Vibrotactile Discrimination of Pure and Complex Waveforms

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ABSTRACT

Here we present experimental results that investigate the application of vibrotactile stimulus of pure and complex waveforms. Our experiment measured a subject's ability to discriminate between pure and complex waveforms based upon vibrotactile stimulus alone. Subjective same/different awareness was captured for paired combinations of sine, saw, and square waveforms at a fixed fundamental frequency of 160 Hz (f_0). Each arrangement was presented non-sequentially via a gloved vibrotactile device. Audio and bone conduction stimulus were removed via headphone and tactile noise masking respectively. The results from our experiments indicate that humans possess the ability to distinguish between different waveforms via vibrotactile stimulation when presented asynchronously at f_0 and that this form of interaction may be developed further to advance digital musical instrument (DMI) extra-auditory interactions in computer music.

1. INTRODUCTION

Acoustic instruments provide vibratory feedback that is tightly coupled with the sound-generating module of the instrument. That is to say, the mechanisms for creating sound and audible resonances are often the same as those that are initiated by the musician. The relationships between physical interaction and the generation of sound are inseparable, and vibrations that are introduced outside of this interaction are sometimes considered as distracting or noisy. With respect to DMI design, we can no longer apply what is perceived as the innate vibrational properties of an acoustic device to a digital one, as the sound generating module is no longer tightly coupled with the gestural interface. However, with DMIs we can extend the vibrotactile feedback element beyond that of the acoustic experience.

The findings of Gillmeister and Eimer [1] have highlighted the function of vibrotactile intensity enhancements when tactile stimulus is presented synchronously with auditory stimulus. The interactions between the two stimuli produce mutual benefits and follow principles of inverse effectiveness, as well as the spatial and temporal rules of multisensory integration [2]. In the principle of inverse effectiveness, it is accepted that multisensory integration is more likely to present a stimulus as perceptually stronger than when the same unisensory stimuli are applied in isolation. Further to this, the spatial and temporal rules of multisensory integration state that the advantages of multisensory integration are strengthened when the stimuli arise from approximately the same place and in relative synchrony. Therefore, the parameters of vibrotactile feedback in DMIs can be used to support auditory output, but also expanded to include other complimentary information, such as score data, or other abstract cues from within an ensemble, with care taken not to distract or confuse the user. The application of this vibratory signal will depend ultimately on the musician's ability to process the information in relation to the audio/visual feedback they are already receiving concurrently.

2. BACKGROUND

Observing the similarities between touch and hearing, we can see indications of a cross modal sensory interaction. This is apparent in terms of the type of physical energy captured; the receptors used in their detection and the relatively short overlap of the frequency domains. This is prevalent in most musical performance, the sound generation and tactile analysis frequently occur in tandem. In tasks that involve textural analysis of an object, the tactile system is dominant; however, in musical tasks, the auditory modality takes precedence. Due to the sensory dominance of hearing over tactile, the interaction between both generally goes unnoticed.

The sensations of tactile signals are bounded to a limited range (approximately 0.3 to 1000 Hz), and an individual's sensitivity to a stimulus. Following this, it can be said vibrotactile feedback from a musical instrument is secondary to that of auditory feedback in a multimodal signal. Moreover, vibrotactile feedback in a musical performance is not the primary source of feedback, but it operates in support of the auditory cues received. Most musical instruments are played with the hands, fingers, or mouth, which have the highest concentration of tactile receptors in the body. This enables fine-grained manipulation of the playing of the instrument. Further studies have shown that other parts of the body are sensitive to vibrotactile stimulus, but to a much lesser extent. The subdivisions of the vibrotactile response of the cutaneous system are due to the arrangement of four major types of receptors in the skin. These being: the Meissner Corpuscles, the Merkel Corpuscles, the Ruffini Corpuscles, and the Pacinian Corpuscles. The upper region of the skin contains the Meissner corpuscles. These corpuscles are responsible for the transduction of light touch, stretching, and texture stimuli. Within the same region the Merkel corpuscles function to detect sustained pressure and low frequency vibration. Deeper within the skin lies the Ruffini corpuscles, which also detect sustained pressure. The deepest of the corpuscles are the Pacinian corpuscles. These are responsible for the detection of deep pressure and high frequency vibrations that are applied to the surface of the skin. The Pacinian corpuscles respond to high-speed displacement of the skin, but not when under sustained pressure.

