10-2012

Tone-2 tones discrimination task comparing audio and haptics

Lorenzo Picinali

Christopher Feakes

Davide Andrea Mauro
Marshall University, maurod@marshall.edu

Brian F. G. Katz

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Abstract—To investigating the capabilities of human beings to differentiate between tactile-vibratory stimuli with the same fundamental frequency but with different spectral content, this study concerns discrimination tasks comparing audio and haptic performances. Using an up-down 1 dB step adaptive procedure, the experimental protocol consists of measuring the discrimination threshold between a pure tone signal and a stimulus composed of two concurrent pure tones, changing the amplitude and frequency of the second tone. The task is performed employing exactly the same experimental apparatus (computer, AD-DA converters, amplifiers and drivers) for both audio and tactile modalities. The results show that it is indeed possible to discriminate between signals having the same fundamental frequency but different spectral content for both haptic and audio modalities, the latter being notably more sensitive. Furthermore, particular correlations have been found between the frequency of the second tone and the discrimination threshold values, for both audio and tactile modalities.

Index Terms—Haptic interfaces, Psychoacoustics.

1 Introduction

INDIVIDUALS with normal hearing are generally able to discriminate auditory stimuli that have the same fundamental frequency but different spectral content (for example an A3 played on a clarinet and the same note played on a flute). This study concerns to what extent it is possible to perform the same differentiation using vibratory tactile stimuli.

Vibratory tactile stimulations are often employed to assist in the creation of virtual objects in a computer simulation, or again to support and facilitate specific tasks within a multimodal interactive application. Haptic vibratory actuators can be found in mobile phones, tablet PCs, etc. and are used to enhance the interactivity of the device, and to transfer selected information to the user (e.g. the arrival of an incoming phone call). Generally, the type of message transferred through vibration is of *boolean* nature, therefore limited to *on* or *off*. Different amplitudes of the vibratory stimulus are normally used as a user-set parameter, and not for conveying additional information. Frequency modulation, as well as changes in the spectral characteristics of the vibratory signal, are very rarely employed. It is in fact generally assumed that the human sensitivity to such differences, in a vibratory tactile stimulation, is not particularly high.

While studies investigating the ability of the human tactile system to discriminate between signals with different frequency have been successfully carried out in the past (see [10] and [11]), similar investigations on the discrimination between signals with different spectral characteristics have only recently begun to emerge (see [5]).

The hypothesis at the base of this study is that the human tactile system can indeed discriminate between vibrations with the same fundamental frequency but different spectral characteristics. The objective is therefore to investigate how spectral variations are perceived through tactile vibratory stimulation, and to compare these results with those measured for auditory stimulations.

A perceptual experiment composed of three distinct tests has been carried out (for an overview of the whole experiment, see [8]). In this paper the results of one of those tests, concerning the

- *L. Picinali and C. Feakes are with the Interactive and Media Technologies research group, De Montfort University, LE1 9BH, Leicester, UK.*
  E-mail: lpicinali@dmu.ac.uk and cfeakes@dmu.ac.uk
- *D. Mauro is with the LIM-Dipartimento di Informatica, via Comelico 39/41, 20135, Milano, Italy.*
- *B. FG Katz is with LIMSI-CNRS, Université Paris Sud, 91403, Orsay, France.*

discrimination between a pure tone signal and a stimulus composed of two concurrent pure tones, are presented and discussed.

2 Background

It is well known that differences in the frequency content and spectral envelope of acoustic signals are often perceived as timbre variations, allowing for the differentiation between stimuli with the same fundamental frequency, loudness and duration, while having different spectral characteristics (an overview on studies in this field can be found in [6], pp. 105-107 and pp. 270-273).

It was once believed that the tactile sense was inadequate for tasks such as transmission and processing of complex information. This perspective has rapidly changed in the past half-century, thanks mainly to the increasingly sophisticated electronic measuring devices, once used only in auditory laboratories, but now also found in tactile research.

Previous studies have investigated the perceptual aspects of frequency and amplitude variations in tactile vibratory stimulations. In [10], the subjective perceived intensity, as a function of the vibration frequency, has been studied and compared in relation to the contact area. Results showed that for pure tones detection thresholds improved with frequency, from 25 Hz to 200-300 Hz, at a rate of about 12 dB/octave, then decreasing with the same slope to about 1000 Hz. The larger the contact area (up to 5.1 cm^2), the lower the threshold.

