

Cutaneous Grooves: Composing for the Sense of Touch

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Abstract

What if the traditional relationship between touch and music was essentially turned upside down, making the tactile sensation the aesthetic end? This paper presents a novel coupling of haptics technology and music, introducing the notion of *tactile composition* or aesthetic composition for the sense of touch. A system that facilitates the composition and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body is described. Relevant work from disciplines including sensory substitution, electronic musical instrument design, simulation design, entertainment technology, and visual music is considered. The psychophysical parameter space for our sense of touch is summarized and the building blocks of a compositional language for touch are explored. A series of concerts held for the skin and ears is described, as well as some of the lessons learned along the way. In conclusion, some potential evolutionary branches of tactile composition are posited.

1. Introduction

In the traditional relationship between musician and instrument, the sense of touch is generally a means toward the end of creating sound. Whether bowing a string or blowing a wind instrument, the production of music has associated with it a certain “feel” which a player, albeit unconsciously, may use as a mechanism for controlling the production of sound. What if we were to turn this relationship upside down, making the tactile sensation the end? In other words, what if we viewed tactile stimuli as aesthetic artifacts and the skin as the receptor of composition, analogous to the way in which the ear is the receptor of music? Certainly our ability to feel rhythm would lead us to believe that the skin could make sense of a compositional form for touch.

Before proceeding to address these questions, let us consider the relationship that sound and touch have hitherto

exhibited in music. For the musician, sound and touch have always been tightly entwined. Haptic feedback – feedback to the musician’s tactile and kinesthetic senses – is an essential part of playing any musical instrument. The role of touch in music has in fact been studied considerably. This research includes studies on the tactile augmentation of non-traditional, gesture controlled electronic instruments (Rovan & Hayward, 2000), the haptic augmentation of computer-based models of traditional instruments (Gillespie, 1996), (O’Modhrain, 2000), (Nichols, 2002), and the use of haptic technologies as enabling devices for the creation of music (Cadoz & Lisowski, 1990). The interrelationships between sound and touch have been explored in non-musical disciplines as well, including *sensory substitution* and *simulation design*.

It turns out that our senses of hearing and touch have some fundamental similarities, specifically their ability to perceive and process vibrations. Research on the psychophysics of touch provides evidence that in certain respects the perceptual ranges and discriminatory limits are roughly compatible, at least overlapping, with those of hearing. Hence the skin should be able to process and ultimately appreciate what we will call a *tactile composition* similar to the way the ear does for music.

The work presented in this paper explores the notion of a tactile manifestation of music. Building upon the multimodal art form of visual music, a tactile composition was initially envisioned to occur in conjunction with music. In this light, it might be referred to as tactile music. The compositional potential of the tactile medium in its own right was quickly recognized, however. By viewing tactile stimuli as aesthetic artifacts, the prospect of a compositional language for the sense of touch arose. We began to think about the role that the fundamental dimensions of tactile stimuli might play in such a language.

In order to embark on this undertaking, a tool for tactile composition was needed. A system that facilitates the com-

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position and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body was designed. The most recent iteration of the system has taken the form of a computer-controlled body suit with thirteen embedded vibrotactile transducers: three small transducers evenly spaced along the length of each limb and one larger, low-frequency transducer against the lower back. A user wearing the suit would experience a tactile dance of vibrations undulating and jittering across the surface of his body, choreographed to music played through a pair of headphones.

In the remaining sections of this article we present a review of some relevant research from several disciplines including sensory substitution, electronic musical instrument design, simulation design, entertainment technology, and visual music. We summarize the psychophysical parameter space for our sense of touch and then address some issues surrounding the idea of a compositional language for touch. The design process for our tactile composition system is outlined. We describe the Cutaneous Grooves performances, a series of concerts for the skin and ears, and discuss some of the lessons learned along the way. In conclusion, some potential evolutionary branches of tactile composition are posited.

2. Background and motivation

It is important, at the first stirrings of this potential art form, to maintain an open mind and avoid constricting our inquiry to one paradigm or vein of research. In this section we identify some of the disciplines that have informed and inspired the conception of tactile composition as well as those that could potentially contribute to its continuing evolution. This section highlights some previous explorations into the connections between sound and touch.

2.1 Sensory substitution

Sensory substitution systems are, as their name suggests, technologies that gather environmental energy which would normally be processed by one sensory system and translate this information into stimuli for another sensory system. This class of systems includes tactile vision substitution, tactile auditory substitution, and teletouch (Kaczmarek, Webster, Bach-y-Rita, & Tompkins, 1991). Sensory substitution research is often concerned with the information processing capabilities of the skin and encompasses the design of tactile aids for the visually and hearing impaired.

The study of the tactile communication of speech is particularly relevant for tactile composition due to its foundation in a cross-modal translation from sound to touch. The body of research from this field has not only provided evidence for the feasibility of tactile composition, but also valuable insights into the interrelationship of audition and touch. This line of research has produced a class of devices known as *tactile hearing aids* aimed at providing deaf individuals

with an additional sensory channel for processing spoken language as well as environmental noise. These devices often make use of vocoding techniques and rely on the principle of *frequency-to-place transformation*, in which the location of stimulation on the skin corresponds to a given acoustic frequency region (Reed, Durlach, & Delhorne, 1992). Evaluations of existing tactile aids are a good source of information concerning the practical aspects of using tactile stimulators.

A rudimentary question regarding composition for the skin is: How complex can a tactile composition be? Even some of the simplest musical compositions involve relatively complex temporal, frequency, and dynamic variations. If it is to keep the feeler's interest, a tactile composition will need to exhibit some degree of complexity. Is the human haptic system capable of resolving and understanding the potentially complex, rapidly varying temporal and spatial patterns presented to the skin in the course of a tactile composition? It turns out that several studies have sought to determine the skin's ability to receive and understand complex systems of symbols, essentially *tactile languages*. Geldard (1966) describes an experimental language for tactile communication called Vibratese. Vibratese was comprised of 45 separate signals; three intensities and three durations were delivered to five different spots on the chest. Letters of the alphabet were each assigned a signal representing a unique combination of duration, intensity, and location. The Vibratese alphabet was mastered by subjects in mere hours. In fact, one subject was receiving at a rate about twice that of proficient Morse Code reception! The successful outcome of the Vibratese study illustrates the skin's astounding ability to cope with complexity.

