(a) 10 mm



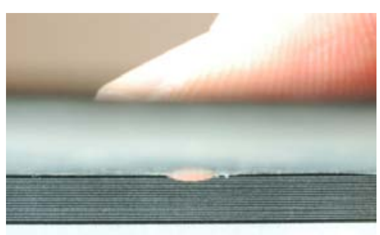
(b) 9 mm



(c) 8 mm



(d) 7 mm



(e) 6 mm

Figure 5.2 Vertical extension of the skin of an index fingertip, through holes of various diameters (marked).

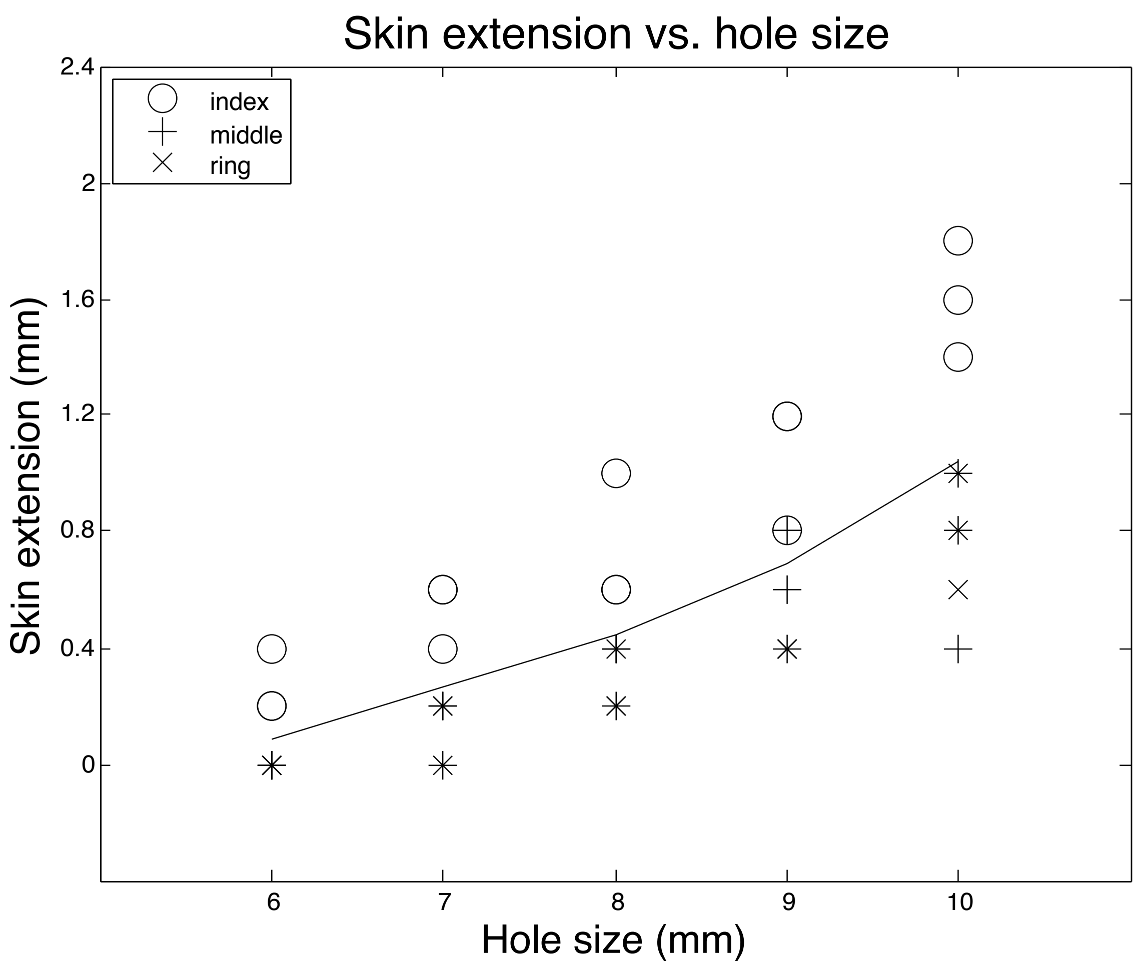


Figure 5.3 Hole size versus skin extension in three fingers on each of three different people. Because resolution was only 0.2 mm, some points overlap. The line represents average skin extension across all fingers.

