A LEARNING INTERFACE FOR NOVICE GUITAR PLAYERS USING VIBROTACTILE STIMULATION

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ABSTRACT

This paper presents a full-body vibrotactile display that can be used as a tool to help learning music performance. The system is composed of 10 vibrotactile actuators placed on different positions of the body as well as an extended and modified version of a software tool for generating tactile events, the Fast Afferent/Slow Afferent (FA/SA) application. We carried out initial tests of the system in the context of enhancing the learning process of novice guitar players. In these tests we asked the performers to play the guitar part over a drum and bass-line base track, either heard or felt by the performers through headphones and the tactile display they were wearing. Results show that it is possible to accurately render the representation of the audio track in the tactile channel only, therefore reducing the cognitive load in the auditory channel.

1. INTRODUCTION

It has been shown in many experiments during the last twenty years (which we will present and discuss in detail in Section 2) that tactile sensation is a crucial component in the exploitation of the haptic channel and in the knowledge of our surrounding environment. Many of this experiments had music and musical interaction as their main focus, studying the role of tactile sensation and vibrotactile feedback, trying to understand to which extent the tactile sensation is crucial in the *embodiment* of the instrument by the performer or in the perception of music by an audience (see [1] and [2] respectively for example).

In both directions, what lies behind the development of this field of research is the understanding of the physiological and neurological mechanisms which guide the tactile perception. None of the projects we have described would have been realized without the fundamental work of scientist like R.T. Verrillo, who at Syracuse University brought on a series of experiments which spanned trough thirty years, trying to identify the processes and the receptors that generate tactile sensation. Verrillo gave, for the first time, a complete picture of how this complex system works, and a large amount of technical data which is essential to design any kind of prototype in this field ([3]).

Others pioneering works in this sense are those by P. Bach-y-Rita, who in the '60s developed one of the first tactile displays to perform sensory substitution. His *Tactile Vision Sensory Substitution* device consisted of a chair embedded with moving rows of pins to draw on the back of the subjects images received by an external camera ([4]).

2. PREVIOUS WORKS ON VIBROTACTILE STIMULATION

The existing work about vibrotactile stimulation in musical interaction can be loosely divided into two categories according to which side of the instrument we decide to take in consideration : the performer's side or the audience's side.

The first category of works is mainly focuses in understanding how tactile vibration is involved in the creation of a relation of intimacy between the performer and its instrument, and how crucial this kind of feedback is in controlling and mastering the instrument itself. The first who analysed in depth this kind of problem is probably Chafe who, in a paper which dates back to 1993 ([1]) showed that introducing vibrotactile feedback in a controller led to a significant improvement in the performance of the subject testing the apparatus when controlling a realtime physical model of a brass.

Other experiences (such as [5], [6] or [7]) were performed in the following years: a recent one was designed by J.Rovan and V.Hayward ([7]) and studied the possibilities of adding vibrotactile feedback to open air wireless controllers, with the aim of improving their playability. This is an important aspect which has been stressed by several authors who remarked how the vibrotactile information is essential when speaking about professional performances ([8]). The tactile channel seems to be the only one fast enough to convey the huge amount of information needed to the performer for proficiently controlling the instrument.

In this category finds his place also D.Birnbaum ([9, 10]) whose work involved the realization of a digital musical instrument, embedded with tactile actuators, all controlled by a synthesizer of vibrotactile events. This projects will be described in Section 4 since it is the base for the realization of our prototype.