The skin has been studied and used as an interface to various kinds of information. There has been a considerable amount of interest in the design of tactile navigation systems. Potential users of such systems include persons who are blind, pilots, astronauts, scuba divers – all of whom need to maintain spatial awareness in their respective unusual environments (Cholewiak & Collins, 2000). Research into the use of tactile warning signals in fighter plane cockpits was initiated as early as World War II, when pilots were shot down too often because they could not hear their wing commanders (Geldard, 1966).

2.2 Haptic feedback for electronic instruments

Since the earliest musical instruments, sound and touch have had an implicit partnership. In the traditional closed loop between performer and instrument, intention gives rise to gesture, gesture gives rise to sound, and feedback – including visual, auditory, and haptic/tactile information – is used to gauge the result. From the buzz of the reed to the bruise of the chin rest, kinesthesia and touch are a part of performance (Rovan & Hayward, 2000).

In many new electronic instruments, this haptic feedback loop is weak or almost absent. Thus there have been many

efforts to augment electronic instruments with artificial haptic feedback. Most of these involve simulating the “feel” of traditional instruments by augmenting their electronic counterparts with mechanisms for providing haptic feedback (Cadoz & Lisowski, 1990; Gillespie, 1996; O’Modhrain, 2000; Nichols, 2002). A second strand of enquiry has been to assess the potential for haptics in the design of instruments that don’t have a real-world equivalent. One interesting study (Rovan & Hayward, 2000) uses a vibrotactile stimulator to create artificial tactile feedback for use with a gestural electronic music controller. The results showed that significant perceptual advantages were derived with the addition of tactile feedback to the controller. Research on haptic feedback in musical instruments is particularly relevant because it provides insight into our perception of tactile stimuli in a musical context.

2.3 Creative applications

Tactile stimulation technology has surfaced in a relatively limited number of entertainment applications. It is increasingly common to find vibrotactile feedback in video game controllers. In addition, a handful of theme park rides and movies have integrated tactile components. For example, at Disneyland’s *Honey I Shrunk the Audience* attraction, puffs of compressed air are used to whip small pieces of rubber tubing against the ankles of unsuspecting audience members, creating a tactile manifestation of the mice shown onscreen. These examples might be categorized under the larger heading of *simulation design*. In the context of simulations, the haptic component is often intended to increase the “realness” of the experience. Much of the research into simulation design, including the area of virtual reality, is concerned with the design of force-feedback devices which allow a user to probe a virtual environment or object, the goal being to realistically reproduce such features as surface texture, object shape, and compliance.

Movies are not the only medium to have flirted with tactile stimulation. There have been isolated attempts at presenting music directly to the body. Wachpress describes a device that uses a waveguide to present audio vibrations to the body (Wachpress, 1975). In addition, a number of commercial products designed to couple musical vibrations to the body are in existence. These include the Aura Interactor, BFG Labs Intensor Chair, and the Sound Box.

2.4 The art world

Although nowhere near as much as its visual and auditory counterparts, the sense of touch has received some attention in the art world. An early example is a piece exhibited by the Museum of Modern Art in New York in 1942. It was a new type of sculpture called *handies* that consisted of small, smoothly rounded pieces of polished wood in abstract shapes that would fit comfortably into the human hand and could be squeezed and turned this way and that to vary the tactile sen-

sation. The artist who created them stressed that they were meant to be felt rather than looked at (Morris, 1971). This was followed by several explorations into the idea of *environmental sculpture*, sometimes embodied as a kind of play space into which the beholder walks, there assailed by a series of varying tactile impressions (Morris, 1971).

A more recent piece of a very different flavor is the *Ping Body* project headed by an artist called Stelarc (1996). This project involved the use of a muscle stimulation device that controlled the proprioception and musculature of the artist’s body based on Internet activity. The basis of the Ping Body project raises the interesting possibility that the activity of tactile composition might one day be expanded to the proprioceptive/kinesthetic channels. The idea of “being moved” by a composition would assume a whole new meaning! In general though, there have not been many attempts at harnessing haptics technology as a vehicle for the presentation of tactile art.

2.5 Visual music

Though not directly related to touch, the thriving field of *visual music* provides invaluable technical as well as creative guidance for the development of tactile composition. Similar to the multi-modal conception of tactile composition introduced in this paper, visual music encompasses the idea of composition across sensory modalities. The birth of the field is often cited as the invention of the first color organs, stringed musical instruments combined with moving transparent and colored tapes. A nineteenth century art movement seeking sensory fusion – comprised primarily by inventors of these color organs – was born (Cytowic, 1995). The tradition of visual music has been carried on into the 21st century, taking on many new and exciting forms. These include video mixing, laser light shows, algorithmic music visualization, and even the music video. This field has witnessed significant leaps with improvements in display technology, a trend that will undoubtedly manifest itself in tactile composition.

3. A few words on touch

The skin is more remarkable and versatile than most of us know, capable of fine spatial and temporal discriminations. This section is intended to briefly familiarize the reader with the skin’s fundamental psychophysical parameters.¹ Because there is no framework in place for tactile composition, it is especially important for the tactile composer to have a good feel for these parameters.

The term *haptics* encompasses all things pertaining to the sense of touch. The *haptic system* typically refers to the

¹For an excellent synopsis of the psychophysics of touch, refer to Chapter One of the book *Tactile Hearing Aids* (see References section).

collective group of anatomical structures which contribute to our sensation of haptic stimuli. Haptic sensations can be subdivided into two main channels. The first channel is that of *tactile sensation* or *taction*. This channel is typically associated with the sensation of pressure, local features such as curvature, orientation, puncture, texture, thermal properties, softness, wetness, slip, adhesion, and vibration. The skin is typically designated as the seat of this sense (Rovan & Hayward, 2000). The second channel is that of *proprioceptive* or *kinesthetic perception*. This channel provides us with information about the position and movement of our body. In this paper we are primarily interested in tactile sensation, specifically vibrotactile sensation. Accordingly the remainder of this section focuses on the psychophysical parameters of touch with regard to vibration.