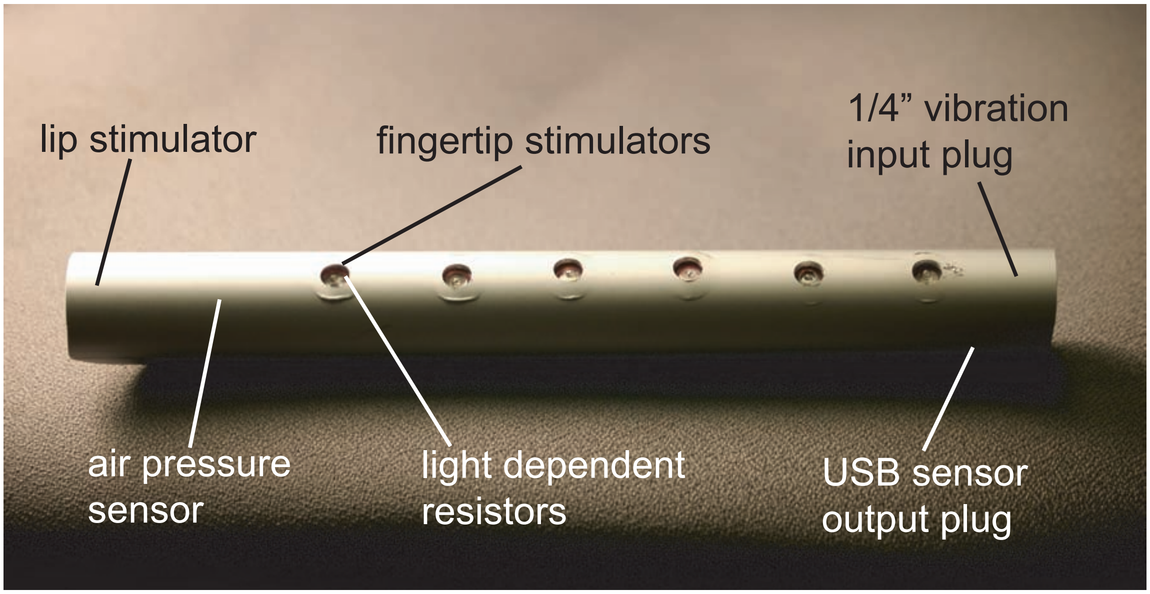


Figure 5.4 The Breakflute.

5.2 Breakflute

The Breakflute is made up of three major subsystems: a gestural control interface, a software synthesizer, and a vibrotactile display.[1] Weight was kept to a minimum by moving the current amplifier and conditioning electronics for the actuators out of the aluminum bore, with the hope of reducing inertia and low-frequency tactile sensations caused by manipulating the instrument. Six holes along the top of the bore and one hole on the bottom side for the thumb present the player with a flute-like open-tonehole fingering interface. Inside each hole, a modified loudspeaker is positioned to stimulate the fingertip covering the hole. The mouthpiece is a wooden structure for containing a *Skin Stimulator*, as this was found to be an excellent tool for lip stimulation in the previous prototype. The interface is driven with a single channel of vibration signal synthesized by the FA/SA software.

For sensing finger gesture, a small notch in the lower half of the tonehole was drilled and a *light dependent resistor* (*ldr*) was positioned underneath the notch.

[1] The vibrotactile display portion of the instrument has previously been presented in [121].