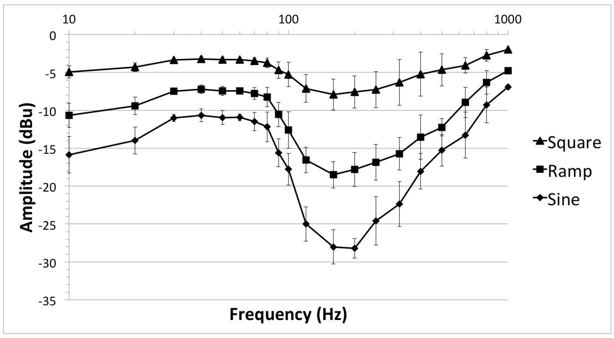

Figure 1: Threshold of perception of vibration applied via the Audio-Tactile Glove [6].

Recent psychophysical studies have focused on the human ability to discriminate between vibrotactile tonalities whilst being masked from an auditory source [3, 4, 5]. These experiments concentrate on the amplitude of fundamental sine waves and the point of which a subject can sense a vibrotactile signal of this sort. These experiments distinguish themselves from the work described here by focusing on pure tone detection or musical timbres. Our experiments have also resulted in similar findings in tactile detection levels, but include controlled complex waveforms containing a fundamental with odd harmonics, or odd and even harmonics. The sub-threshold of detection for each of these wave-shapes has been previously measured as output amplitudes in dBu (Figure 1). The sub-threshold of vibrotactile stimulus detection can be divided into distinct ranges, pertaining to the frequencies that are cutaneously detectable and the waveform of the stimulus. The main range considered is that from 0.3 Hz to 1000 Hz, which corresponds with the response range of the tactile system. Within this range, the region of 100 to 500 Hz is the most sensitive [7]. Other studies have divided this range even further [8], stating that within the span from 20 Hz to 40 Hz, the threshold for vibration detection is independent of the frequency of vibration. However, between the frequencies of 40 Hz to 700 Hz our threshold of sensitivity is a function of frequency, with peak sensitivity around 250 Hz [9]. With the amplitude of a tactile signals detection being dependent on frequency and the waveform shape being delivered, we have attempted to reduce our subject's perception of waveform intensity differences by using a fixed fundamental frequency and adhering to the waveform sub-threshold values discovered during our earlier experiments with vibrotactile feedback [6].

3. DISCRIMINATION OF PURE AND COMPLEX WAVEFORMS

Our experiment sought to investigate the relationship between the tactile receptors of the skin, and to determine if it is possible to use these to distinguish between pure and complex waveforms. As musicians are regularly exposed to combined audio and vibrotactile stimuli, we also aimed to compare musicians with non-musicians to determine if the increased exposure to combined multisensory feedback presents with increased sensitivity to vibrotactile feedback. Our previous research findings regarding stimulus amplitude detection were used to present each waveform at relative perceptual level [6].

3.1 Stimuli

The vibrotactile stimuli applied during all experimental conditions were sine, saw and square waveforms of 160 Hz (S_1, S_2, and S_3 respectively). This frequency was chosen as it was found to have the lowest sub-threshold of perception in earlier experiments conducted with the Audio-Tactile Glove [6]. The chosen frequency lies between the musical notes D3# and E3 (equal temperament scale), removing any advantage a musician may have through experience. The output amplitude of each waveform sample was adjusted to fit within the tactile sensitivity range of 160 Hz (Figure 1). Output levels from the test equipment to the vibrotactile gloves were pre-set to the following parameters: S_1 = -25 dBu, S_2 = -17 dBu, and S_3 = -8dBu. Waveforms were outputted via a digital-analogue audio converter (Avid Fast Track C400) with a sampling frequency of 96 kHz and 24-bit resolution. The audio output was routed through output channel one of the converter, split to the left and right glove in parallel. Participants were presented with digitally generated waveforms using Audacity (an open source wave editing software) at the pre-set fundamental (f_0 = 160 Hz). Waveform clips were recorded and then randomly selected from an audio library. Each clip consisted of a 2-second waveform sample, a one second inter-stimulus time (IST), followed by a second 2-second waveform sample.