3.1 Anatomy of the skin

Tactile sensations can be divided into four channels, each mediated by a specific type of mechanoreceptor in the skin. The four types of receptors are typically categorized in terms of their field of sensitivity, the rate at which they adapt, situation within skin layers, and the general classes of stimuli they encode. The density of these receptors throughout the skin is not constant, but rather a function of body location. Differences in receptor density are manifested as differences in threshold sensitivity, suprathreshold function, and the potential interference or confusion of signals delivered to different sites, also known as masking (Verrillo & Gescheider, 1992). Spatial resolution is dependent upon the density of mechanoreceptors in different areas of the skin. Thus the highest spatial resolution is found on the fingerpad and is approximately 1.0mm (Phillips & Johnson, 1981). It is important to consider all of these variables when designing a tactile stimulator; especially one that incorporates multiple body sites.

3.2 Basic psychophysics

The range of the skin's vibrotactile frequency response is roughly 20–1000Hz, with maximal sensitivity occurring around 250Hz. The skin is relatively poor at frequency discrimination, lacking the exquisite analysis mechanisms found in the ear. Reports on the frequency discrimination abilities of the skin are dependent on experimental paradigm and thus tend to vary. Sherrick proposes that the results suggest that between 3 and 5 values of vibration rate can be distinguished between 2 and 300 pulses per second (Verrillo & Gescheider, 1992). Rován and Hayward (2000) report that ranges broadly divided into 8 to 10 discrete steps are perceptible over a range of 70 to 800 Hz.

The intensity range of the skin reaches about 55 dB above threshold of detection, beyond which vibrations may become unpleasant or painful. A range of values for the just noticeable difference (JND) of intensity have been reported in the literature, the smallest (0.4 dB) reported by Knudson in 1928

and the highest (2.3 dB) by Sherrick in 1950 (Verrillo & Gescheider, 1992). The dynamic range is not constant over the whole range of frequencies to which the skin responds. The dynamic range of the pacinian corpuscles, for example, is greatest at 250 Hz.

When composing with tactile stimuli, certain physiological constraints enter the picture. Prolonged tactile stimulation can result in adaptation, a decrease in the sensory magnitude of a stimulus. Sensation magnitude declines during the exposure to the adapting stimulus and then gradually recovers after the stimulus is removed; recovery time ranges from a few seconds to several minutes depending on the duration and intensity of exposure (Verrillo & Gescheider, 1992). Because different receptors respond to different stimuli and operate over different frequency ranges, the rate and conditions of adaptation vary across receptor types.

3.3 Spatio-temporal patterns on the skin

It is common for tactile stimulators to use multiple channels, spatially distributed in some manner on the skin. We now briefly consider the psychophysics associated with temporally and spatially varying groups of stimuli presented to the skin.

There are four perceptual phenomena that arise from the application of multiple stimuli to different body sites. *Masking* is the reduced ability to detect a stimulus in the presence of a background stimulus. *Enhancement* occurs when the presence of a brief stimulus causes a second stimulus to appear to be of greater intensity than when it is presented alone. *Summation* refers to the total or combined sensation magnitude of two stimuli occurring close together in time. Lastly, *suppression* occurs when the presence of one stimulus decreases the ability of the subject to detect a second stimulus when the two stimuli are delivered to different places on the surface of the skin (Verrillo & Gescheider, 1992).

Gap detection is the minimum detectable separation in time between a pair of stimuli. Gescheider (1967) measured the minimum detectable separation between a pair of tactile clicks as a function of click intensity and found that gap detection improves as a function of the timer interval separating the clicks and the intensity of the clicks. Gap detection thresholds were found to be about 10 ms, but may be as low as 5 ms for highly damped mechanical pulses.

When a sequence of tactile stimuli is presented to spatially distributed sites on the body, our ability to determine the order of presentation is a function of the rate of presentation. Hirsch and Sherrick (1961) found the threshold for temporal order judgments to be about 20 ms between the onsets of two brief stimuli. This threshold, however, was found to increase progressively as the number of stimuli increased beyond two (Sherrick, 1982). When the number of stimuli is increased to five or six, the stimulus onset intervals needed for correct identification of the sequence may be nearly 500 ms.

3.4 Tactile illusions

Sensory illusions arise when some set of conditions forces a sensory system to misinterpret the stimuli being presented to it. In fact, one of the first sensory illusions investigated by Weber, the father of modern psychology, involved the haptic senses (O'Modhrain, 2000). Helson and King (1931) demonstrated the *Tau effect*, in which perceived distance between two tactile sensations is positively related to the temporal interval between stimulation of the two sites. Another interesting illusion was discovered in the course of experiments on tactile sound localization. Gescheider (1965) amplified the outputs of two spatially separated microphones and fed them into two tactile stimulators placed on different fingers of the same hand. Subjects were asked to localize different sound sources using only the tactile cues provided by the setup. The results demonstrated that the accuracy of localization was nearly the same for the skin as for the ears. The really interesting phenomenon arose in later sessions of the experiment, when many observers reported that tactile sensations were projected out into space between the two fingertips to a position corresponding to the sound source (Verrillo & Gescheider, 1992).

There is a powerful set of tactile illusions – which have also been shown to operate in vision and audition – collectively referred to as *apparent motion*. When tactile stimuli are sequentially presented to two distal points on the skin with the right inter stimulus timing, a single stimulus is perceived to move continuously from one point of stimulation to the next. A particularly salient type of apparent motion, in which a properly timed and distributed train of taps creates the illusion of a phantom tap ‘hopping’ between two or more points on the skin, is known as the *cutaneous rabbit effect* or *sensory saltation* (Geldard & Sherrick, 1972).

4. Building a compositional language for the sense of touch

For most people, the association of language with touch is foreign. As we move about and interact in a world dominated by visual and auditory cues, our sense of touch often falls into the background of our consciousness. Despite the fact that we generally do not give tactile stimulation the same amount of attention we do to visual and auditory stimulation, we do in fact obtain a great deal of information about our surroundings through the sense of touch. Taking into account the impressive psychophysical parameter space of touch summarized above, a question arises: Why can't our skin comprehend a language of touch in the way that our eyes and ears can respectively understand visual and auditory manifestations of language? More specifically, can our skin comprehend and appreciate an expressive language of composition in the way our ears can appreciate music?