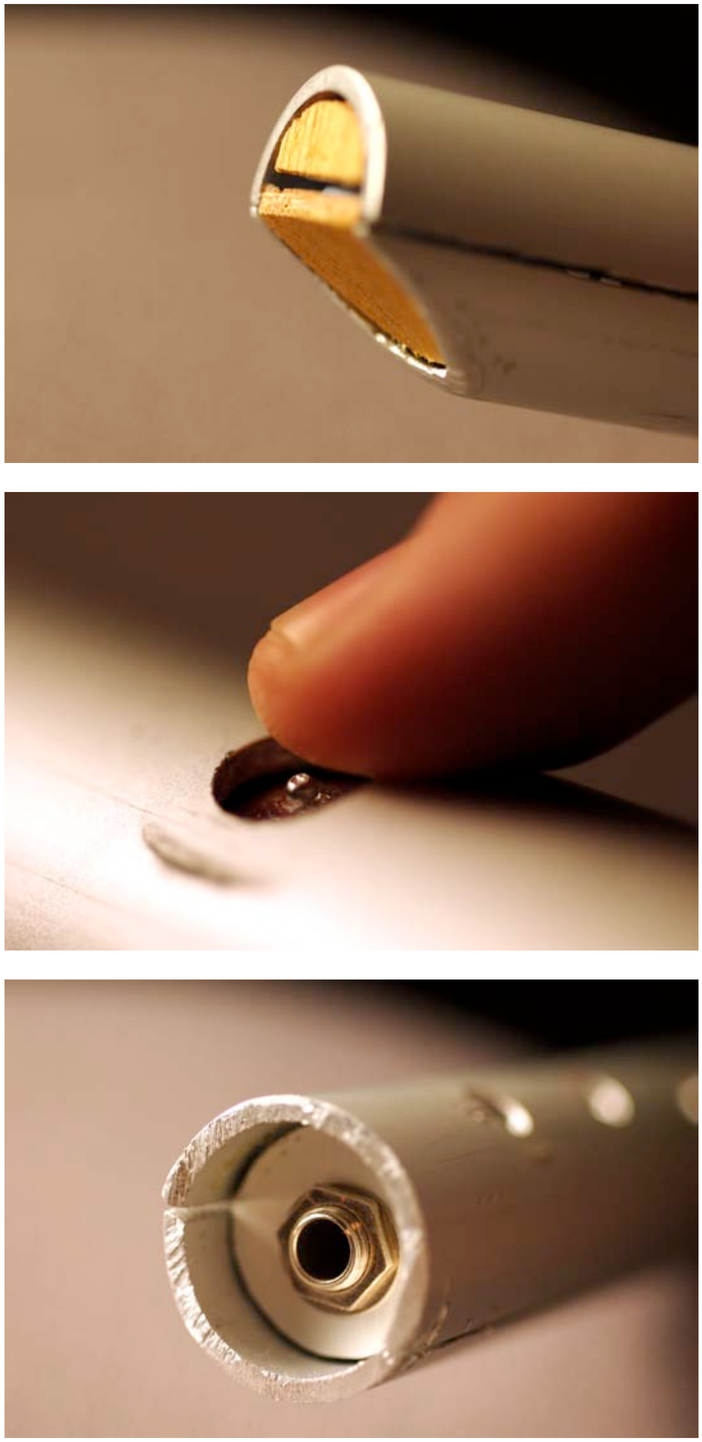


Figure 5.5 Closeup of vibrotactile components of the Breakflute. Top: the mouthpiece. The blue object just visible in the gap between the wooden pieces is the actuator. Middle: A tonehole with voice coil actuator. The small metal ball is a mass load which lowers the diaphragm's resonant frequency and increases inertia. Bottom: the 1/4" jack plug for vibrotactile feedback input.

Thus tonehole coverage is approximated as the amount of light entering the bottom end of the tonehole. Although sensitive to ambient lighting conditions, this technique nonetheless proved very responsive to fingering gestures. For breath control, an *XFPN* air pressure sensor was used once again. All of the sensors were connected to an Arduino *Mini* microcontroller board, which was in turn connected to an Arduino *Mini USB Adapter* [122]. Using the readily available *a/d* software for the Arduino platform, digitizing the signal from the sensors and sending it to Max/MSP as serial data was straightforward.

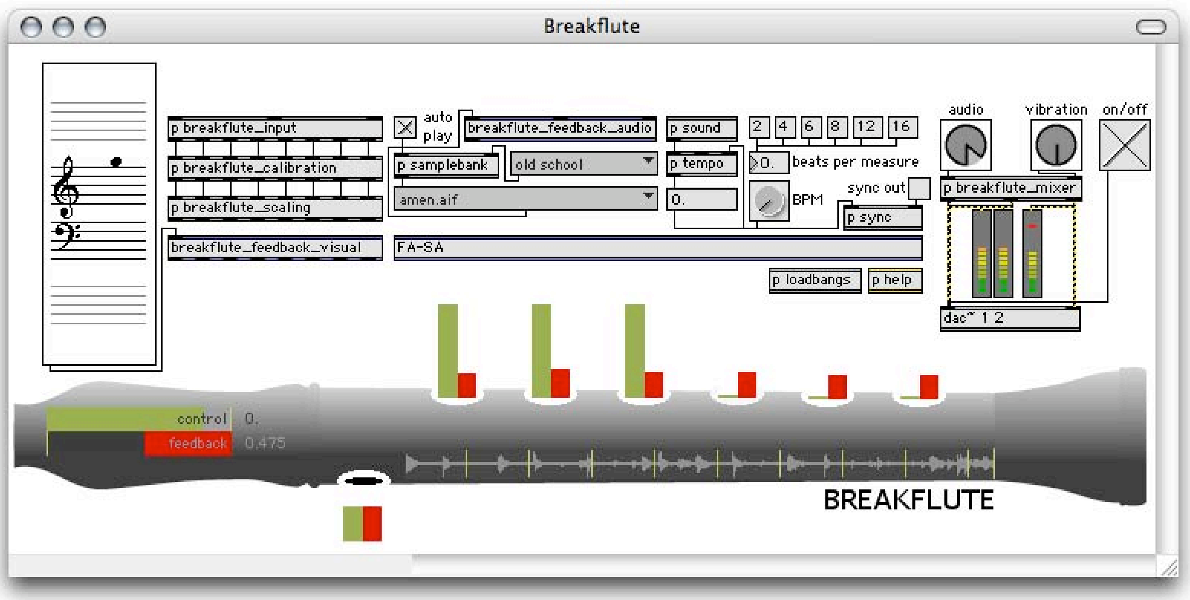


Figure 5.6 The Breakflute patch. The green sliders represent sensor data and the red sliders indicate vibration intensity.

