Perceptual and Technological Issues in the Design of Vibrotactile-Augmented Interfaces for Music Technology and Media

Marcello Giordano and Marcelo M. Wanderley

Input Devices and Music Interaction Laboratory,
Centre for Interdisciplinary Research in Music Media and Technology,
Schulich School of Music, McGill University,
Montréal, Québec, Canada.
`marcello.giordano@mail.mcgill.ca`, `marcelo.wanderley@mcgill.ca`

Abstract. In this paper we present tactile feedback and stimulation design principles for applications in music technology and media. We discuss features and limitations of the human sense of touch, in the context of conveying musical content solely via the tactile sense. These factors should be firmly taken into account when designing a tactile-augmented interface. Applications of tactile displays in the field of music and media are then presented using a three-fold taxonomy of tactile feedback.

Keywords: haptics, vibrotactile feedback, vibrotactile stimulation, sensory substitution, music technology

1 Introduction

In the last century, the number of "new" systems for generating sound and music has witnessed a constant growth which reached its climax with the availability of computer-based synthesizers [1]. In this context, the idea of defining a new family of instruments, called digital musical instruments (DMIs), rose naturally to indicate a class of instruments in which control interfaces and sound generators are physically separated, the sound generator usually being a computer-base synthesizer. The control interface is a "gestural controller" [2], capable of sensing performer's gestures which are then mapped to the sound synthesis engine; in this context, the mapping process becomes the core of the instrument design.

The decoupling of control and sound generation in two independent units also has a secondary effect, it breaks the tactile and kinesthetic feedback loop coming from the resonating parts of the instrument. This feedback has been proven to be an essential component in the player-instrument interaction [3] especially in expert performance [4] and has been suggested to be the only form of feedback fast enough to control articulation [5].

In DMIs, haptic feedback becomes a design factor [6] in a way that was unknown to traditional instruments. The type of actuators used to deliver information to the user, their placement and the signals used to drive them become a fundamental component in the architecture of the instrument. The use of haptic and particularly tactile technology in the musical domain is of course not only limited to DMIs; tactile-capable devices have been used for creating learning interfaces for music education [7], notification tools for live performances [8], displays for hearing-impaired people [9] and so on.

The purpose of this paper is to provide both technological and perceptual guidelines that, in our experience, need be taken into account when designing interfaces for music and media applications.

2 The Sense of Touch: Physiology and General Properties

Tactile perception operates through a network of cutaneous receptors present in human skin (17,000 receptors have been estimated to be present in each hand [10]) and is responsible of sensations like pressure, temperature, texture, orientation, vibration and many others. Its role is crucial in motor control and in the execution of many simple and complex tasks.

In glabrous skin we can identify four *mechanoreceptors*: Pacinian and Meissner corpuscles, Ruffini end-organs and Merkel disks [11]. These detect skin deformations and are connected to two families of afferent nerve fibers: the Fast Afferent (FA) family, ending in Meissner (FA I) and Pacinian (FA II) corpuscles, and the Slow Afferent (SA) one, connected to Merkel (SA I) and Ruffini (SA II) end-organs. FA fibers cease responding very rapidly after the end of the stimulation, while the SA ones keep responding for a longer period of time. This behavior is called the *adaptation property* [11]. Each of these four separate sensory channels is sensitive to very specific features in a tactile stimulus [12], and the FA I and FA II are considered to be the ones responsible for vibration sensation [13]. The firing behavior of Pacinian cells in particular is very similar to the way in which the auditory system reacts to a stimulus [14]. This seems to be evidence to the fact that the FA II channel is the one to be mainly exploited for the mediation of musical vibrotactile events [15].

The frequency response of glabrous skin has a characteristic U-shaped form which spans from 40 Hz to 1000 Hz with a peak sensitivity at around 250 Hz for every kind of tactor used in the tests and at any amplitude [11]. A set of equal sensation magnitude curves, relating perceived intensity of a tactile stimulus to frequency, has also been identified [11]. These curves are very similar to Fletcher-Munson curves for auditory perception [16].

For what concerns hairy skin, experimental studies have shown [17] that hairy skin presents higher threshold and lower peak sensitivity values compared to glabrous skin.