Evidence from psychophysics research suggests that our skin can indeed understand a language of communication. Furthermore, the work presented in this paper suggests that

the skin can understand and appreciate an expressive language for touch, analogous to the sonic language of music. Hence the ideas addressed in this section are facilitated by the strong analogies that exist not only between sound and vibrotactile stimuli, but at a higher level, between music and tactile composition. The primary aims of this section are to identify the fundamental building blocks of a language for tactile composition and to propose their respective roles in such a language. Several other issues surrounding the formation of a compositional language for touch are also addressed.

4.1 The building blocks

It is indeed premature to hammer out the details of a language for tactile composition. It seems more productive at this point in time to identify the underpinnings of such a language, specifically those dimensions of tactile stimuli that can be manipulated to form the basic vocabulary elements of a compositional language. By understanding the significance of these dimensions for aesthetic perception on the skin, we can begin to build larger compositional structures and ultimately a language for tactile composition. Taking into account the infinite number of combinations of frequency, intensity, waveform, duration, and body locus, the realm of compositional possibilities on the skin is vast.

The notion of a language for the sense of touch is not a new one. Geldard (1966) examined the basic elements of a tactile language for communication. His *Vibratese* language capitalizes on the skin's discriminatory and detection abilities and represents an efficient means of communicating the English language via the sense of touch. The following discussion is in fact modeled after Geldard's approach with one fundamental difference, however. His primary interest lay in the skin's ability to understand a *language* in the sense of a complex impersonal system of symbols such as Morse, semaphore, or even English. The authors of this paper, on the other hand, are primarily interested in an expressive language for the sense of touch and thus view tactile stimuli as aesthetic artifacts rather than symbols that encode hard information. Aesthetic perception, writes Behrend (1998), is similar in kind to all other aspects of perception, but allows freer reign to imagination and emotion. Correspondingly, the interpretation of psychophysical parameters made herein differs from those found in other tactile language studies, such as Geldard's (1966), where the limits of detection and discrimination are more crucial and absolute identification of stimuli is a priority.

4.1.1 Frequency

Unlike the ear, the skin has not evolved complex mechanisms for frequency analysis. Geldard (1960) points out that the correspondence between vibratory frequency and perceived “pitch” is a tenuous and uncertain one. Vibratory pitch proves to be a joint function of both frequency and amplitude. Due

to the poor frequency discrimination abilities of the skin, frequency is less likely to assume a position as a first order dimension of composition, as it does in music. Nonetheless, it is relevant for tactile composition. First, frequency will represent a qualitative dimension for tactile composition. Subjects in psychophysical experiments have reported a sensation of periodicity or buzzing at low frequencies (below 100Hz) while at higher frequencies a more diffuse, smooth sensation is perceived (Verrillo & Gescheider, 1992). Second, the two mechanoreceptors that code vibrations in the skin are tuned to different frequency ranges. This anatomical fact might be harnessed for compositional purposes. For example, when stimulated with a 600Hz stimuli, the Pacinian Corpuscles will eventually adapt or cease to respond while the Meissner corpuscles will continue to respond to lower frequency vibrations subsequently presented to the same area of skin. Lastly, depending on the intensity and coupling of vibrations to the body, the frequency of tactile stimuli will influence the vibration of internal body parts. Due to the relatively low resonant frequency of internal organs, this factor is particularly relevant when presenting high-intensity, low-frequency vibrations to the body. This factor is also pertinent when vibrations are tightly coupled to the skeletal system, since bones are good conductors of vibration.

4.1.2 Intensity

The gamut of dynamic articulations – from the accent to the crescendo – are an important aspect of tactile composition. Tactile composition calls for a continuum of intensities ranging from threshold of detection up to the limits of discomfort. By drawing from this broad range of intensities, we allow for subtle dynamic variations. These variations may be readily perceived they may be appreciated only after extensive training, or they may only be processed subconsciously. In any case, they will contribute to the aesthetic power of a compositional language for touch. A dynamic balance, referred to in the recording studio as the *mix*, will also come into play as multiple compositional strands are layered in space and time on the skin.

Of particular relevance is the amplitude envelope of tactile stimuli. The attack, sustain, and decay of a tactile event can be varied to create a wide range of perceptual effects. For instance, an abrupt attack will be perceived as a sudden tap against the skin whereas a more gradual attack seems to rise up out of the epidermis. By applying subtle variations to the envelope of stimuli, it is possible to generate a continuum of sensations between these two extremes. There is evidence that people are more sensitive to intensity modulations imposed on a carrier signal. One study (Gescheider et al., 1990) found that the best intensity discriminations were made when an intensity increment was imposed upon a continuous background ‘pedestal’ of vibrations. Periodic and non-periodic intensity modulations – such as musical vibrato – will prove to be perceptually powerful techniques for the

compositional toolbox. Based on the authors’ experimentation, we believe that amplitude envelope will assume a salient role in tactile composition.

4.1.3 Duration

Vibrotactile stimuli of duration less than 0.1 seconds are perceived as taps or jabs against the skin, providing the tactile equivalent of musical staccato. Longer duration stimuli with gradual attacks and decays, on the other hand, may be used to construct more smoothly flowing phrases. Differences in duration provide an important means of grouping tactile events when layering multiple voices on the same area of skin. However, stimulating an area of skin for an extended period of time results in adaptation. This happens relatively quickly on the skin and thus is an important psychophysical phenomenon to keep in mind while composing. In fact, adaptation itself might be harnessed compositionally to cause a compositional strand to fade into the background on a particular part of the body.

4.1.4 Waveform or spectral content

Due to the skin’s poor frequency analysis abilities, subtle variations in spectral content cannot be perceived in the way timbre is by the auditory system. The haptic system is, however, able to recognize the qualitative differences between say, a sine wave and a square wave presented to the skin, perceiving them respectively as smooth and rough. The vibrotactile gamut from pure sine tone to frequency-rich spectrum to noise is characterized as a continuous transition from smoothness to roughness (Rovan & Hayward, 2002). For tactile composition, waveform can be correlated to the “texture” of tactile stimuli, as is often the case in music.