The other category of research investigates the role of vibrotactile information in the perception of sounds and music. The applications are many : spatialization tools, multi-modal displays and sensory substitution. An application of this latter one is the prototype developed at Ryerson University by M. Karam and D. Fels for their *Model Human Cochlea* project ([11]) which uses the tactile channel to help deaf or hard-of-hearing people experience music through a special chair embedded with speakers. Each speaker received only a part of the spectral content of the music, although the criteria by which the frequency bands were chosen and mapped to a particular speaker does not seem to be evident.
Another project is *Cutaneous Grooves* ([2]) which was developed at the MIT Media Lab : the objective was to create a real ”tactile composition language” and accompany a musical performance with a series of vibrotactile events expressly designed for the specific composition. The audience had to wear a special suit embedded with tactors and other kinds of vibrating actuators which received the signals from the tactile composition environment. This multimodal experience aimed to expand the musical experience with extra tactile stimulation and allowed the composer to *”highlight different parts of the music [...] and focus the audience's attention on different aspects of the music”* using tactile stimulation.

3. THE TACTILE SENSE

3.1 Physiology of the tactile sense

Tactile perception operates trough a network of cutaneous receptors present in human skin 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 the glabrous skin we can identify three different layers: *epidermis*, *dermis* and *subcutis*; each of these layers contains different kinds of receptors of which, those responsible for the perception of vibrotactile events are the corpuscles of *Meissner*, *Merkel*, *Pacini* and *Ruffini* ([9, chap. 3] and [3]). Each is associated to a different sensory channel which analyses different features of the stimulus.
Two families of corpuscles exists, the Fast Afferent (FA) family and the Slow Afferent (SA) one; the first one is characterized by the fact that the response of these corpuscles to a given stimulus ceases very rapidly, while the SA ones keep responding longer after the stimulation began. This behaviour is called *adaptation property*.
Meissner and Pacini's corpuscles belong to the FA family, while Merkel and Ruffini's belong to SA family; here is a brief description of each receptor and its main properties (see [9] and [3] for more details):

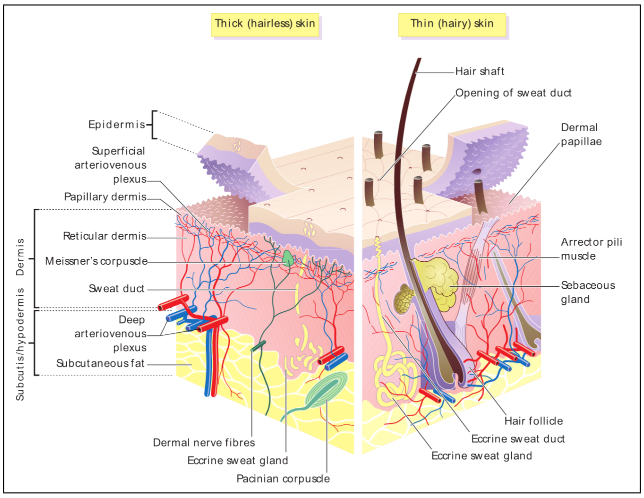

Figure 1. The structure of the skin with the different corpuscles in evidence (Image from en.wikipedia.org, released under the Creative Commons Attribution-Share Alike licence).

1. Pacini (FA) : Pacini's corpuscles are present in the deeper layers of the skin and their primary role is to protect the nerves from the vibrations given by the manipulations of objects in everyday life. They operate as a high pass filter, not allowing the low-frequency but energy-rich vibrations to reach the nerves. On the other hand they are very sensitive to the frequencies higher than 40Hz. The way Pacinians receptors behave when firing neural signals after the reception of the stimulus, is very similar to the way the auditory system reacts. This seems to be an evidence to the fact that the Pacinian channel is the one to be mainly exploited for the mediation of musical vibrotactile events ([9, Chap. 3]).

2. Meissner (FA) : these receptors are very sensitive to lower frequencies and are disposed in the superficial part of the dermis. Their spatial resolution is not very high, meaning that they cannot accurately sense where the stimulation is taking place; their principal function is to guide the grip control on the objects we manipulate.

3. Merkel (SA) : These cells have a very good spatial resolution and are very sensitive to the changes in texture of the objects manipulated.

4. Ruffini (SA) : The functionality of these cells is the most difficult to identify. They are sensitive to lateral stretching and this gives rise to two hypothesis about their role. They could be involved in the control of moving objects or in the determination of the position of the body parts, according to the superficial tension of the skin.

