Haptic Music Player - Synthetic audio-tactile stimuli generation based on the notes' pitch and instruments' envelope mapping

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ABSTRACT

An entertainment environment to enrich music listening experience is presented. This environment is composed of 3 modules: a MIDI player, a music animation and a haptic module that translates the notes, played by one instrument, into a resemblant vibration. To create the haptic vibration, the notes' relative pitch in the song are calculated, then these positions are mapped into the haptic signals' amplitude and frequency. Also, the envelope of the haptic signal is modified, by using an ADSR filter, to have the same envelope as the audio signal. To evaluate the perceived cross-modal similarity between users, two experiments were performed. In both, the users used the complete entertainment environment to rank the similarity between 3 different haptic signals, with triangular, square and analogue envelopes and 4 different instruments in a classical song. The first experiment was performed with the proposed amplitude and frequency technique, while the second experiment was performed with constant frequency and amplitude. Results, show different envelope user preferences. The square and triangular envelopes were preferred in the first experiment, while only analogue envelopes were preferred in the second. This suggests, that the users' envelope perception was masked by the changes in amplitude and frequency between the notes. Even so, it is necessary to perform further studies to clarify the envelope's role on the perceived cross-modal similarity.

Author Keywords

virtual reality, haptic music, audio-tactile, cross-modal perception

ACM Classification

H.5.5 [Information Interfaces and Presentation] Sound and Music Computing, H.5.2 [Information Interfaces and Presentation] User Interfaces—Haptic I/O

NIME'16, July 11-15, 2016, Griffith University, Brisbane, Australia.

1. INTRODUCTION

The sound of physical music instruments are usually generated by the mechanical vibrations of different kinds of objects, like: the string in a piano or the stretched membrane in a drum. When some physical instruments are played, the player can listen to the produced sound and also feel the mechanical vibration though the instrument itself. Almost the same phenomena happened to music listeners, while listening to a live concert, the listeners ear the music and simultaneously feel the music mechanical vibrations from the sound source that reproduce the music. So, we consider that in some unknown degree music can also be perceived trough our touch sense. Then, by emulating this phenomena a novel method to translate the basic elements of music into a resemblant synthetic haptic vibration is proposed.

So, this project aims to translate the basic music structure elements of a song, as: the instrument characteristic envelope, the notes' pitch, timing and duration, into an enjoyable and resemblant haptic vibration. To achieve an immersive and enjoyable experience, we build an special entertainment environment, that consists of 3 main modules: a MIDI player module, a music animation module and a haptic module. The MIDI player module is only a MIDI player build from scratch. The music animation module provides a self-understandable 3D animation of the music structure. And the haptic module provides a synthetic haptic vibration of one particular instrument of the song. These 3 modules are synchronized on real time, so while the user hears the music, he can also see the correspondent animations and feel the vibration of any specific instrument in the musical piece (see project's video [4]).

Even if the proposed environment is composed by 3 modules, the haptic module is considered the most important one. So, our efforts are concentrated on creating a novel method to translate the auditive stimuli, from only one instrument of the song, into a resemblant haptic vibration. Consequently, we are not focused on recreating the haptic mechanical vibration that an instrument when it is played, instead we are focus on creating a synthetic haptic stimuli that resembles the sound's timbre of specific instruments. Also, the haptic module only transforms the sound of only one instrument of the song into a resemblant haptic vibration, because we seek to focus the user's listening attention into an specific instrument.

We performed several informal user observations during previous public demonstrations of the system. On those occasions, we observed that the users could easily understand the role of an specific instrument into the complete song, even without having any proper musical knowledge. Also, small children (less than 10 years old) were able to understand the complete system by themselves without any previous explanation. Additionally, most users verbally gave good comments about the system and actively mention different applications for the system. These informal observations show us, that most participants enjoyed using the environment to listen music. Even so, on this paper we do not evaluate the users enjoyment or measure their subjective perception, instead we focus in update the haptic signals and evaluate the perceived similarity between the audio and tactile stimuli.