4.1.5 Space

Granted the spatial acuity of the skin is impressive, in the context of tactile composition it makes most sense to treat the entire surface of the body as the universe of discourse. The location and relative positioning of tactile stimuli on the body surface will assume a first order dimension for tactile composition, representing the closest analogue to musical pitch. The harmonic manifestations of tension and resolution in music are matched most closely in tactile composition by movement of vibration across the surface of the body. Thus, the compositionally crucial concepts of departure and return are represented well by movement away from and back toward a particular site on the skin. In this regard, the body becomes a stage of sorts on which a vibrotactile dance unfolds. Building on this analogy, the body is a dynamic, shape-shifting stage. Thus the posture of the observer comes into play in both the creation and experience of a tactile composition. For example, a saltatory train of pulses that traverses the body from the hands to the toes with the observer seated with hands at his sides will feel noticeably different

when the observer is standing with his arms raised above his head.

Of particular compositional value with regard to space on the skin is apparent motion (see Section 3.4 above). When applied over relatively large areas on the body surface, this tactile illusion can result in some extremely vivid sensations ranging from a miniature rabbit (of the cutaneous species) darting up the arm to smooth waves of vibration washing over the body from shoulder to toe. Different patterns of apparent motion may be sequenced and layered, resulting in a synergistic sum of movement on the skin. This holistic scenario leads to the notion of *tactile landscapes* – higher level patterns and sensations that emerge from complex combinations of stimuli which may not be easily resolvable.

In addition to being grouped – by composer and observer alike – on the bases of rhythm, dynamics, duration, and envelope, tactile phrases will be grouped spatially. Based on the observations of the authors, spatial grouping is a potent dimension for compositional and perceptual organization.

4.2 Cross-modal relationships

Despite the commonly held view, the five senses do not operate independently. Current knowledge of the physiology of the brain shows that the superior colliculus is one of the sites in the central nervous system in which a convergence of visual, auditory, and somatosensory inputs occurs. Consequently, there are a number of interesting phenomena resulting from the stimulation of multiple senses. The multi-sensory stimulation involved in an audio-tactile composition paves the way for a host of interesting and compositionally valuable perceptual phenomena. Our collective knowledge of psychoacoustics far exceeds our knowledge of the multi-modal interaction between sight, audition, and tactile sensations. Despite our limited knowledge of these interactions, we propose a few possible scenarios in which cross-modal phenomena might be applied to tactile composition. A working knowledge of such interactions will likely be accumulated through further practice and experimentation with tactile composition.

Any attribute that can specify similar information across modalities is considered to be *amodal* in nature. Intensity, spatial location, rate, and rhythmic structure are other common types of amodal attributes (Lewkowicz, 2000). One amodal attribute that has great potential for intersensory exploration is spatial location. Auditory and tactile stimuli can be combined in a number of interesting ways to transform the observer's sense of space on and around the body. A simple example of this is the mutual reinforcement that tactile and auditory stimuli complexes can have on each other. For example, the placement of a sound between the left and right ears might be reinforced by the mapping of stereo space onto the length of the arms, with the midline of the body corresponding to stereo center. Furthermore, the manipulation of spatial location in the tactile domain can expand the sense of space possible with just auditory cues.

For instance, simulating changes in the apparent elevation of recorded sounds using only two-channels of audio is a challenging task. To this end, we might imbue sounds with altitude – and an enhanced sense of three-dimensional space in general – by adding a tactile component that maps the sounds onto the height of the body from head to toe. Another interesting compositional technique would be to map different instruments in an orchestra to different locations on the body, a “part-to-place” mapping, creating the illusion of an invisible orchestra distributed across the surface area of the skin; the tympani against the back, the bassist on the left shoulder, the cellos on the elbows, the violins on the wrists, etc. On the other hand, a composer might wish to confound the observer's sense of space, presenting conflicting auditory and tactile cues; essentially a *cross-modal counterpoint*.

The body's a priori response to music may also play a role in the perception of a tactile composition. Galejev (1993) emphasizes that not only may exteroceptive (externally stimulated) sensations act as components of synesthetic interrelationships, but interoceptive (internally generated) sensations may also contribute. For example, variations in the physiological state of the skin induced by music, such as “chills,” may influence the perception of vibrotactile stimuli.

It is worth mentioning that there is a pre-existent link in our minds between musical sounds and tactile sensations. Mursell (1937) remarks that tone is found to possess very definite and consistent tactile values. We speak of a tone as hard or soft, rough or smooth. Low tones give the impression of a dull puff-puff; high tones are sharp, keen, or cutting. The loosely defined characteristic of sounds relating to their texture, timbre, is also naturally expressed in tactile terms. Mursell proposes that the remarkable unanimity with which certain of these characteristics are attributed to certain sounds strongly suggests a connection more than associative and external between tone and tactile values.

4.3 The massager misnomer

The most salient analogy in people's minds upon encountering a device that produces vibrations against the body is none other than the personal massager. What are massagers designed to do? Relax and heal you. There is in fact an entire field of medicine called *vibrational therapy* that applies vibrotactile stimulation in a therapeutic context. As opposed to these relatively one-dimensional views of vibrotactile stimulation, the approach taken in this paper harnesses the broad spectrum of emotions achievable with vibration.

Part of the emotional potency of the tactile composition – when coupled with music – comes from its ability to enhance, intensify, and expand the preexistent emotive elements of music. In addition to modulating the a priori affective response to music, the tactile composition can stand on its own as an emotionally potent compositional medium. Because sound is essentially vibration, tactile composition that is based on vibrotactile stimulation shares many of the fundamental elements that give rise to the emotional potency