To produce music, the sensor data are used to control a breakbeat slicing and arrangement sampler.[2] Each tonehole corresponds to a slice in the pattern. Tonehole coverage is mapped to the decay time of its particular slice. If a hole is entirely covered so that no light reaches the *ldr*, the slice plays normally. As a hole is slowly uncovered, the decay time of the corresponding slice is decreased; a totally uncovered

[2]See [17] and [123] for a discussion of breakbeat slicing techniques.

hole removes that slice from the sequence. Covering different combinations of holes plays different sequences of the breakbeat slices. The air pressure sensor is mapped to the cutoff frequency of a low-pass filter configured so that a small amount of breath pressure produces the full spectrum of sound, while stopping the breath prevents any sound from being output.

In this chapter, the design and construction of two prototypes of vibrating flute interfaces have been described. The next chapter discusses implications for digital musical instrument and vibrotactile interface research.

Chapter 6

Discussion

The incorporation of vibrotactile feedback into digital musical instruments presents some interesting issues for instrument design theory. This chapter will discuss some of these issues. The way in which the *dmi* definition relates to multi-modal feedback will be examined, followed by a discussion of vibrotactile devices as haptic interfaces.

6.1 Gestural control

The possibility for creative design of musical instruments has expanded out of the simultaneous development of new gestural sensing techniques and synthesis algorithms (see Section 1.2). The notion of "gestural control of sound synthesis" extends parametrical control of sound properties to the body. Parametrical control is included within, and afforded by, gestural input. It is gesture, not sound, that can account for the entire range and multiple modalities of musical interaction. Put succinctly, "force feedback interaction leads to a promising shift... from the concept of *parameter control* of signal based models, to the concept of an energetically coherent *gesture interaction* with a physically-based digital artifact" [124].

At the same time that the notion of gestural control reasserts the participation of a musician's body, it also defines a *mapping envelope* around the system that produces musical signal (such as a synthesizer), separating it from the repertoire of gestures used to control it. The mapping and remapping of gesture to sound parameters can be arbitrary, but is not always effective. From an engineering perspective, it is just as easy to build a new instrument based on a flute that varies pitch with air flow and varies sound intensity with finger positions as it is to build one that behaves in the opposite, traditional way. However, an analysis of the gestures used to control this experimental "backwards" flute would likely expose irreconcilable design flaws: for cognitive, psychoacoustic, and biomechanical reasons, the instrument would not afford skill-based musical performance behavior to the same extent as does the acoustic version with the "regular" mapping. The reason for this is that music is based on concrete phenomena, including the dextrous excitation and manipulation of an acoustic resonance, movement through space, and the short-term memory of component auditory and tactile sensations. Mapping strategies for electronic instruments fill the role normally played by the natural physical laws of force and resonance in acoustic instruments. Thus the abstraction of mapping parameters is a direct contradiction of the human experience of instrumental music as a physical interaction. The notion of a *dmi* offers one possible solution to this problem by "freezing" a particular mapping configuration, and declaring that an instrument is defined in part by its mapping. Change the mapping, and you have a new instrument [4].

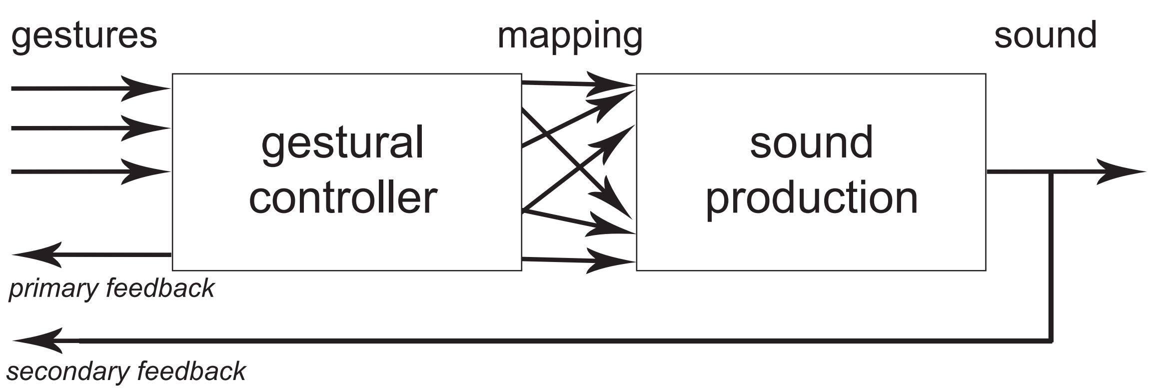


Figure 6.1 The original *dmi* model. [4]