2. MOTIVATION

The motivation of this research is very simple, this system is aimed to exchange the music listening experience though a haptic vibrations and provide the user with the opportunity to enjoy the basic elements of music with a different perspective. Consequently, our efforts are focused on finding a novel way to use the music elements like: notes' pitch, timing and duration to create a resemblant and enjoyable haptic stimuli.

Apart of the complete system itself. We consider that the most important value of this project are the human perception observations and the presented techniques used to create the synthetic haptic vibration. We consider that these and future results could be directly applied to enhance the perception correlation in diverse entertainment systems that use synchronized audio and haptic signals, like: electronic instruments without haptic feedback, video games, immersive cinema theatres and virtual reality applications.

3. PREVIOUS WORK

A simpler and more rudimentary version of this system was presented as a demonstration on the EC 2013 (Entertainment Computer Symposium) in Takamatsu, Japan [5]. Also the same version was presented as a demonstration for Eurohaptics 2014 [10], [3]. Even so, we considered it necessary to renovate the current system, because the human perception limitations were overlooked when the haptic module was designed. In contrast, the present method considers the human perception limitations to generate the resemblant haptic stimuli.

$$f(t) = A \cdot \exp^{(-d \cdot t)} \sin(t \cdot f * 2\pi) \tag{1}$$

where:

- t: time
- d: exponential damping rate
- f: frequency in Hz
- A: initial exponential amplitude at $t = 0$

Also, an improved algorithm to transform the note's properties into a synthetic haptic vibration is presented. The previous version used only an exponential damped sine wave function (see Equation 1), to represent any kind of instrument, without considering the envelope characteristics of the musical instrument itself. Consequently, if the envelope shape was generated by an exponential sine wave function, then the haptic envelope shape will not match for instruments with a steady sustain, like: organ or flute. In contrast, the present method generates audio-tactile signals with a correlated envelope shapes, in order to represent the envelope characteristics of different musical instruments.

4. RELATED RESEARCH

The system proposed by Nanayakkara et al.[13] used the same 3 module configuration as in this proposal. This system also used 3 different modules to visualize, ear and touch the music vibration. Also it was specifically aimed to enriching the listening experience of deaf users. In addition, a custom made chair with several conventional diaphragm speakers was built to be used as haptic device, in order to amplify the vibration of music. In contrast to our proposal, Nanayakkara et al. used the amplified audio signal itself as a haptic signal, but we consider that due the haptic sense limitations [16] is more effective to build a synthetic haptic signal to resemble the notes' properties.

Hawng et al. introduced a novel dual-band haptic music player [9]. This system used an special dual-mode actuator attached to a mobile device and a vibration generation algorithm to build the haptic signals from a music file. Hawng also evaluated the subjective performance of the dual-band method versus a bass-band vibtotactile playback, showing that the dual-band had a better subjective performance. Contrary to our proposal, this method relayed only a dual-band strategy, to separate the bass and tremble frequencies of music into different vibrations; so displaying the vibration of individual instruments was implausible. Also the method design did not consider the individual notes' properties to build their respective haptic signals. In contrast, we propose a simpler and granular strategy to generate the haptic vibration of an specific instrument, where the instruments' envelope, note's pitch and notes' duration are considered to create an specific vibration for every note.

5. SYSTEM'S DESCRIPTION

This entertainment environment is composed of 3 main components: a MIDI player, a simple 3D music animation and a haptic vibration module, that transforms the audio signal of one instrument into a resemblant haptic signal. All these components are synchronized in real time, so the listening music experience is enriched with a self-explanatory visual animation that shows the music score and a haptic stimuli that resembles the sound of an specific instrument inside the song.