3 Conveying Information through the Sense of Touch

3.1 Temporal Domain

Pitch When designing interfaces that rely on *vibrotactile pitch* discrimination, a few important points should be considered. Several experiments have tried to define the ability of tactile sense to elaborate pitch information. Rovan and Hayward, for instance, [18] have informally suggested that the glabrous skin is capable of discriminating between 3 to 5 different values for a continuous change in frequency from 2 Hz to 300 Hz and from 8 to 10 values when going from 70 Hz to 1000 Hz. Branje et al. [19] measured the ability of participants to discriminate vibrotactile frequencies, using large voice-coils placed in contact with the back; results showed that participants in the study could effectively discriminate frequency separated by 1/3 of an octave, ranging from 67 Hz to 1047 Hz.

These and other studies [11] suggest that, compared to auditory perception, frequency discrimination performance using solely tactile information is poor, but the tactile channel is nonetheless able to determine gross frequency changes. Tactile frequency discimination is also dependent on several factors, such as: the amplitude of the vibration [20]; the presence of an adapting stimulus [21]; and training [22].

Rhythm A few studies suggest that the sense of touch performs surprisingly well in *rhythm recognition*.

Kosonen and Raisamo [23] and Jokiniemi et al. [24] have compared performance of participants in same/different judgments of rhythmical patterns presented unimodally in the auditory, tactile and visual modality. Results showed that the tactile modality performed better than the visual one, and close to the auditory. Rhythmical patterns have also been used by Brown et al. [25] as a parameter for defining tactile icons (Tactons), a set of messages for delivering information through the tactile channel: a series of three different rhythms were used to deliver messages about the interaction with a mobile phone. Results showed a rate of recognition of the pattern up to 90%.

Roughness Different authors have reported that it is possible to convey information about *roughness* of a stimulus through the tactile sense. There is however some ambiguity about what tactile roughness means: based on Weisenberger [26], Brown et al. [25] characterized "roughness" using a sinusoidal stimulus modulated in amplitude by another one. They showed that the perception of roughness can be adjusted acting on the frequency of the modulation signal (the higher the frequency, the rougher the final signal is perceived), and that this parameter can be used for encoding information about the priority of an event in the interaction with a mobile phone with a recognition rate that goes up to 80%. Other authors provide a different definition for tactile roughness: for Rovan and Hayward for example [18], a rough signal is one that has a richer spectrum, consisting of many partials, such as a square wave, as opposed to smooth sine wave which only consists of one partial. Verrillo [11] reported that participants in his experiments defined as "smooth" a stimulus of higher frequency, while low frequency ones were identified as more "buzzy". Recent experiments by Park and Choi [27] indicate that amplitude modulation techniques seem to be more suitable for modeling tactile roughness.

Timbre In a recent experiment, Russo and colleagues [28] investigated the capability of participants to distinguish between cello, trombone and piano samples, matched for fundamental frequency and perceived magnitude, only by the sense of touch. The results indicate a discrimination level that is above chance, indicating that timbre information could be conveyed by means of tactile-only information.

3.2 Spatial Domain

Acuity, pattern recognition and numerosity Evaluating spatial resolution of the tactile sense is crucial in the design of devices that depend on the user's capability of distinguishing the part of the body to which a tactile stimulus has been applied. Cholewiak and colleagues [29,30] performed a series of experiments to test participants' ability to discriminate the location where a vibrotactile stimulus was presented. The possibilities consisted of seven points of the forearm, three points on the upper arm, two points on the shoulder and seven points around the lower torso. Results showed poor performance for what concerns the fore-arm, with results superior to 70% only in two points, the elbow and the wrist. Better results were achieved for the torso, for which all the points were identified more than 70% of the time, with peaks up to almost 100%.

Other studies seem to confirm these results; van Erp [31] showed that the torso has a spatial acuity of about 3 cm, remarking however that the discrimination is highly dependent on two temporal factors as well: the duration of the simuli and the temporal offset between two consecutive stimuli. Piateski and Jones [32] presented vibrotactile patterns using a tactile display on the forearm and on the lower back. While the recognition rate attained almost 100% for patterns displayed on the back, performances were unsatisfactory for the fore-arm.

Another important aspect to consider is the capacity of the tactile sense to make numerosity judgements. Gallace et al. [33] conducted an experiment in which participants had to identify how many tactile stimuli were presented simultaneously on their body, while wearing a tactile display composed of seven different actuators. Results show that the error rate increases to more than 50% when more than two stimuli are presented at the same time.

Tactile illusions A particularly interesting phenomenon is represented by tactile illusions, i.e. phantom tactile sensations created by tuning the onset of two or more real tactile stimulations applied at different sites [34]. The most well-known is the so-called “cutaneous rabbit” illusion [35]. A specific temporal and spatial pattern of stimulation between two points on the skin can give rise to the emergence of the sensation of a moving point that flows between the two stimulated points.