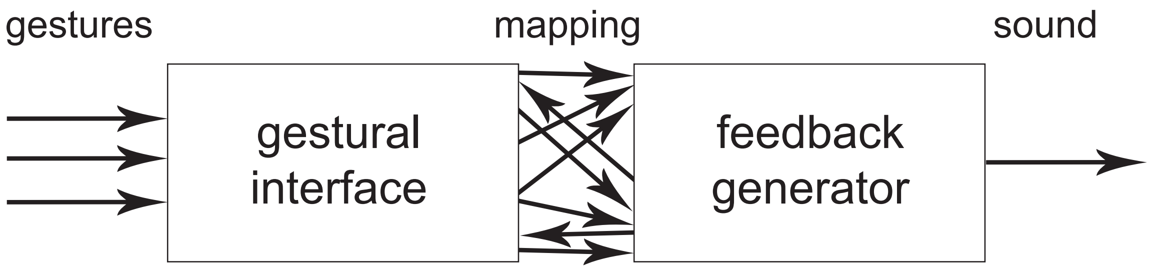


Figure 6.2 The *dmi* model, revised.

As new digital instruments tend toward becoming self-contained devices with multi-modal feedback, perhaps a revised *dmi* definition would be concerned with "gestural control of musical feedback", avoiding the prioritization of one mode of feedback (sound) over another. Indeed, the definitive success with which deaf people can use vibrotactile feedback to perform music [18, 125] brings to the forefront the question of whether sound is even a defining characteristic of musical feedback. In the revised model, "gestural controller" is replaced with "gestural interface", to better accomodate the likelihood that sensors and actuators are both present in the device. The mapping envelope is traversed bidirectionally by musical feedback in multiple modes (e.g., sound, vibration). The "sound production" block has been relabeled "feedback generator", to better represent feedback in multiple simultaneous modes.

6.2 Feedback typologies

Feedback is characterized in many different ways. This is because the word "feedback" is used in musical situations as both a metaphorical and a literal concept. Metaphorically, the application of human-computer interaction (*hci*) principles to gestural control systems has resulted in the word being applied to any information perceptible by a user about the internal state of the system, regardless of whether this signal is actively used to monitor and stabilize the sound output. At the same time, "feedback" is also used to describe output signal such as the music produced by a synthesizer, which becomes literally self-stabilizing through the interaction with the gestures of a performer. The three characterizations of feedback that will be discussed in this section are as follows:

- primary/secondary [126]
- passive/active [127]
- inherent/augmented [128]

Primary feedback refers to that which is provided by the gestural interface itself, including how it looks (visual), how it feels when interfacing with the body (tactile-kinesthetic), and the incidental sounds produced by the movement of keys and mechanical parts (auditory). *Secondary feedback* refers to the sound produced by a digital component, including, but not limited to, a sound generator. There is an assumption built into this distinction regarding the *role* of the feedback signals. Using the word "primary" to encompass all of the percepts "provided directly by the input device" would seem to indicate that the gestural device provides data for the most immediately deterministic stage of feedback processing undertaken by the player. In contrast, the musical output of the synthesizer being termed "secondary" implies that, because it arises out of an abstract mapping layer, the music is less characteristic of the interaction than is the input device itself. This distinction can be quite useful for describing systems in which mapping is arbitrary. However, the mapping component of a *dmi* would ideally not distort the system's behavior in any perceivable way; rather, the user's internal model of the instrument would indeed be based on this configuration, as is the case with acoustic instruments. Moreover, digitally synthesized vibrotactile feedback does not fit easily into either category, as it depends on a mapping scheme but is also a physical property of the gestural interface. As vibrotactile feedback is incorporated into gestural control systems, the distinction between primary and secondary feedback will obsolesce.

In another typology, the term *passive feedback* is used to refer to feedback provided through the intrinsic qualities of a physical interface, while *active feedback* refers to that which is produced by the system itself. This is similar to the primary/secondary typology with the notable exception that focus is shifted away from the role of feedback and toward how it relates to *user agency*. Passive feedback *reflects* the variation of input parameters, such as the variation in tension of a string as it is plucked, whereas active feedback *is generated* by the system as a result of being controlled by the player. Usually, active feedback signal is synthesized digitally and output through a transducer such as a loudspeaker or an actuator. Acoustic vibrotactile feedback would thus be considered passive, but digitally synthesized vibrotactile feedback would be active. Presuming that the acoustic and the digital varieties of vibration are indistinguishable from a psychophysiological point of view, the passive/active typology has little to offer a functional or phenomenological analysis of vibrotactile feedback.