5.1 MIDI player module

For this module a MIDI player was developed. This specific format was selected for 3 specific reasons: First, the MIDI format is discrete, so the notes' pitch, notes' duration and instrument information can be read directly, then any further audio processing analysis technique isn't needed. Second, in MIDI it is easy to precisely measure the envelope characteristic of any MIDI instruments, then this lets precisely measure the audio signal envelope, of different MIDI instruments, to design the haptic signals envelopes. Third, the sequence of MIDI messages was used to synchronize the haptic and visual modules with a relative precision (± 2 ms).

5.2 Music animation module

This module generates a music animation, by using the songs' notes' pitch, duration and timing, so implicitly the animation provides the information to the user. Also the same animation shows other information like: the number of tracks (instruments) that are involved in the song and the currently played notes. The main purpose of this animation is to help the most inexperienced users to match the notes' sound of an specific instrument in the song with their respective haptic stimuli.

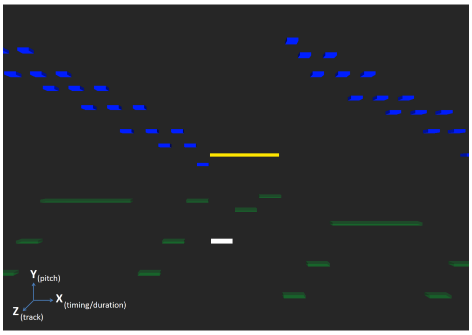

Figure 1: The animation of a song with 2 tracks, shown in blue and green. The active haptic track is shown in blue. Also the current haptic played notes are shown in yellow, while the current played notes of the other tracks are shown in white.

The animation was build using OpenGL, and it is based on Kevin Kelly's Music Animation Machine project [11]. In the animation every individual note is represented using 3D rectangles. The rectangles' length, position and color represent different properties of every note. The notes' length is represented by using the rectangle length. The rectangles' position in X-axis represents the note position in the song's time-line. The rectangle's position in the Y-axis represents the note's pitch, so notes with a higher pitch are placed higher that the notes with a lower pitch. The rectangles' Z-axis position and color are used to order the different instruments (tracks) of the song, therefore when the haptic active track changes all the rectangles are re-order and the current haptic active track rectangles are placed over the others (see Figure 1).

Additionally, the rectangles move around the screen from right to left with the same tempo as the music. Then the notes that are going to be played are on the right of the screen, the current notes that are being played are in the middle and the notes that had been played are on the left side of the screen. Also when the rectangles' respective notes are played their color change to identify them. Then, after the notes are being played, the rectangles continue their way though the screen from left to right until they disappear from the screen. Then new rectangles come from the right of the screen and the cycle repeats until the complete song is played. To synchronize the animation we take advantage of the the MIDI ticks and the MIDI messages to generate and synchronize the animation on real time. so the delay between the audio, visual and haptic signals was measured and controlled around $\pm$2ms.

5.3 Haptic Music Module

This module creates the haptic signal by considering: the notes' pitch, notes' duration, the note's timing and the instrument envelope characteristics.

This method employs two lineal mappings to establish the frequency and amplitude of the haptic signal between a previously selected range. Therefore, this method is not a straight forward mapping between the auditive perception range and the tactile perception range. Instead, the purposed method takes advantage of the MIDI data structure to narrow the possible audio frequencies to be mapped. First the method calculates the relative position of the notes' key in between the song, and then this relative position is used to determine the amplitude and frequency of the haptic signal. In addition, the haptic signal is built with the same temporal amplitude characteristics as the instrument, in order to resemble the instrument's audio envelope characteristics.

Spidar G6 [1] was selected as a haptic interface, because it is more versatile if compared with and speaker based haptic display. Also, it can be also used to haptically interact with the music animation in order to: switch the haptic instrument or touch the notes individually. In addition, this interface can transmit frequencies between 60 Hz $\sim$ 1 kHz; strongly and accurately [1].