In [11], various studies are reported on frequency and amplitude discrimination for tactile stimuli using pure tones, pulses, and narrow-band noise signals. Comparing the frequency discrimination thresholds between audio and tactile highlights that whilst the ear can discriminate frequency differences of the order of 0.3%, the performances of the skin were found to be much lower, of the order of 30%. In terms of amplitude discrimination, the threshold for vibratory stimulation was found to be between 0.4 and 2.3 dB, values that are very similar to the threshold for auditory stimulation (between 0.5 and 1 dB, as reported in [6], pp. 139-139). Furthermore, the tactile system was found to be capable of processing vibrations within a dynamic range of 55 dB, with a notably larger range for the auditory system (120 dB, see [6], pp. 127-128).

The ability to discriminate between different signals and design parameters for the generation of tactile feedback has been investigated in [5]. Experiments were conducted in an attempt to determine whether one can distinguish different looped audio signals rendered through an electro-dynamic shaker positioned under a touch-sensitive screen. Stimuli differed in their spectral content and rhythmic characteristics. Results outlined that a distinction was indeed possible.

Some applied studes have employed audio and haptic stimuli for the discrimination between different non-visual stimuli [4] or for the cross-modal comparrison of values during exploration of complex spatial data [1], [2]. These studies have shown the utility of audio-haptic renderings in virtual environments. This is particularly useful in conditions where the visual chanel is already saturated.

Basic studies performed using pure and/or very simple tones for quantifying the discrimination thresholds in terms of spectral variations for tactile stimuli have not been found in literature. Furthermore, studies have not been found in which the evaluation was carried out for both audio and tactile stimulation within the same experiment, using exactly the same stimuli and protocol.

3 Method

Aiming at investigating the differences between audio vibratory tactile perceptions relative to the detection of spectral variations between signals with the same fundamental frequency, a perceptual evaluation test has been designed and carried out.

The use of the same hardware and software for the delivery of the auditory and haptic feedback was made in order to facilitate a consistent comparison of results between the two modalities.

A total of 26 subjects, male and female, between 19 and 65 years of age participated in the current study.

3.1 Experimental apparatus

The experimental apparatus is composed of a software component, a computer, an audio interface, an audio amplifier and two 8 inch loudspeaker woofer drivers, mounted on a wooden board (see Fig. 1): one of these has been modified by removing the speaker cone. A coupling system (a rigid 10 cm diameter plastic dome, on which the fingers of the subjects are placed) was installed in order to transfer the vibrations of the coil to the hand. The

(a)

(b)

Fig. 1: (a) Haptic test stimuli protocol, including the use of noise-suppression headphones. (left driver) Cone removed and added dome for haptic stimuli, (right drive) unmodified for audio stimuli. (b) Hand of a participant, showing the wrist resting on the wooden board and the three mid-fingers placed on the plastic dome.

subjects are instructed to rest their dominant hand on the wooden board surrounding the driver, and to position the last phalanx of their middle three fingers (index, middle and ring fingers) on the plastic dome, without applying any pressure (see Fig. 1). These choices (hand position, parts of the finger to be in contact with the vibratory actuator, etc.) have been made based on studies from [9] and [10]. Considering the audio rendering modality, the subjects have been asked to place their head at 1 m from the driver. All subjects completed tests for both modalities. The generation and processing of the signals, the testing procedures and the data collection have been implemented in a Max/MSP[1] platform/patch. The digital signals (44.1 kHz and 24 bits) are sent to a MOTU Traveler FireWire audio interface, converted to analogue signals, and sent to an Omniphonics Footprint 150 amplifier, and then to one of the two drivers, depending on the testing modality. This equipment provided a flat (±3 dB) frequency response between 10 and 4000 Hz.

3.2 Calibration

After a series of informal trials and evaluations, and reviewing previous literature in the field of auditory and vibratory-tactile perception (see Section 2) as well as the limitations of the playback system, the frequency ranges for the tests have been set at 10-500 Hz for haptic, and 60-3000 Hz for audio.

For the audio modality the signal amplification was calibrated in order to generate an SPL value of 70 dB A-weighted for a 1000 Hz pure tone at 1 m distance from the loudspeaker driver (head location during audio tests). This value has been chosen considering the standard levels used in audiological evaluations [7].

Due to the sensitivity of thresholds to contact area, the tactile calibration stage was performed for each subject individually. The participants were asked to place their fingers on the plastic dome (see Section 3.1) while a 100 Hz sinusoidal stimulus was reproduced. The level was amplified until the subjects could just perceive a vibration. The signal gain was then increased by 20 dB, in order to have a clear presentation level and to assure consistency in the haptic presentation stimuli across subjects. The rendered level was therefore calibrated at *Threshold of Perceptibility* (250 Hz)+20 dB.