It is interesting to note that the slash in both of these typologies (primary/secondary, passive/active) functions as a symbol for the mapping envelope.

A third way feedback can be characterized, which contrasts with the previous two approaches because it does not necessarily imply a disconnect between control and output systems, is as *inherent* or *augmented feedback*. The distinction is made by examining how the feedback relates the interactor to the task. Feedback that is inherent is perceived as being task-intrinsic, whereas augmented feedback incorporates external information. Acoustic instruments display inherent feedback because inherent musical feedback is defined by interaction with acoustic instruments. It follows that, for the trained acoustic performer, vibrations emanating from an acoustic instrument are perceived as inherent feedback, and vibrations that do not arise during acoustic playing could be considered either as augmented feedback or noise. With a *dmi*, however, the issue becomes complicated because the capabilities of vibrotaction extend beyond acoustic musical experience. "Inherent vibrotactile feedback" may imply that the parameters of stimulation are within the range of acoustic vibrations, or more specifically that the vibration signal mimics the sound accurately according to a musician's pre-existing cognitive model of acoustic vibrotactile feedback. Augmented feedback, on the other hand, may lie outside of the musical range and exploit other modes of human information processing. This extra channel could be utilized in many different ways, such as vibrotactile communication amongst musicians in an ensemble, or for score-level cues.

There are plenty of applications in which the line between augmented and inherent feedback begins to blur, because it is not necessary to limit artificial vibrotactile feedback for a *dmi* to a simulation model. While it has been shown that vibrations in the frequency and amplitude ranges of acoustics increases controllability of certain musical processes [129, 130], other ranges and forms of vibrotaction may also be redundant and complementary to the musical output. For pedagogy, for example, a continuous error signal could be generated by deviations from practice directives. The signal may indeed be within acoustic vibrotactile range, and be tightly coupled to the musical output, but its reliance on score-level context means that it may not be considered a property of the *dmi* itself. On the other hand, if the musical score is considered a dynamic temporal property of the instrument (as is the case with "composed instruments" [131]), such an error signal would indeed fall under the inherent category. It becomes clear that, because feedback can be characterized by whether it is interpreted as an attribute of the system, the differentiation between inherent and augmented feedback depends on the definition of the performance system boundaries.

Ultimately, the effectiveness of augmented feedback in musical applications will turn on the capacity of the musician's bandwidth and whether it is wide enough to accommodate additional modes of information processing. However, it is certainly evident that if a goal of the design is to mimic the acoustic musician's experience with vibration, we can use acoustic vibration properties as a guide for producing sensory stimuli already familiar to the player; an understanding of the "inherent vibrational properties of resonating objects" plays an unavoidable contextual role in musical vibrotaction. Moreover, if an accurate simulation of acoustic vibrations is a design goal, vibrotactile stimuli outside of the acoustic range constitute noise (whether born of the physical interface or the vibration signal), and so must be minimized.

Vibrotactile feedback that is derived from musical sound, either with minimal signal analysis or by extracting high-level audio features to drive subsequent low-level synthesis parameters, tends toward the inherent pole. Because the FA/SA vibration synthesizer is continuously driven by musical feedback generated by instrumental gestures, offers no way to excite vibrotactile events independently, and does not incorporate score-level or environmental awareness, it is a generator of inherent feedback.

A new, supplemental approach to characterizing feedback is proposed here, termed *collateral* and *derivative feedback*, where collateral refers to feedback that is based on the control signal and derivative refers to feedback based on an ensuing signal such as the system's output. If feedback is based on control signal, stimuli in two perceptual modes arise from parallel mappings — one mapping of gesture to sound, and one of gesture to some other mode (such as vibration). The alternative is for the feedback signal to be generated serially by first synthesizing one feedback signal, and then processing it to synthesize another signal. This typology is useful because it describes the signal processing chain without commenting on the role, user agency, or informational content of the feedback. The vibrations of the Breakflute are derivative: vibrotactile feedback is synthesized by performing calculations on sound signal that is gesturally controlled.

6.3 Vibrotactile instruments as haptic devices

Using the definition for *haptic* presented in Section 2.1, it is debatable whether the Breakflute is an example of a haptic feedback device. One could argue that it is not, because the player of the Breakflute does not use her haptic perceptual system to form an internal representation of an external force field. Neither does the contiguous musical signal analogize to abstract symbolic data such as a vibration alphabet. So what do the vibrations of the Breakflute really *tell* the player?