5.4 Notes' pitch haptic mapping

If the human and auditory senses are roughly compared in terms of their perception limitations. The auditory sense performance to perceive different frequencies is outstanding, with a frequency JND (Just Noticeable Difference) of 0.6% for frequencies around 1000Hz [6]. In contrast the haptic sense has a very poor performance with a frequency JND of: 18% [14]. Now, if both modalities are then compared based on their perception range, the frequency hearing range is very wide, with: 0.0032 kHz $\sim$ 16 kHz [8], while the somatosensory sense has a narrow perception range between: 20 Hz $\sim$ 700 Hz[15]. In contrast, there is evidence that humans are able to tell if a pure tone haptic vibration has the same frequency as a pure tone audio signal. But this this has only been proven for low frequencies rates between 50 Hz to 250 Hz [2].

Is evident that the somatosensory sense is unable to detect frequency with the same sharpness and wideness as the auditory sense. Then we consider, that trying to directly map all the audible frequencies or to use audio itself as a haptic signal are inadequate methods to create a resemblant haptic vibration.

Therefore, we only consider the frequency range and the number of different keys played in the MIDI song to find the relative pitch position of every note in the song and map it into the haptic signal's amplitude and frequency. Also, to improve the perception between haptic signals, we decided to cut off the total number different MIDI keys (127), to only the range between the lowest note's key (k_{MIN}) to the highest note's key (k_{MAX}) in the song. By these means, the number of MIDI keys to be mapped is limited, so there are less keys to be mapped and consequently there is more room to fit different keys in the haptic range.

$$\triangle k = k_{MAX} - k_{MIN} \quad (2)$$

$$\triangle f = f_{MAX} - f_{MIN} \quad (3)$$

$$\triangle a = a_{MAX} - a_{MIN} \quad (4)$$

The proposed algorithm uses two lineal relations to map the notes' pitch into predefined frequency and amplitude ranges ($\triangle f$, $\triangle a$) for the haptic signal. The first lineal relation uses: the current note key (k), the range between the lowest and highest key of the song ($\triangle k$), the number of different notes with a different key inside the song (k_ϵ), and the lowest key in the song (k_{MIN}); to find the note's relative pitch position in the song (n). (see Equation 5)

$$n = \frac{k_\epsilon \cdot (k - k_{MIN})}{\triangle k} \quad (5)$$

After this, another lineal relation is used to map the previous computed relative position (n) into the selected frequency and amplitude ranges, by using the following for-

Instrument	t_1 ms	t_2 ms	t_3 ms	$s = a_h\%$	$r = a_h\%$
Instruments' ADSR Parameters					
Organ	5	0	t_4−25	100	1
Flute	75	0	t_4−60	100	1
Harpsichord	55	0	t_4−55	100	17.39
Guitar	15	0	t_4−15	100	1.36
Trumpet	30	110	t_4−100	32.09	1
Violin	66	376	t_4−225	57.14	1
Cello	40	290	t_4−200	47.45	1
Contrabass	55	355	t_4−225	52.74	1
Simple Envelopes' ADSR Parameters					
Square	0	0	t_4	100	0
Triangular	0	t_4	0	100	0

Table 1: ADSR envelope parameters, used in the Equation 10, in order to generate the haptic envelope of different music instrument. Also the parameters of the simpler envelopes, used in the evaluation, are mentioned in the table.

mulas:

$$f_h = f_{MIN} + \left(\frac{\triangle f}{k_\epsilon} \cdot n\right) \quad (6)$$

$$a_h = a_{MIN} + \left(\frac{\triangle a}{k_\epsilon} \cdot n\right) \quad (7)$$

So, the equations 6 and 7 define the frequency and amplitudes values that are relatively to the current key position in the song. By these means, treble instruments will be represented with haptic signals with high pitch and amplitude, while bass instruments will be represented with haptic signals with low pitch and amplitude.