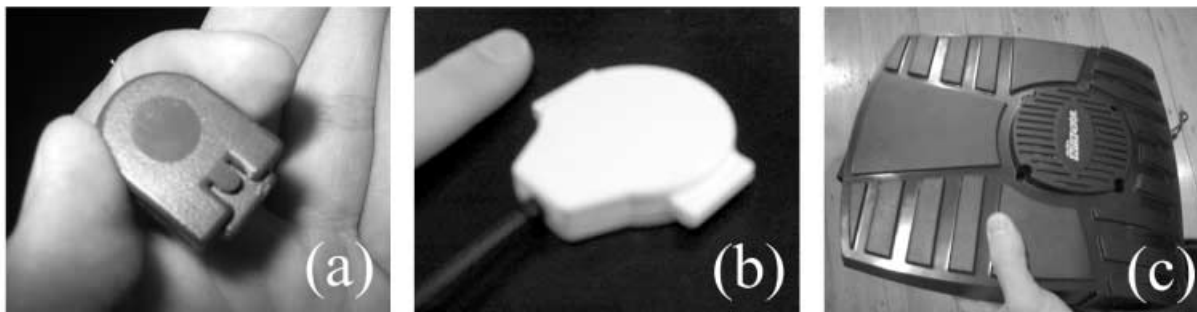


Fig. 1. Transducers used in system. (a) V1220; (b) modified flat speaker; (c) Aura Interactor.

of music. Although tonal and harmonic structures do not translate well to tactile composition, rhythmic and dynamic elements certainly do. When the tactile manifestations of these musical features become recognizable and appreciable to the common observer, they are likely to evoke an affective response similar to that of their musical counterparts. With regard to space and movement on the body, the tactile composition might result in an emotional response similar to the one experienced when watching a dance. According to Pratt (1952), if an emotion is to be real, the organs of the body, and in particular the viscera, must be made to vibrate. In the case of tactile composition, we actually go a step further than music by putting the composition *on* the body. The inherent intimacy of the experience lends significant weight to the affective elements mentioned above. A detailed analysis of the affective response to tactile composition is premature and beyond the scope of this paper.

5. A system for tactile composition

The ideas expressed above sounded great on paper, but without the proper tools they could not be actualized. The pieces were already in place, so we proceeded to design our first tool for tactile composition. A system that facilitates the composition and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body was designed. At the heart of the system is a full-body vibrotactile stimulator comprised of thirteen transducers worn against the body. In this section, some key factors of the design process are discussed.

5.1 Why vibrotactile?

A number of tactile stimulation devices are available, each of which stimulates a specific tactile response. These include pressure, thermal, slip, electrocutaneous, and vibrational displays. The vibrotactile modality was chosen for two reasons. First, vibration devices are generally easiest to work with and in particular, to control. Second, the bandwidth of the skin's vibrotactile response coincides most closely with that of music and hearing.

5.2 Transducers

Because they are inexpensive, compact, and easy to control, pager motors were initially considered as transducers. However, they tend to operate in an on/off manner, usually vibrating at a set frequency. A primary specification for the transducers was versatility with regard to output waveform. The transducer chosen for the first version of the system was the V1220, manufactured by Audiological Engineering for use in their line of tactile hearing aids. The V1220s are compact as shown in Figure 1(a). They have a coil-based design and can thus be driven with any waveform in the tactile frequency range. They produce very clean, localized vibrations, have a relatively high power output, and exhibit a frequency response that peaks at 250 Hz. The requirement that they be worn close to the skin, however, makes them somewhat impractical, since clothing frequently presents too much impedance for the transducers to be effective.

The second version of the system used a predecessor to the V1220 as illustrated in Figure 1(b). This transducer is also coil-based, but has a simpler design. Specifically, the transducer is made by attaching a weight to the center of a 40 mm flat speaker and enclosing it in a small plastic case; this modification serves to lower the resonant frequency of the speaker into the tactile range (Franklin, personal communication). Although they have a larger surface area contacting the skin and consequently do not produce as localized a sensation as the V1220s, they are more powerful (partly due to spatial summation in the skin) and can penetrate clothing more effectively. Manufacturing a set of these transducers with a consistent frequency response has proved to be a difficult problem; center frequencies fall in the neighborhood of 350 Hz. Future versions of the system might employ the V1220s and require the user to wear the transducers directly against the skin.

The perceptual and compositional importance of low-frequency vibrations was realized midway through the design process. Accordingly, a low-frequency transducer was added to the system. The Aura Interactor, a backpack-like wearable intended for use with video games, was chosen. The device is shown in Figure 1(c) and consists of a woofer mounted inside of a hard plastic case.

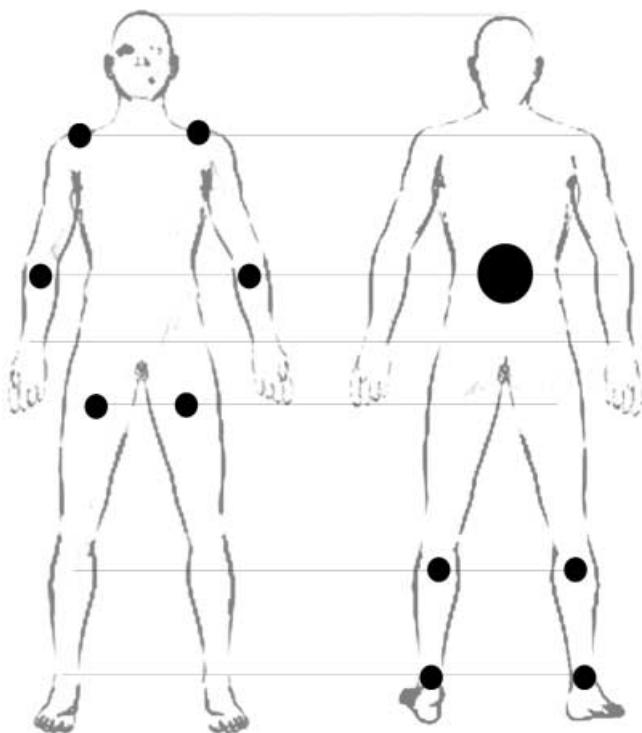


Fig. 2. The small black circles represent the high-frequency transducers. The large circle on the lower back represents the Interactor.

5.3 Transducer Placement

There are thirteen transducers in the device: twelve high-frequency and one low-frequency. The number of transducers was limited by the control hardware used; future versions of the suit will likely contain more than thirteen channels. It should be noted though, that the compositional and perceptual value added by increasing the number of channels eventually asymptotes due to the diffuse receptive fields of some mechanoreceptors in the skin. For the following discussion, please refer to Figure 2, which illustrates the transducer distribution on the body.