A very important remark we have to make is that there exists a difference in the mechanisms which control vibrotactile perception in glabrous skin (which we have just described in the previous section) and in hairy skin. For hairy skin the data we can find in the literature is not so accurate as for glabrous skin, but it is anyway sufficient to form a solid base on which design a project involving a whole-body vibrating experience.

The most important differences characterizing hairy skin is a higher threshold and lower peak sensitivity values compared to glabrous skin. Verrillo and others made a series of experiments on different parts of the body trying to identify this values ([14, 12, 13]), and other possible important features. When developing our prototype we tried to take into account this differences as much as possible, according to the available data.

3.2 Properties of the tactile sensation

A fundamental step in understanding how the perception of vibrotactile stimuli works is the individuation of frequency thresholds and frequency ranges to which the skin is responsive. Verrillo ([3]) in the following years, made intensive studies on this subject, producing very detailed data about threshold, frequency ranges of sensitivity depending from amplitude and size of the actuator used.
The best data we have concerns the skin in the fingertip area, which has probably been the one studied more in depth; less accurate but still valuable data is available for other parts of the body. Also other important parameters have been identified by these studies like a set of equal sensation magnitude curves, very similar to the ones we have for the auditory system.

The frequency response of the skin has a characteristic inverted U-shaped form which spans from $40\,Hz$ to $1000\,Hz$ with a peak sensitivity around $250\,Hz$ for every kind of tactor used in the tests and at any amplitude. Another important aspect to consider is the discrimination of different frequency values; it has been shown that the tactile system has a very poor resolution compared to the auditory system when taking into account this particular feature. Rovan and Hayward ([7]) have suggested that the glabrous skin is capable of identifying from 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 $1000\,Hz$. This shows that, even if far away from the accuracy of the auditory system (for which the just noticeable difference goes down to 0.3%) , the tactile channel is still able to determine gross frequency changes. Speaking about spectral content, Rovan and Hayward ([7]) have also showed how a sinusoidal wave is normally associated to a smooth vibration, while rougher vibrations are connected to signals with richer spectra, such as a square wave. This property can be used to give very interesting effects to the kind of signals used for vibrotactile feedback, allowing to stress some properties of the signal more than others. For example, a sine wave could be used for lower frequencies and a square wave could be suitable for increasingly higher frequencies, producing an effect of perceived *brightness* in the tactile stimulation ([9, Chap. 3]).

Another aspect to take into account is the appearance of *masking* and *adaptation* phenomena, which can have a significant impact on the overall perception of the stimulus : *Masking* occurs when the presence of a background stimulus makes the primary one go undetected; it's an important factor to consider since it can dramatically increase the threshold value for the given signal. *Adaptation* is instead present when the extended exposition to a given stimulus decreases the sensitivity to the following ones, also increasing threshold or decreasing the magnitude perceived. When designing an experience involving vibrotactile feedback, those two aspect have to be seriously taken into account to avoid any possible interference with the final results.
Beside that, there are also two other phenomena which can be important to consider : *Enhancement* and *Summation*. The first one works essentially in the opposite way than *Masking*, in fact a second signal can be used to amplify the perceived magnitude of the first one, and this can be done in two different ways; spatially, by presenting simultaneous stimuli in different loci, or temporally, by presenting the two stimuli one immediately after the other. *Summation* occurs when the second stimulus is integrated with the first one, without changing its perceived magnitude.

4. THE PROTOTYPE

The most important thing we had in mind while conceiving this project was to reunite in one testing prototype the two main categories we describe in Section 2. As in the second category we described, we designed an experience where a performer would play on top of an existing base track and using a whole body display we created a representation of the sound of the base track *on the skin* of the performers. The aim was to design a multi-sensory environment involving the normal auditive stimulation and the added vibrotactile stimulation to test if this added information could be useful to increase the performer's degree of control of the instrument (problem usually addressed in the first category of experiments seen in Section 2).
The conception of our prototype started from the comparison of the works cited in Section 2, [2] and [11] in particular; after the analysis of the technology and the methods used for conducting those experiences we realized that most of them were based on some arbitrary decisions in the designing phase, meaning that the choice of the type of signal or of the actuators for example, seemed to be led more by an a priori decision than by a clear and systematic use of the data on vibrotactile perception. Most of the times, the prototypes and the testing environment we considered did not have any counterpart in the literature about physiology of the tactile sense to justify why they were designed in a certain way more than in another.