During the haptic testing, the SPL produced by the driver was 57 dB A-weighted (measured at 250 Hz), while the background noise in the testing environment was 32 dB A-weighted. In order to avoid auditory stimulation from the haptic driver, a pair of passive noise-suppression headphones were worn (see Fig. 1) which provided a sound level reduction of 20 dB (manufacture's statement).

3.3 The test

Using a simple up-down 1 dB step adaptive procedure [3], the discrimination threshold is measured between a pure tone signal and a stimulus composed of two concurrent pure tones, changing the amplitude and frequency of the second tone.

The participants are presented with groups of two stimuli in the following sequence: first signal for 1 s, 200 ms of silence, second signal for 1 s, with each signal processed with a 5 ms fade in and fade out. Initially, the two stimuli are the same (a pure tone a with frequency f_a). The second stimulus is then iteratively modified by adding to a another pure tone b with frequency f_b, increasing adaptively the amplitude of b and decreasing the one a, in order to maintain the same RMS level for both signals. The participants are then asked to determine when

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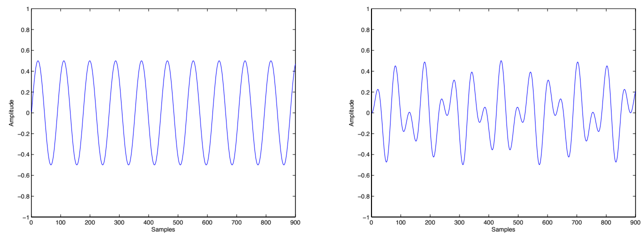


(a) (b)

Fig. 2: (a) Waveform of the pure tone audio signal used for test two. (b) Waveform of the two-tones audio signal ($f_2 = f_1 \times 1.7$) used for test two. The diagrams correspond to the signals before the RMS calibration. For the haptic rendering, the same signals have been used, but with a fundamental frequency of 100 Hz instead of 500 Hz.

a difference can be heard between the first and the second stimulus. The test is then carried out adaptively until a threshold value is found (after 5 up-down direction changes).

The values of f_1 are set at 500 Hz for the audio modality, and 100 Hz for haptic. Six values have been chosen for the signal b, where f_b is a multiple of f_a defined by the multiplier factor m (for both modalities): m = 0.5, 0.7, 1.7, 2.0, 2.7, 3.0. These values are chosen in order to allow various combinations of two concurrent tones at different frequencies, with and without harmonic relations. Example waveforms are shown in Fig. 2.

4 Results

The discrimination threshold values, expressed in terms of dB difference between the a and the b components in the second signal, are reported for each modality and for each value of m in Table 1 and as boxplots in Fig. 3 and 4.

There is a notable difference between the mean discrimination threshold values for the haptic modality (mean of -20.6 dB, std 12.8) and for audio (mean of -46.2 dB, std 12.3), the latter being distinctly lower (higher sensitivity). This highlights the fact that the human hearing system is more sensitive in discriminating between a pure tone and a complex tone composed of two pure tones if compared with the tactile system.

Furthermore, it can be observed that for the haptic modality the values are generally lower (better performance) when f_2 is not in harmonic relation with f_1 (i.e. when f_1 is a multiple of f_2, or vice versa). For $m = 0.7, 1.7, 2.7$, the mean discrimination threshold is -22.8 dB (std 12.6), while for $m = 0.5, 2.0, 3.0$ it is -18.4 dB (std 12.7), a difference of 4.4 dB. A similar tendency can be observed for the audio modality, but in this case the difference is only of 2.1 dB.