5.5 Envelope haptic mapping

In addition, the envelope of the haptic signal was defined to have the same amplitude temporal characteristics as the audio signal. By these means, the same envelope characteristics of different musical instruments can be represented in the haptic signal. To generate an audio-tactile stimuli with a perfectly correlated envelope, first the envelope shape of different MIDI instruments were measured, by using an oscilloscope and the Windows MIDI synthesizer without any extra audio filters. So, the instruments' timing and amplitude during attack, decay, sustain and release phases was measured (see Figure 2). Then, these measurements were used in an ADSR filter to precisely define the haptic signal envelope. So by these means the can be designed to have the same envelope and fundamental frequency properties as any MIDI instrument.

$$b(x) = \sin(x \cdot f_h \cdot 2\pi) \quad (8)$$

$$m = \frac{s - a_h}{t_2 - t_1} \quad (9)$$

$$E(x) = \begin{cases} \dfrac{x \cdot a_h}{t_1} \cdot b(x) & x < t_1 \\ [(m \cdot x) - (m \cdot t_1) + a_h] \cdot b(x) & t_1 \le x < t_2 \\ s * b(x) & t_2 \le x < t_3 \\ \left[s \cdot exp\left(\dfrac{\log(r) \cdot (x - t_3)}{t_4 - t_3}\right)\right] \cdot b(x) & t_3 \le x < t_4 \end{cases} \quad (10)$$

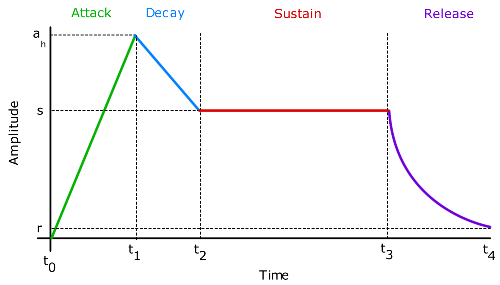

Figure 2: Equation 10 timing $(t_0, t_1, t_2, t_3, t_4)$ and amplitude (peak amplitude a_h, sustain s, final amplitude r) parameters.

The final haptic signal is created by using: an ADSR filter (defined in Equation 10), the mapped haptic frequency and amplitude (defined in Equations 6 and 7) and the MIDI envelope measurements (see Table 5.4). So, the haptic signals masimum amplitude will by defined by a_h, it's frequency will be defined by f_h. So by these means the haptic signal could have the same envelope and fundamental frequency as any MIDI instrument. Also the purposed method (see Equation 10) keeps the signal frequency constant even if the envelope shape is modified.

6. EVALUATION

Two psychophysical experiments were performed to evaluate if the envelope correlation of an audio-tactile stimuli can improve the subjective perceived similarity between both signals. In both experiments, the users ranked the similarity between an specific instrument in a song and several haptic signals build with different envelope shapes. On the first experiment, the frequency and amplitude of the haptic signals was changed accordingly to the notes' key (as described in Section 5.4), while in the second experiment the notes' key was ignored and the haptic signal used only constant frequency and amplitude.

6.1 Experiment #1 setup and description

In the first experiment the user task was to rank the perceived similarity between 3 different haptic stimuli and the sound of 4 different instruments in a song. The haptic signals were build using different types of envelopes: a triangular envelope, a square envelope and the actual sound envelope. The haptic signal with the same envelope characteristics as the audio signal was defined as the analogue envelope. The haptic signals' frequency and amplitude was defined by the technique mentioned in the Section 5.4. So, the amplitude haptic range was set between: a_{MIN} = 7.5dB and $a_{MAX} = 30dB$, while the frequency was set between: f_{MIN} = 50Hz and f_{MIN} = 250Hz. This particular frequency range was used in order to avoid aliasing in the haptic signal, due the haptic device refreshing rate (1000Hz).