As we said, D. Birnbaum's work was the only one between those we considered to approach the problem of exploring vibrotactile feedback using the physiological basis as guidelines to develop his prototype.
He investigated the role of each of the four channels involved in tactile perception and developed a synthesizer of vibrotactile events, the *FA/SA* application, expressly tuned to stimulate the skin with the right frequency range, avoid-

ing as much as possible masking phenomena, balancing the effect of the augmented sensitivity to lower frequencies ([9, chap 4]). The application receives in input the sound coming out from his *BreakFlute* instrument (a flute-like controller embedded with little actuators on the holes, to stimulate fingertips upon pressure) and applies the series of processes we will describe in Section 4.2 to output the signal to send to the vibrating actuators. In this way the final signal still preserves the features of the original sound, but rescaled and tuned to the different sensitivity of the tactile channel. The feedback sent to the fingertip is a "projection" on the tactile space of the original sound in the auditory space.
The test Birnbaum conducted on its prototype gave very interesting results : all the performers who tried the prototype experienced a bigger connection with the instrument, and an improved ability to control the output sound when the vibrotactile feedback was activated.

The design of the display we built was inspired in particular by two already cited works we already spoke about : the *Cutaneous Grooves* ([2]) and the *Model Human Cochlea* ([11]). What we wanted to do was to go in the same directions given by those two experiences (whole body display, mapping different bands of the audio signal to different parts of the body) but keeping in mind as much as possible the physiological limits and the peculiarities of the tactile sense. With these considerations in mind we tried to identify the best distribution of the actuators on the body, ending up with the scheme in Figure 2.

The distribution is symmetrical on the limbs and has as center the two actuators placed on the back; it is also specular on the right and left side of the body. The actuators on the limb marked with the same number receive the same signal from a single output channel. The two actuators on the back, even with a different numbering also receive the same signal, but they have each one their own output channel to increase the intensity of the signal and also to allow different, non symmetrical dispositions in future tests.
This set-up seemed to suit the idea of creating a tactile, spatial representation of sound onto the body of the performer, allowing to map different features of the audio channel on different loci. What we did was to map the lowest frequencies to the back, and increasing them symmetrically going further on the limbs, towards the wrists and ankles. The center of the frequency bands selected via the band pass filtering changed according with the spectral distribution of the different base tracks.
We decided to double the channel on the back with two independent actuators driven by the same signal, since the frequencies mapped to this area would likely correspond to the drum-kick of the base tracks in our catalogue. This is very important for the tempo and we wanted to make this parameter as evident as possible for the players.

For the software part of the project we implemented a synthesizer of vibrotactile events, following the directions given by Birnbaum in [9].

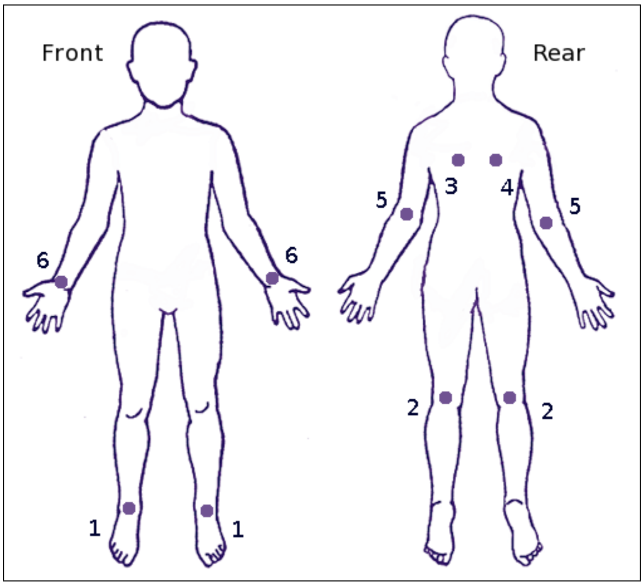

Figure 2. The distribution of the actuators on the body.