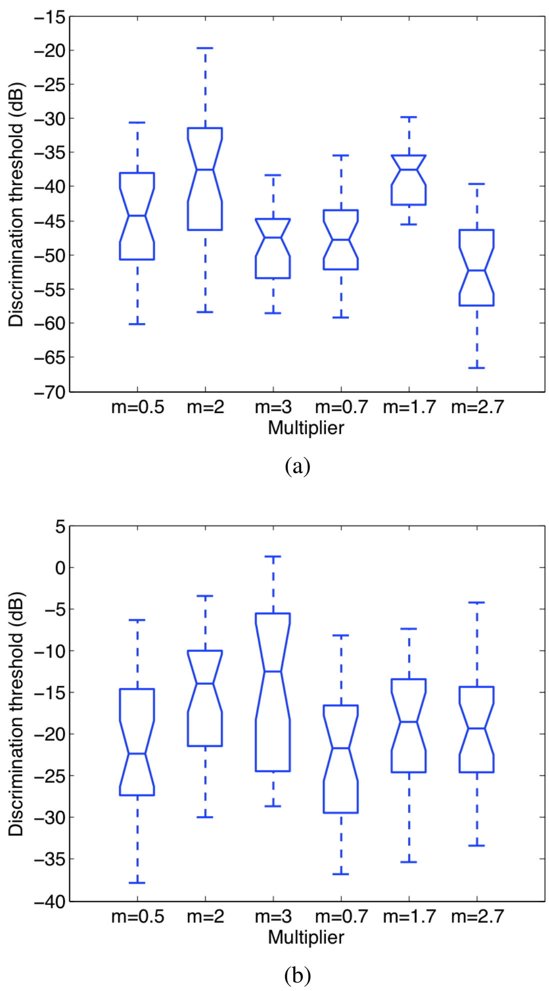
TABLE 1: Mean and std of the discrimination thresholds for the different values of m, displayed for the two modalities.

	Haptic		Audio	
m	Mean	St. Dev.	Mean	St. Dev.
0.5	-21	8.4	-45.3	9.4
0.7	-24.2	11.9	-48.1	11.1
1.7	-22.3	14.1	-40.7	11.8
2.0	-18.1	12.7	-40.5	15.6
2.7	-21.9	12.1	-52.8	10.2
3.0	-16.2	15.8	-50	10.4

4.1 Impact of harmonic and in-harmonic *m* values

Inferential statistics have been performed to identify whether the differences between harmonic and in-harmonic m value groups are statistically significant. The data sets are normally distributed, therefore a paired-samples t-test was conducted. For the haptic modality, there is a significant decrease in the discrimination threshold values from harmonic m to in-harmonic m value, $t(77) = 3.52$, $p = 0.001$ (two-tailed). The mean decrease in values, as outlined above, is 4.4 dB with a 95% confidence interval ranging from 1.9 to 6.8 dB. The η^2 statistics (.30) indicates a large effect size. Considering the audio modality, the difference is less significant, $t(77) = 1.69$ and $p = 0.095$ (two-tailed). Consequently, the mean decrease lowers to 2.1 dB, with a 95% confidence interval from -0.3 and 4.2 dB, and an η^2 statistics (.09) that indicates a moderate effect size.

An explanation of this result could consider the fact that non-harmonic overtones are more likely to generate amplitude beats with the fundamental component, and these could be used to discriminate between different stimuli, offering a further cue for this experimental task. From the t-test analysis, it seems clear that this cue is more relevant for the haptic modality than for the audio modality.



(a)

(b)

Fig. 3: Discrimination threshold values for audio (a) and haptics (b). The values are displayed by rendering modality and f_2 multiplier m.

4.2 Overall impact of m values

A more detailed analysis of the data in Table 1 suggests that the mean value variance for different m multiplying factors is larger for the audio modality (std 5) than for the haptic modality (std 2.9).

A one-way between-group analysis of variance was conducted to explore the impact of m on the discrimination threshold values. For the haptic modality, there is not a statistically significant difference between the different m value groups: $F(224,161) = 1.393$, $p = 0.23$. In contrast, for the audio modality the difference between the m value groups is statistically significant: $F(70,130) = 4.835$, $p < 0.001$. Post-hoc comparisons using the Turkey HSD test indicated that the mean values (audio modality) for $m = 1.7\&2.0$ differ significantly from the values for $m = 2.7\&3$, while no

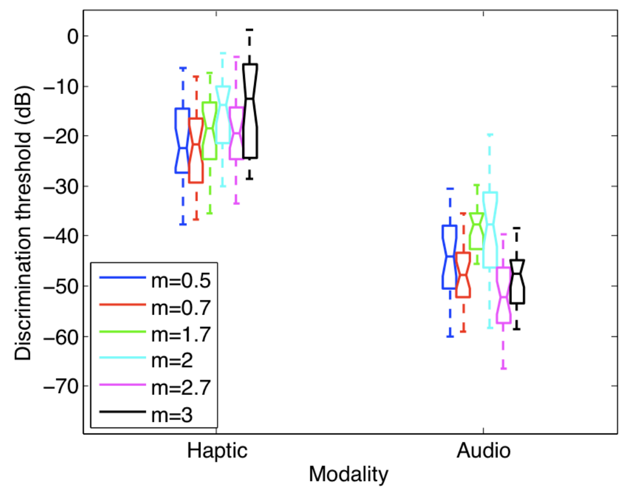


Fig. 4: Discrimination threshold values for both modalities. The values are displayed by rendering modality and f_2 multiplier m, and are grouped on the left for harmonic m values, and on the right for in-harmonic ones.

significant difference was found between the values for $m = 0.5\&0.7$ and any of the other groups.