Three main principles guided the situation of the high-frequency transducers. First, it was decided early on to distribute the transducers across the entire surface of the body. This decision was motivated by the analogy of a dancer, whose compositional tool is essentially the entire body. Three transducers are distributed roughly evenly along the length of each limb. The middle transducers on the arms and legs were placed, respectively, just below the elbow and knee creases for comfort and ease of movement. Second, each transducer was positioned as close to glabrous (non-hairy) skin as possible. Glabrous skin contains more receptors than hairy skin, making it more sensitive to stimulation. The thigh transducers are the exception; they were placed on top rather than below the thigh for increased comfortability while the user is seated. Third, due to skeletal leakage of vibrations into the ear – resulting in undesirable sonic artifacts – no trans-



Fig. 3. Second version of the vibrotactile composition suit.

ducers were placed on or near the head. A transducer located on the nape of the neck was considered, but rejected for this reason.

The low frequency transducer is situated against the lower back. It seemed intuitive to present low frequency vibrations to the torso, as this is generally the region of the body in which one experiences powerful low frequency vibrations at a club or concert, for instance.

5.4 Wearable design

When working with vibrotactile devices, it is essential to maintain a tight interface between the tactor and the skin. Elastic straps with Velcro were used toward this end; in addition to providing the necessary pressure, they are inherently adjustable. The first version of the suit required the user to strap on each transducer individually. The shoulder transducers were held on via a harness-like contraption and the Interactor was strapped to the back of a Herman Miller chair (which was chosen for its low-impedance mesh backing). In version two of the system, all of the transducers and wires were embedded in a nylon suit as shown in Figure 3. A one-size-fits-all design was required, so the suit was designed to be loose fitting, with external elastic straps at each transducer point. An elastic shoulder harness, which could be adjusted by pulling down the straps located just above the breasts, was sewn into the suit to secure the shoulder transducers. The Interactor is held against the lower back by two adjustable belt straps that wrap around the torso. The outer cover of the device was removed to reduce the weight load. The transducer wiring was routed through channels running along the lengths of the arms and legs and down the back, and exits in the form of a tail. A tail was chosen over an umbilical chord because it hangs from the suit more naturally.

During initial experimentation with the system, the perceptual quality of the vibrations was found to be dependent on the pressure of the transducer against the body. Specifically, when the strap is relatively loose and the transducer

rests comfortably against the skin, the vibrations are perceived superficially on the skin. Tightening the strap couples the vibrations to the bone structure, resulting in a deeper, more diffuse sensation. The latter is undesirable because the vibrations are less isolated (due to skeletal conduction) and excessive tightening of the straps often impedes circulation.

5.5 Control

The transducers are controlled via a Protools Digi001 interface. The Digi001 is a multi-channel digital audio hardware interface that performs the D/A conversions necessary to drive the transducers. Each Digi001 output is independently amplified and sent to one transducer. While the signal quality is admittedly overkill for this application, the Digi001 package was chosen as a quick solution as well as for its versatility, extensibility, and strong support base.

5.6 Composition Environment

Protools, a standard MIDI and digital audio sequencing environment for the Macintosh, is used to compose for the suit. The software is configured so that each audio track is routed to a specific transducer. Because the Protools interface was not designed for this type of application, composing with it is painstaking. The author has developed some useful techniques using MIDI based software synthesizers to speed up the process, but it remains awkward. The benefit of working in ProTools though, is the ability to compose the music and tactile components in parallel within the same environment. Before the full potential of the tactile medium can be realized, better compositional tools must be designed.

5.7 Audio presentation

Presentation of audio through headphones was determined to be optimal for two reasons. Practically, the headphones help to isolate the music from transducer noise. In addition, the phenomenon of internalization, the perception of sound to originate from within the head, increases the “overall intimacy” of the experience; both the audio and tactile components of the composition appear to originate on or from within the body. The overall experience – in particular the observer’s sense of space and the interaction between the tactile and audio elements – is markedly different when the music is played through loudspeakers.

6. Cutaneous Grooves: A concert for the skin

In September of 2001, a series of concerts was held to introduce tactile composition to the greater MIT community as well as to test the technology and hypotheses presented in this paper. The concert was as much an experiment as it was an artistic event. A space was set up at the MIT Media Lab in which ten audience members at a time, each equipped with

their own full-body vibrotactile stimulator, experienced a one hour concert of music and tactile compositions. The pieces comprising the concert are briefly described in order to give the reader some insight into the compositional process.

Two of the pieces in the concert were soundscapes. To build suspense, the first piece opened with a minute of just audio, including a robotic voice lecturing on the anatomy of touch. It then imitated the sound and feel of a heartbeat and the flow of blood down the limbs. On the tactile side, this was accomplished by a low-frequency sinusoidal burst on the back, shortly followed by a rapid wave of saltatory taps from the torso outward on all four limbs simultaneously. The other soundscape began with a purely tactile introduction (no music), with white noise played to mask sonic leakage from the transducers, and transitioned into a three minute simulated thunderstorm. Random taps were presented to the shoulders, forearms, wrists, and thighs, their intensity and temporal density corresponding to perspective shifts in the audio recording of the rainstorm. Audience members reacted strongly to this piece; it was an effective demonstration of the synergistic sum of a simple vibrotactile pattern and a more complex piece of audio.

One musical selection² consisted of simple repeating percussive patterns layered over one another. The tactile accompaniment was an attempt at translating this compositional idea to the body. It demonstrated the notion of *selective attention* on the skin; when simultaneously phrases are grouped spatially or by other means, the observer can selectively attend to each phrase as one can tune in to different voices while listening to music. Furthermore, by highlighting different parts of the music with the tactile accompaniment – bringing some into the foreground and others into the background – the audience’s attention could be focused on different aspects of the music. The layered phrases were often given orthogonal motions on the body, with one phrase bouncing back and forth between the knees and ankles and another between the shoulders and elbows, for example. While these percussive patterns were iterated on the arms and legs, smooth sinusoidal waves would wash down the arms from shoulder to wrist, corresponding to the legato melody of the music. By grouping the tactile phrases in terms of duration and envelope, two phrases could be simultaneously presented to the same area of the body and remain distinguishable.