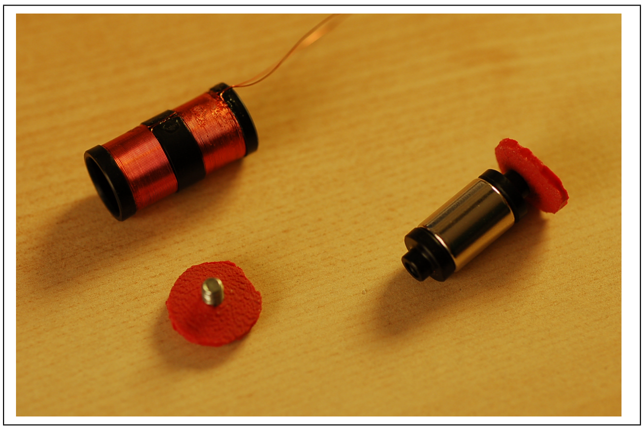

Figure 3. One of the actuators as used in [15] (Photo by courtesy of J. Malloch).

4.1 Actuators

The hardware prototype we built up consisted of ten vibrating actuators, based on the design of Hsin-Yun Yao ([16]). Similar actuators were used by J. Malloch in his vibrating version of the T-Stick instrument ([15]) (these actuators can be seen in Figure 3).
Each of the actuators consisted of a small plastic pipe of $5\,cm$ length and $1.5\,cm$ diameter, wrapped in a very thin conductive cable. The two coils formed on the two halves of the pipe are wrapped in opposite directions so to create a varying magnetic field in the interior of the pipe when an electric current flows in the cable. A magnet of the same size of the internal part of the pipe is then enclosed into it by two plastic caps with an added foam layer which allows the magnet to rapidly move with the change of the magnetic field, causing the vibration (see [16, Appendix A]).
The choice of this particular type of actuators among the many types available on the market (see [17, 18] for a comprehensive list) was made because of their wide amplitude and frequency ranges, an independent control of these two parameters, a cylindrical form which made easy to apply

them in the designed loci on the body.
The actuators were connected to six $1\,W$ mono amplifier designed by M.T. Marshall and based on the Philips TDA 7052 integrated circuit powered by two $9\,V$ batteries connected in parallel to give a consistent current intensity. Each amplifier controlled two actuators for channels 1, 2, 5 and 6 (Figure 2) while the two actuators placed on the back were connected to one amplifier each (channels 3 and 4). Medical elastic gauzes were used to apply them on the body, allowing the performer to easily move and, at the same time, assuring a constant contact with the skin.
A 6.35mm Jack connector was used to plug the amplifier in the external sound card used, a firewire Digi 002 produced by Digidesign. This sound card provided a sufficient number of input and output channels and an easy configuration on both Microsoft Windows and Mac OS X.

4.2 Control Application

The Control Application (CA) was written in Max/MSP, and performed the necessary operations on the input audio to finally synthesize the signal fed into each of the 6 channels used by the actuators.
As mentioned this was essentially an extension of the *FA/SA* application written by D. Birnbaum ([9, chap.4]) with modifications and improvements needed for the specificity of this project. The input sound is preliminary converted to mono and band-pass filtered into 6 different signals centred on a given frequency to take only the desired part of the spectrum.