This question is complex but is also of vital importance. By developing a cognitive model of vibrotactile information processing we can begin to exploit its potential for interaction design. But it is important to note that an interface may effectively and satisfactorily display feedback without directly addressing information transfer. As long as vibration is interpreted as a gesturally-variable feedback signal intrinsic to a physical object, it plays an active role in the player's haptic perception of the gestural interface. Thus vibrotactile feedback is not a subcategory of haptic feedback, but rather it defines a specific frequency and amplitude range within the wider haptic feedback signal.

Acoustic instruments do not communicate as much information via vibration as is possible using electromechanical stimulators — a flute bore is a single-channel resonator that cannot convey any additional information through vibration than it can by sound. The vibration signal it radiates is space-invariant, and correlated to acoustic output by a simple one-to-one mapping. Yet musicians rely heavily on vibrotactile feedback for realizing several aspects of their performance. This might imply that electronic instruments may easily be made more playable with the addition of a "crude" form of vibration feedback — the presentation of musical material to the skin somewhere on the body using a small loudspeaker as an actuator. This anecdotal approach is widely known to musical device designers, used for example in the *REXband* interactive musical installation:

> *We hid a small speaker next to each instrument; we found in early user evaluations that this addition significantly improves the user experience. Not only does having the sound source co-located with the instrument more realistically imitate the real instrument, the vibrations emanating from the speaker also provide subtle haptic feedback to the user... [t]he additional haptic feedback from the speaker vibrations reproduce the haptic feedback that is normally obtained when the instrument itself is the sound generator.* [132]

Thus it is not necessary to rigorously engineer a vibrotactile display in order for it to be effective. However, engineering does have its advantages. For a highly complex task such as musical control, music perception is better represented by a generative model that extracts high-order musical invariants and resynthesizes them as tactile stimuli. The approach presented in this thesis, which involves placing an actuator in a highly sensitive body location and conditioning audio output to model the mechanical aspects of touch, promises to further improve the design of vibrotactile musical instruments.

This chapter has discussed some of the issues that arise when considering musical vibrotactility within the context of gestural control and the nature of feedback. The next chapter offers some concluding thoughts about this research.

Chapter 7

Conclusions

7.1 Summary

This thesis presented an overview of some of the issues relevant to musical vibrotactile feedback design. First, the concepts of digital musical instruments and cross-modal mapping were introduced. Related research on cross-modal audio and touch interfaces, as well as on flute interfaces, was reviewed. In order to formulate a design strategy for a new instrument, the history of some of the most widely adopted invented instruments was briefly examined. This history seemed to suggest that new instruments may be more inspiring to work with when they had been conceived to play existing musics. It was thus decided that the new prototype would play recognizable music. Breakbeat sequences were chosen specifically in order to explore the plasticity of a cross modal-mapping from hearing to vibrotaction, and to experiment with a flute interface playing rhythm patterns.

Vibrotactile feedback was then contextualized with an overview of tactility. To help clarify touch terminology, a short list of common words and concepts was compiled. When two contradictory definitions for the same word were found to be in wide usage, effort was made to select the one that seemed more robust and applicable to this research. A brief history of tactility studies was presented, helping to explain some of the cultural influences on our modern concept of touch as a sense and a phenomenon. A subsequent examination of touch in language revealed that its effect on thought and experience seems limitless — when a person's touch sense is engaged, it is their body and their sense of existence that is engaged.

A summary of the psychophysiological aspects of mechanical touch was then provided. The physiology of the peripheral nervous system that mediates touch perception was reviewed, as well as research on the psychophysics of tactile perception. The way in which the nervous system codes tactile information was used as a basis from which to form a design approach for a vibrotactile device.

This approach was implemented with a software program that synthesizes vibrations. The FA/SA synth analyzes sound and manipulates it in a way that makes different components of the sound more easily discriminable by glabrous skin.

Two hardware prototypes were constructed as a part of this research: the Touch Flute and the Breakflute. The Touch Flute is a keyed instrument with limited control capability and outputs only simple tones. The Breakflute utilizes the FA/SA vibration synthesizer and affords considerably more musical control than its predecessor, outputting complex rhythm patterns as well as separate channels for sound and vibration.

Finally, some of the complex issues regarding feedback and interaction design were discussed. A revision of the *dmi* model was proposed in order to better accomodate the proliferation of musical devices that display multi-modal feedback.