The previously mentioned virtual environment let the users listen to the music, see the animation and feel the instrument's vibration. For this experiment the environment was slightly modified to let the user rank and change between different haptic vibrations. The particular music piece used for the experiment was a MIDI rendition of Bach's 1079 Sonata - Largo movement [12]. This particular song used 4 difference instruments: harpsichord, violin, contrabass and flute. So, we presented 3 different envelopes for every instruments, then in total every user had to rank 12 different audio-tactile stimuli. While listening to the music, the user was able to change between the 3 different envelopes at any time, and rank them using an A,B,C scale. Also, the user was instructed to rank the 3 haptic envelopes before continue to the next instrument. In addition, the 3 haptic envelopes were presented in random order and the next instrument to rank was also randomized. The experiment finished after the user ranked the 12 different audio-tactile stimuli presented in the song.

Due Spidar G6 particular design, the contact stiffness between the user's finger and the haptic pointer depends on the user's grasping force. Therefore, this issue can create an amplitude variability on the haptic signal between the participants. Then, to tackle this problem the user's right index finger was attached to the haptic pointer using a Velcro strap. Also, the user was not allowed to touch the haptic pointer with any other finger. And, before every experiment, the peak amplitude (a_{MAX}) for every subject was measured and controlled to be around 1mm.

The participants listen the audio signal though a Sennheiser MX 475 earbuds and to isolate the participants auditive sense they also used industrial grade noise cancel earmuffs. To minimize inadvertent vibration of the haptic device, this was placed over urethane foam over a solid 1.5cm iron plate. Also the user's right arm was placed on a armrest separated at the same height as the haptic interface. Finally, to avoid any visual clue from the Spidar's mechanisms movement, the haptic interface was placed behind a tall white screen.

In order to clarify the similarity concept among the users, without bias the their particular preference, 2 rounds of practice were performed before the main experiment. For the practice rounds the isolated tracks of violin and contrabass from Bach's BWV 1079 Sonata - Allegro movement [12] were used. As in the main experiment, we randomly presented 3 different haptic signals build with different envelopes and then we asked the participants to rank the presented vibration accordingly to the similarity between the instrument's sound and the vibration. After finishing every practice round the analogue envelope position was reported to the user, so the participant could understand the similarity between both signals by his own perceptional means. Also these practice rounds helped the users to familiarize with the keystrokes used to: change the vibration (0~1), rank the vibration (A,B,C) and change the instrument (t).

6.2 Experiment #2 setup and description

Also a second experiment was performed with the exact same conditions, methodology and participants. Contrary to the previous experiment, a constant haptic frequency and amplitude were selected for this experiment. So, the notes' pitch were overlooked and constant frequency of 250Hz and a peak amplitude (a_{MAX}) of 1mm was used for every haptic signal. This experiment was performed to evaluate the cross-modal similarity perception of the signals' envelopes under more controlled circumstances. By these means, we evaluate if the amplitude and frequency variability affect the users' cross-modal envelope perception.

7. RESULTS

Both experiments were performed by 11 participants, 5 females and 6 males. All of them healthy adults between 23 to 30 years old. A computer with an Intel i7-3770S, Windows 7 and a Realtek ALC662 sound card was used to perform both experiments.

If the Copeland's method is applied to the results of the first experiment, then the Copeland's favourites of each instrument are: the square envelope for violin and flute, the triangle envelope for the harpsichord and the actual sound envelope for the contrabass (see Figure 3). These results suggest, that the participants preferred haptic signals with simpler envelopes (square and triangular) over the analogue envelope, when the frequency and amplitude of the haptic signal was variable.