For each of the 6 signals we then perform a spectral analysis, producing the psychoacoustic descriptors necessary to generate the signals sent to the actuators; this parameters are used to generate the final tactile signal so that the main perceptual features of the signal will remain in the final *tactile signal*. An adjustable envelope triggered is applied to this signal to give it a pulse effect so to reduce the presence of masking and adaptation, which will be unavoidable with a continuous signal (see Section 3.2). The spectral centroid is used as base frequency to generate a sinusoidal and a square wave. This two waves are then added one to the other in a ratio which also can be defined by the user; This implementation allows us to chose the amount of ”smoothness” or ”roughness” to give to the output, so to enhance the perception and distinction of low and high frequency at the tactile level. The signal so generated is modulated in amplitude by the value of the loudness parameter.

After the signal has been generated, another filter is applied to eliminate any frequency out of the maximum and minimum skin receptivity range. Furthermore an equalization is made, to compensate the increased sensitivity of the skin to higher frequencies (Verrillo ([3]) found that equal sensation magnitude curves, similar to Fletcher-Munson curves for the auditory sense, exist for the tactile sense. We tried to take this into account with this last treatment of the signal).
After this final treatment each signal is sent to the specific actuators chosen to represent that predetermined frequency band on a specific location.

Figure 4. One of the players testing the display.

5. PRELIMINARY TESTS

We decided to perform the first test on five beginner guitar players, even if the prototype and the software can be adjusted to work in different configurations, suitable for other instruments. The choice of taking guitar players was mainly based on the availability of the subjects and on the fact that we wanted to concentrate only on one class of players to have more comparable results in this preliminary phase.
We asked the subjects to participate to a simple experiment and recording their overall impression about the display. After placing the actuators on the body, we asked them to chose in a catalogue a song they knew or felt comfortable to play (the 20 songs listed in the catalogue were *”classics”* of pop and rock music, no longer than five minutes; the most chosen one was *”Smells like teen spirit”* by Nirvana). We then played the part of the track consisting only of base and drums through the headphones they were wearing and asked them to play the missing guitar parts. We repeated the experience feeding the track to the FA/SA driven application which subsequently activated the tactile display, and asked the player to perform again on the same track.

When we asked about their impressions between the two modalities, all the novice players agreed that the presence of the vibration helped them to keep ”more focused on the instrument”, freeing them from paying too much attention to the accompaniment coming from the headphones; some of them stressed in particular the benefit of the presence of the actuators on the back, more sensitive to the low frequency of the kick-drum, which helped them to stick on the tempo. They also remarked how the experience felt more ”immersive” and how they felt more involved in the task.

These results seem to suggest that the extra tactile information could be useful for beginner players, since it seems to be capable of augmenting their ability to focus on the instrument, therefore allowing them to be more in control when performing the the given task. This factor could be useful to develop new strategies for the learning of the instrument, in which the player can *feel* the presence of other instruments playing, rather than just listening to them. The remark our subjects made about the more ”immersive” connotation of the experience with the use of vibrotactile display, seem to suggest that they felt the tactile stimulation as something correlated to what they were listening, and not as a distinct stimulation. They felt to interact more with the base track, rather than passively listening it trough the headphones.

6. CONCLUSIONS

The use of vibrotactile stimulation in musical applications has been an important topic of research in the last twenty years, but the role of this kind of sensation and the ways to exploit it for conveying musical content are yet to be fully understood.
With this project we tried to proficiently use our knowledge of the physiology of the tactile sense to build a tactile display capable of translating acoustic properties on the tactile dimension. The preliminary tests we performed indicate that we are probably following a good path in this sense; the subjects seemed to be able to catch the connection between the track they were listening and the tactile stimulation built from that. Our goal was to build a display capable to help beginner guitar players in the control of the instrument and also the preliminary results show that the vibrotactile stimulation could be useful in this sense.

For our future work we plan to perform more accurate tests on guitar players, designing a formal and measurable framework by which precisely evaluate the effectiveness of the tactile display. We will start testing also on other instruments and we will develop new tasks and configurations for the placement of the actuators to find the most efficient ones according to the kind of instrument we will be testing on.

7. ACKNOWLEDGEMENTS

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