Attention Vibrotactile stimulation can be used to attract attention to a specific part of the body. Spence and Gallace [36] present evidence showing that after the presentation of a tactile stimulus to a part of the body, subsequent stimuli in the same location, in the tactile or also other modalities, can more easily be detected. Tactile stimulation can so be used to direct users' spatial attention to events taking place in other modalities.

4 Technical Remarks

When designing interfaces that rely on the communication of tactile events, the aforementioned perceptual properties and limitations that are inherent to tactile perception must be considered. These perceptual issues reflect precise choices that should be taken into account from a technological and a design point of view when defining the system's architecture.

4.1 Choice of Actuators

Many different kinds of vibrating actuators exist on the market. A review of the properties of commercially available actuator technologies is beyond the scope of this paper. A general, thorough review on available tactile-displays and actuators can be found in [3] and [13].

An analysis of the most popular actuators used in DMIs and tactile displays for music and media can be found in [3]; this survey shows that the type of actuators mostly used in the field are loudspeaker-like ones.

Generally speaking, the choice of the actuators to be used is mainly determined by the role of vibrotactile feedback in the interface design, by other factors such as size or power consumption and by the information to be conveyed.

Simpler actuators, such as unbalanced masses or solenoids for instance, have the advantage of requiring low power and they can be driven by very simple signals such as pulse-width modulation [3]. Loudspeaker-like actuators usually require proper amplification (i.e. suitable for an audio signal), which requires in turn proper power source, but they can provide independent control of amplitude and frequency of vibrations [3].

4.2 Frequency Response

When using loudspeaker-like actuators, the signals used to drive the chosen actuators should be equalized [15] to compensate for the previously mentioned equal-sensation magnitude curves [11] that relate frequency of vibration to perceived intensity. Moreover, the actuator itself, together with the circuitry needed to drive it (i.e. power amplifiers) and the whole interface in which it is eventually embedded, possess a specific frequency response. This has to be taken into account if a "perceptually-flat" frequency response of the system needs to be achieved; in the design phase, the choice of materials with a linear mechanical response should be preferred to simplify the compensation process.

4.3 Placement and Activation Patterns

When designing distributed, whole-body displays, relying on the stimulation of multiple body sites at the same time, the placement of the actuators is a crucial factor to ensure that the desired information is successfully conveyed to the final user.

Results presented in the previous section indicate that the sense of touch can proficiently be used to give directional information or to give the user specific directives, associated with pre-determined patterns. As we have seen, however, this ability varies considerably with the chosen body sites. For instance, better results were achieved on the waist and torso than on the forearm for example[31,32].

On the other hand, the amount of information that can be processed at the same time, when only relying on the tactile sense, is modest, at least if the tactile stimuli are not presented in a specific pattern [33].

5 Applications

We present exemplifying tactile displays chosen from both our previous work and from the most relevant literature on the topic. These displays show the relevance of the perceptual and technological issues previously described. Using a functional organization, we will distinguish between tactile notification, translation and synthesis. We believe that these categories describe the three main roles that tactile feedback can play in the context of designing interfaces for musical expression and media. They determine the choice of the actuators, their placement and the synthesis algorithms needed to produce the signals used to drive them.

Our taxonomy aims to clearly state what this roles are, what receptive capabilities of the sense of touch they address, and which technology approach is better suited for each category.

5.1 Tactile Notification

The most straightforward application of tactile stimulation is for notifying the user about events taking place in the surrounding environment or about the results of their interaction with a system. Usually, the stimuli needed for this kind of application do not need to have any specific characteristics other than being supra-threshold; they only need to direct user attention without necessarily having to convey any other extra information. For this reason, the actuators used in this context are generally simple rotating eccentric masses, which require very low power (usually 3V or less) and can be driven, for instance, directly from the PWM output of an Arduino[1] microcontroller.

Michailidis et al. [8] used these devices investigate ways of conveying haptic feedback in live-electronics performance. Using small vibrating motors, the authors managed to give musicians valuable information about the successful triggering of effects in a live-electronics performance, using an augmented trumpet.

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[1] `http://www.arduino.cc`

Following a similar approach, we are developing a tactile notification tool to be used in conjunction with *CLEF*[2] (CIRMMT Live-Electronics Framework). This tool, consisting of two vibrating motors placed on the ankles, can give the performer feedback about the successful activation of events in CLEF by means of simple clicks or "buzzes". The internal state of a particular effect can also be represented; for instance, leveraging the cutaneous rabbit illusion, a tactile "flow" can be induced (from left to right or vice versa) to give the performer information about the panning of the sound as perceived by the audience.