This indicates that the discrimination threshold for the audio modality varies more than the haptic modality for the different values of the multiplying factor m, with an increased sensitivity when the frequency of f_2 is between the one of f_1 and its double.

5 Conclusion

The outcome of this perceptual evaluation comparing audio and haptic-vibratory senses is that, for both modalities, spectral differences between different stimuli with the same fundamental frequency can be perceived, with the auditory perception being more sensitive if compared with the tactile perception.

In terms of discrimination thresholds between a pure tone and a stimulus composed of two pure tones, the difference between the two modalities is 25.6 dB, with the audio sensitivity being distinctly higher. Furthermore, a lower discrimination threshold (4.4 dB) for the tactile modality is found when the two tones composing the second stimulus are not in harmonic relation. A similar tendency, but with reduced magnitude, is also observed for the audio modality, but this cannot yet be considered statistically significant. Finally, the audio modality discrimination threshold is more variable for the different values of the multiplying factor m, with an increased sensitivity for $m = 1.7\&2$.

Considering the observations outlined in Section 1 and 2 regarding the use of haptic vibratory actuators in mobile devices, the results of this test can be used in the development of applications that take full advantage of tactile vibratory feedback, towards increasing the amount of information that can be transferred to the user via haptic stimulation.

The perceptual evaluation described in this paper is one of a set of three, eachl aimed at identifying and quantifying differences between audio and vibratory tactile senses in discriminating spectral variations. The results of the other tests will soon be published. Furthermore, all three tests are currently being carried out on visually and hearing impaired groups, in an attempt to compare the results between individuals with and without sensory deprivations.

ACKNOWLEDGMENT

The authors would like to thank Steve Regester, Dave Tunnicliffe, and Dr. Nathan Jeffery (CTS, De Montfort University) for the continuous support during the preparation and execution of the test.

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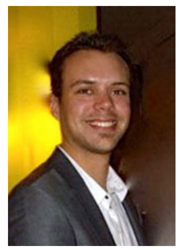
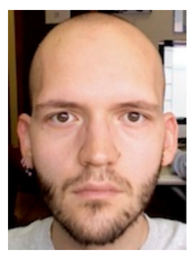
Lorenzo Picinali Lorenzo is a Senior Lecturer in Music/Audio Technology in the Department of Media Technology at De Montfort University (Leicester, UK) and an active researcher in the Interactive and Media Technologies (IMT) and in the Virtual Reality and Assisted Living (ViR.AL) research groups. Currently, his main research interest is in the use of virtual reality interactive applications for hearing and visually impaired individuals. Dr. Picinali is also involved in national and international research projects in areas such as music technology, binaural auralization, audiology and audiometric techniques, audio-haptics interaction design and multimodal interfaces.



Christopher Feakes Chris Feakes is a Ph.D. student in the Interactive and Media Technologies (IMT) research group (De Montfort University, Leicester). Chris is currently working towards a Ph.D. and is interested in a number of factors relating to virtual auditory environments for the blind, such as the ways in which head movement may be used to facilitate sound localization, the comparative study of auditory perception in blind and sighted individuals and the use of motion tracking and movement control in user interfaces for auditory virtual reality.



Davide Mauro Davide A. Mauro is currently a post-doc researcher at Laboratorio di Informatica Musicale (LIM). He received his Ph.D. title in Computer Science in 2012 at the Universit degli Studi di Milano with the thesis "On binaural spatialization and the use of GPU for audio processing." His research interests are currently in the field of computer music and 3D audio, and include binaural spatialization techniques.

Brian FG Katz Since 1987, Brian F.G. Katz is involved in various technical and academic areas of acoustics and audiovisual design. His responsibilities have included acoustical design of various architectural spaces, project management, acoustical research and development, and audiovisual system design. His areas of technical expertise include large and small room acoustics, acoustical - measurements, signal processing, hardware/ software development tools, and acoustical computer modeling. His experience has included a variety of performing arts projects in the USA, Europe, and Asia. Since 2003, Brian FG Katz is a researcher and is responsible for the working group Sound&Space" within the group "Audio&Acoustic" at the LIMSI (Orsay, France), a CNRS laboratory.