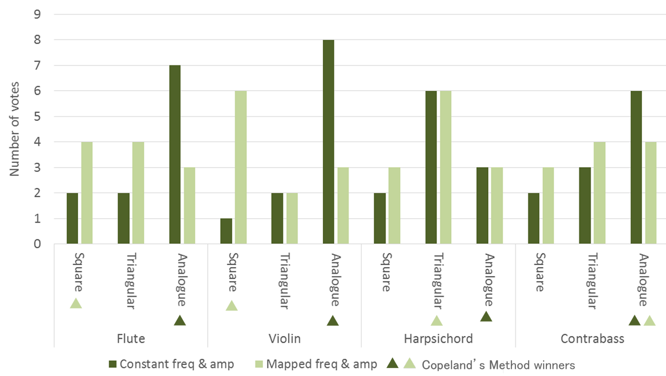

Figure 3: The figure shows the number of votes received by the best ranked audio-tactile stimuli. The votes of the experiment with a constant amplitude and frequency for haptics are shown in lightgreen, while the results in dark green are for the constant frequency and amplitude experiment. And the small triangles indicate the Copeland's winners for every instrument.

On the other hand, in the second experiment the Copeland's method results show, that the analogue haptic vibration was the best raked haptic audio-tactile stimuli for all the instruments. So these results show a clear preference to the analogue envelope for all instruments. In addition the same preference is clear by counting the number of votes given to the best raked envelope.

As mentioned before both experiments were performed under the same conditions and with the same participants. So, the contrast in the results suggest that, the frequency and amplitude variability between the notes, created by the presented mapping technique, masked the haptic envelope perception. Then, we consider that, the participants were not able to perceived the envelope similarities of both signals with the same accuracy as in the second experiment.

The results of the first experiment show that even if the participants preferred the simpler haptic envelopes, however the participants chose simpler envelopes, who had more amplitude similarities to the audio envelope. For example, for the flute and violin the square envelope was preferred over the triangular, so in this case we suppose that the steady sustain of violin and flute caused a preference of the square envelope. Also we suppose that the similar decay rate between the harpsichord and triangular envelope caused the preference of the triangular envelope over the square envelope. Even so, for the contrabass the users preferred the analogue envelope. So, we suppose that the particular amplitude fluctuations in the contrabass envelope shape helped the users to perceive the haptic envelope shape. In any case it is necessary to perform further studies to clarify these observations.

8. CONCLUSION

The proposed entertainment system introduced a novel way to map the notes' pitch, duration and the particular instrument envelope into a haptic vibration. To measure the subjective perceived similarity between the envelope shapes of the audio and haptic signals; two perception experiments were performed. Both experiments were performed under different amplitude and frequency conditions for the haptic signals. In the first experiment the amplitude and frequency were variable and defined by the proposed mapping method (Section 5.4) while in the second experiment the amplitude and frequency were constant, at 1mm peak amplitude (a_{MAX}) and 250 Hz respectively. The obtained results, clearly show that the users preferred the analogue envelope, when the amplitude and frequency of the haptic signal were constant. But, at variable amplitude and frequency the users preferred the simpler analogue envelopes (square and triangular), overlooking the envelope shape similarity of both signals.

Therefore, we suppose that the dynamic amplitude detection range of the haptic receptors is more narrow if compared to the same range in audio. So, it seems that displaying the notes' key though amplitude and frequency variations in addition to the instruments' envelope though a haptic signals saturates the haptic mechanoreceptors. Consequently, it seems necessary to omit the frequency and amplitude variations, so the user could be able to perceive the envelope cross-modal similarity.

In conclusion the experiments suggest that the haptic signals' amplitude and frequency variation produced the perception masking of the haptic envelope. Even so, it has been reported that the vibrotactile intensity discrimination is not affected by the stimulus frequency condition [7]. So, we suspect that phenomena could be caused only by the amplitude variations between the vibrotactile stimuli. On the other hand, the selected frequency value at 250Hz, used in the second experiment, might helped the users to identify the envelopes' attack easily, due that the human absolute detection threshold has a minimum value of 0.12μ at 250Hz [15]. In anyway, we consider it necessary to perform further and a more detailed evaluation on the reported envelope perception masking and on audio-tactile envelope correlation perception.

9. ACKNOWLEDGEMENTS

We want to thank professor Takako Yoshida for her continuous advice and support.

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