5.2 Tactile Translation

In sensory substitution, a stimulus usually addressed to one sensory channel is transformed in a way that it can be received and processed by another sensory channel. Tactile translation is a form of sensory substitution. Leveraging the neuro-physiological similarities between auditory and tactile sensory channels [14], one can *translate* an auditory stimulus to the tactile channel by means of frequency rescaling and cross-modal mapping between features in the original sound and in the target tactile stimulus.

Loudspeaker-like actuators are evidently better suited to render stimuli as (spectrally) complex as those produced by a tactile translation process. As we mentioned in Sect. 4, proper amplification and frequency compensation techniques must be considered when using this kind of devices. For the tactile stimulation to be meaningful, the actuating signals need to be tuned to the receptive range specific to the part of the body where the actuators are to be applied.

Birnbaum's work [15] is one of the first examples of tactile translation in a purely musical-related domain. A flute-like controller for breakbeat loops, the BreakFlute [15], was augmented with small voice-coils placed in the keyholes. A tactile translation environment called FA/SA performed the translation of the sound output into tactile stimuli played by the voice-coils, with the aim of recreating a feedback loop between sound output and haptics in a DMI. Performers informally reported a greater degree of "control" while interacting with the instrument.

In our previous work [7] we have studied the possibilities given by vibrotactile stimulation, to enhance the learning process of novice guitar players. Our prototype consisted of a vibrotactile whole-body display composed of 10 loudspeaker-like vibrating actuators. Following Birnbaum's approach a multi-channel version of the FA/SA environment was developed to drive the suit. A tactile translation of a base-track (base-line and drums) was spatially mapped onto the body of the performers. Novice players were asked to play along with the base track; they remarked that the presence of the display, particularly because of the actuators on the back (mapped to the drum-kick), gave valuable information about the tempo, allowing them to keep a better focus on the instrument.

Karam et al. [9], developed a prototype of augmented chair (the "Emotichair") embedded on the back with an array of speakers. The aim was to create a

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[2] `http://clef.sf.net`

display for deaf people to enjoy music through vibrations. Following their "Model Human-Cochlea", a model of physical translation of the cochlear critical band filter on the back, the authors mapped different frequency bands of a musical track, rescaled to fit into the frequency range of sensitivity of the skin, to each of the speakers on the chair.

5.3 Tactile Synthesis

Tactile synthesis is the attempt to create compositional languages solely addressed to the sense of touch, so as to be able to convey more complex information than in the tactile notification paradigm. This information is not issued from a direct transposition of a signal normally addressed to another sensory modality, as is the case for tactile translation.

An example in a musical context is the work of Gunther [37] who developed a musical compositional language for the sense of touch: the "Skinscape" system is composed of a tactile display and a tactile composition environment. The building blocks of this language (also at the base of the "Cutaneous Grooves" project [38]) are frequency, intensity, envelope, spectral content and spatial position on the body of the user; the aim is to create a language that could be used to accompany music. The author does not provide formal results about the effectiveness of his tactile display, but, based on perceptual evidence [33,39], it seems that amount of information he plans to deliver to the user could become quickly overwhelming, not allowing to attend to all the stimuli presented simultaneously.

A DMI featuring tactile synthesis capabilities is the Viblotar by Marshall et al. [40]. The sound output from the instrument can be redirected to the embedded speakers or to an external sound system. In this case, the internal speakers can be used to generate additional vibrotactile feedback and the authors hypothesize the use of the internal speakers to simulate the frequency response of another instrument.

6 Conclusions

Vibrotactile feedback and stimulation can be implemented in interfaces for musical expression and media with a great variety of uses: restoring the intimacy in instrumental interaction with a DMI, providing notification cues and alerts, allowing hearing-impaired people to experience music.

In this paper we provide a review of the most important features and limitations of human tactile perception, with special attention to the factors most relevant to the communication of musical-tactile information. We believe that the knowledge of these perceptual aspects is fundamental for achieving coherent tactile experiences that reflect the designer's intentions. Relevant technological issues are also presented as a natural counterpart to the perceptual properties of the sense of touch. Finally, we present a taxonomy of tactile feedback and stimulation, to provide exemplary applications of tactile-augmented interfaces in the domain.

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