7.2 Limitations

The FA/SA vibration synthesizer and the vibrotactile display in the Breakflute are important steps toward an accurate musical vibrotactile perceptual model, but the system is far from perfect. Measures have been taken to optimize actuator placement for this application (see Section 5.1). However, it was of course necessary to select vibration actuators while considering cost, availability, and complexity. Advanced vibrotactile stimulators that been developed for research on tactual perception could help eliminate the questions regarding how the Breakflute really engages the vibrotactile system. The software model of mechanoreception attempts to flatten the frequency response of cutaneous afferents, and accounts for the multichannel nature of vibrotactile sensation, but is not accurate. Furthermore, it does not begin to take advantage of the incredible bandwidth of vibrotaction — one could imagine an actuator system that better engages the entire range of vibrotaction working in concert with vibration signal that is synthesized using advanced psychoacoustic analysis, as well as metadata such as score cues, gestures of ensemble musicians, or fidelity to a previous performance.

The Breakflute is not suitable for rigorous musical training and performance. Using an air pressure sensor to capture respiratory gestures is not an adequate model of the breath interface on a wind instrument, as acoustic wind instruments respond to air flow rather than air pressure. A refined breath sensing technique would much improve the playability of the interface. The use of *ldr*s to sense fingering gestures also entails problems. Sensitivity to ambient light is incompatible with serious performance, as musical instruments should not need to be calibrated with every change of ambient lighting conditions. Moreover, the accuracy of the *ldr*s' representation of tonehole coverage is quite limited.

An additional problem was posed by the fact that the flute must be attached to both a current amplifier (for the vibration feedback) and a laptop (for the sensor interface). The presence of the two cables, which have stiffness and inertia, causes haptic noise and physical limitations that interfere with the whole-body gestures made by acoustic flute players. A wireless system is absolutely necessary if the fidelity of the somatic experience of flute playing is to be accurately modeled. Wireless sensor systems are beginning to become more readily available than they have been in the past, but a wireless system for vibrotactile feedback would need to transmit and receive in both directions. There is likely a host of challenges specific to wireless vibrotactile feedback that would be very interesting to explore.

7.3 Future work

With more time to focus on the engineering specifics of the sensor input system on the Breakflute, the instrument could be much improved. A sensor interface with specifications more tightly based on flute performance would make the interface much more flute-like. For example, the tonehole sensor would ideally measure not only proximity to one section of the hole, but complete tonehole edge coverage. A capacitive sensing technique such as the one implemented in [43] would be a very interesting upgrade to the current design. Moreover, as the biomechanics of instrumental performance become better understood, gestural interfaces like the Breakflute will be able to be designed to better enable skill-based performance. For example, motion capture and analysis could shed light on the ranges of motion utilized by flute performers. Sensors could then be selected to capture these parameters more accurately. With regards to the sound of the Breakflute, the breakbeat sampling, slicing, and rearranging algorithm implemented in the sound synthesizer is rather lacking in nuance. Enlisting the expertise of an electronic music composer might elevate the sound output of the Breakflute to a level that could hold the interest of a classically trained musician for the long term.

Eventually, standardized protocols for vibrotactile feedback, and specifically musical vibrotactile feedback, will be needed. Just as the *midi* protocol first allowed synthesizers to communicate on stage, so could vibrations be shared amongst several physical interfaces with a robust abstraction of cutaneous stimulation parameters. As vibrotactile feedback becomes utilized more often for everyday computer interactions, a standardized vibration display specification will be quite useful.

Systems for computer-mediated haptic interaction are being currently developed for a wide range of applications. Musical interaction is an excellent application for this research because it is a definitively tactual activity. The innate link between music and body movement is expressed when digital musical instruments vibrate their players.

Acknowledgments

I would like to dedicate this thesis to Jack and Janina, my parents, who always fought to give me every opportunity they could, *always*; to my wise sister Deborah for her brilliance and kindness; to my friends (back home, in Montreal, and worldwide) for keeping it interesting; and to Elizabeth, who came out of nowhere and showed me a deeper love.

Marcelo Wanderley, the research supervisor of great patience and extraordinary enthusiasm, introduced me to this field. He also taught me the true meaning of ambition and thoroughness, for which I could never be grateful enough. Bill Verplank, whose lectures and workshops are the reason I started studying haptics, fascinated me with the possibilities for creative design. Sile O'Modhrain has patiently answered my questions on several occasions, and her cogent writings are invaluable to my understanding of this topic. I was even lucky enough to know Joseph Malloch, who took his own journey alongside mine, as both a colleague and friend.

I would also like to express my appreciation for the inventors and composers who recognize the artistic potential of new technology. A few of my favorite mothers and fathers of electronic music include Bruce Haack, Pierre Henry, Bob Moog, Steve Reich, Clara Rockmore, Karlheinz Stockhausen, and Léon Theremin.

Thank you to all of my colleagues in the Music Technology area. Throughout my time at McGill, your friendship and support have enriched my studies and my life beyond words.

And finally, in this time of struggle I would like to solemnly acknowledge the courageous men and women who, during the course of this writing, have made great sacrifices so that I may study a subject rather than be one.

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