Two of the musical pieces involved the concurrent creation of the audio and tactile components. By engaging in this kind of parallel or multi-modal composition, the author was able to explore the interplay between the two composition processes. It was indeed a two-way street, with the music composition often influenced by a specific tactile idea and vice-versa. One tactile idea, for example, was to have a repeating sequence of eighth-note stabs that climbed the body from foot to shoulder. In the accompanying passage of

²“Purus River” by Philip Glass, performed by *Uakti*.

music this idea was manifested as a sequence of octave hits fed through a low-pass filter, in rhythmic unison with the tactile phrase, with the filter frequency increasing and then dropping back down periodically. The periods of the tactile movement and the filter modulation were different, creating a continuous feeling of ascension on the body. Through this kind of reciprocal process, the interrelationship between the musical and tactile components was explored. They need not always mirror each other; they are ultimately independent compositional strands and can coexist in any number of ways ranging from rhythmic unison to cross-modal counterpoint.

Much technical knowledge was gleaned from holding the concerts. More interesting, though, is the feedback from the audience about the experience, which confirmed many of the initial hypotheses surrounding tactile composition. Each performance was immediately followed by a 10 minute discussion session in which audience members could ask questions and share their thoughts on the experience. The following points are taken from these discussions as well as observations of audience members during the performance.

This was a novel experience for all participants. Thus the overall degree to which people made sense of and appreciated the tactile compositions was quite astounding. A tactile equivalent of the psychological phenomenon of expectation found in music was experienced by audience members. Specifically, when a pattern was repeated for some period of time, audience members expressed surprise at variations or spatial straying of the pattern. With regard to the kinesthetic response to tactile composition, several audience members noted that at certain instances it actually felt as if the tactile stimulations were making them move. One audience member who was a drummer claimed that it gave him a sensation similar to that of playing the drums; where different body parts are moving rhythmically in an orthogonal fashion. Granted, further experimentation would be required to distinguish the respective kinesthetic responses to tactile and music elements.

There were consistently strong reactions to larger patterns in the composition that spanned the entire body, such as saltatory vectors that rapidly swept from shoulder to feet. Audience members often reported that at first it was difficult to make sense of what was happening on their skin, but that even during the brief duration of the show, their ability to comprehend and appreciate the compositions improved. In a process akin to developing a “musical ear,” people may develop a “feel” for the experience with increased exposure to tactile compositions. The more seasoned feeler will likely be able to recognize and appreciate a higher level of compositional complexity and subtlety.

With regard to affective interactions between the two compositional media, one audience member reported that if the music was calm and soothing, then the tactile patterns felt even more so, whereas if the music was dissonant or jarring, the tactile patterns made him feel on edge, almost uncomfortable. This hints at the ability of the tactile component to

modulate the affective response to the music; in this case probably to intensify or enhance it.

The concerts were an overall success in that they stimulated discussion on the idea of tactile composition, yielded practical technical knowledge as well as encouraging audience feedback, and provided a novel and enjoyable artistic experience. The concerts definitely fell more on the side of being an artistic event as opposed to a controlled experiment.

Ron Pellegrino described the young electronic arts of sound and light as existing in the sphere of the experimental arts. As such they involve extended periods of play and exploration, protocompositional stretches of the free flight of imagination. The opening play-phase of such experimental arts, he explains, is born of curiosity, a sense of wonder, and the confidence that the presently unfamiliar material has immense expressive potential. Serendipitously one discovers significantly expressive forms that warrant further manipulation, extension, and testing (Pellegrino, 1983). The same scenario characterizes tactile composition in its current state. Tactile composition, as an emerging art form, will derive significant energy and momentum from compositional exploration and experimentation.

7. Moving forward

At the risk of constructing an exaggerated dichotomy, one might say that the Cutaneous Grooves Project represents a bridge between the artistically rooted world of music and the more practical, technologically driven world of computer haptics research. From the perspective of the haptics research community, this project represents a shift toward more artistic and expressive applications of haptics technology. As we have shown, when tactile stimuli are viewed as aesthetic artifacts, many currently held notions on the psychophysics of touch and on haptic technologies are opened for reinterpretation.

In addition to music, composed aesthetic tactile stimulation may be coupled with existing visual media. Experiments aimed at the tactile augmentation of movies are underway, bringing us one step closer to the Feelies of Huxley's *Brave New World*. The inherent corporeal nature of tactile composition lends it well as an accompaniment to dance. More interesting perhaps, is the real-time translation of the movements of the dancer into tactile sensations experienced by the audience. Another possible prong of inquiry is the automation of the music-to-touch translation, allowing one to use digital audio as input and to experience a real-time tactile interpretation of music – analogous to the colorful visualization plugins packaged with software MP3 players.

It is safe to say that the majority of mental images conjured during music related activities are visual and auditory. As the tactile medium becomes more established and widespread, it will be interesting to see how musical thinking is affected. Perhaps as people begin to think in tactile terms, their approach to both music composition and listening will

be altered, ultimately expanding the sphere of music in new directions.

The full body vibrotactile stimulator was somewhat ambitious for a first step. For the time being, we have moved toward simpler manifestations of tactile composition in order to facilitate more fluid experimentation and development. Accordingly, several smaller projects exploring various artistic applications of tactile stimulation are currently underway.

The concepts as well as the system presented in this paper have approached tactile composition from a multi-modal standpoint, analogous to visual music, where the forging and perception of the tactile component are coupled with music. The idea of tactile composition was in fact germinated by a desire to push music down unexplored avenues. Its attachment to music is not, however, a prerequisite for its existence. Based on the authors' first-hand perceptual experiences with the system described above, we believe that tactile composition can stand on its own as a viable compositional medium. This raises a multitude of exciting possibilities. It is hoped, for example, that the tactile medium will open a whole world of artistic opportunities for hearing-impaired individuals.

In conclusion, tactile composition – as both a potential new art form and a vein of haptics research – is interested in the ways in which our sense of touch can be harnessed as a sensory channel capable of understanding artistic expression as well as with the design of tools that will facilitate compositional activities and artistically compelling experiences for the skin. The Cutaneous Grooves project is just the beginning. With the first tools in place, we can begin to explore the compositional universe of the tactile medium.

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