Participants wore audio-tactile gloves, each comprised of six voice-coil actuators that are capable of outputting vibrotactile signals simultaneously and at frequencies that the hand is most sensitive to. These actuators are located on each finger and on the palm of each hand. The vibrotactile waveforms were delivered to each actuator in unison. The signal was applied to both hands simultaneously in order to control for increased dominant hand sensitivity and other variances of hand sensitivity that may have existed. In order to mask incidental sound production from the glove, and bone conduction through the skeletal structure, a white noise signal was presented over Sennheiser HD 215 headphones at 60 dB SPL. The same white noise signal was applied to the lower mastoids via HiWave HIHX14C2-8 audio exciters contained within a specially constructed collar. Validated bone conduction masking parameters were followed [10].

3.2 Participants

Thirty participants partook in this experiment; three were subsequently removed as outliers. Physiological pre-testing was not performed on individual participants; however, participants self-reported as having no reduced feeling or other impairments of their hands. Three participants were removed from the study as they presented with reduced sensitivity to vibrotactile stimuli. All participants were recruited from University College Cork and the surrounding community area. 17 of the participants classified themselves as musicians, having been formally trained or regularly performing in the last five years. The participants who identified as being musicians were aged 21 to 35 (*MD* = 24, *SD* = 7.23). This group consisted of 10 males and 7 females. The participants who identified as being non-musicians were aged 23 to 49 (*MD* = 35.5, *SD* = 8.15). This group consisted of 5 males and 5 females.

3.3 Experimental Conditions

The experiment examined the ability of participants to discriminate between different vibrotactile stimuli presented at the appropriate sub-threshold for the waveform type. For all experimental conditions, participants were seated in a soundproof room with both forearms resting on armrests, and hands in a relaxed position. Participants were asked to make same-different judgments for each trial. This experimental procedure was chosen to remove any ambiguity in participants explaining the differences they experienced between the three waveforms presented. Participants were asked to indicate if the two stimuli were the same or different by saying “Same” or “Different”. Our objectives were not to determine the specific cue of the stimuli, but to simply determine the discriminability of each waveform. Three blocks of recorded trials followed a practice period of two blocks. Each trial consisted of the presentation of two stimuli, which were either the same or different. The waveform pairs were presented in counterbalanced order. All possible waveform pairs were presented within each block. Each block of samples contained three matched and six mismatched pairs. Thus, the recorded results consisted of 27 clips in total; 9 matched and 18 mismatched paired samples.

4. RESULTS

A Wilcoxon Signed Rank Test revealed that there was no statistically significant effect in the order of waveform presentation; S_1- S_2 / S_2 - S_1 ($z = 0$, p = ns), with no significant effect size ($r < 0.00$); S_2 - S_3 / S_2 - S_3 ($z = 1.13$, $p = .26$), with a small effect size ($r = 0.14$); S_3 - S_1/ S_1- S_3 ($z = 1.73$, $p = .083$), with a medium effect size ($r = 0.22$). There was also no change in the median for each waveform pair. Therefore, it was deemed possible to collapse the proportion of correct response results across these complementary pairs. Table 1 shows the same-different responses for each stimulus pair after collapsing. This Data was subjected to a signal detection theory analysis and the effects of bias were removed. Specifically, hit and false alarm rate data were analysed to calculate a sensitivity measure of d` and an unbiased proportion correct probability, determined from table 5.3 in MacMillan and Creelman’s textbook [11]. An independent-samples t-test was conducted to compare the adjusted mean percentage correct of musicians and non-musicians. There was no significant difference in scores for musicians (M = 0.89, *SD* = 1.15) and non-musicians (*M* = 0.94, *SD* = 0.1; t (14.09) = -1.06, *p* = .3, two-tailed). The magnitude of the differences in the means (mean difference = 0.17, 95% CI: –0.17 to 0.06) was small (eta squared = 0.04).

5. DISCUSSION

The results from our experiment identified how the participants successfully recognised different waveforms based on waveform shape (as distinct from envelope) when presented in isolation to the hand. These findings support previous research findings undertaken by Russo et al. relating to the vibrotactile discrimination of musical timbres [5]. However, our experiment here have expanded some of these findings further by applying stimuli directly to the subject’s hands with the Audio-Tactile Glove, applied waveforms that have a controlled waveform envelope, and compared musicians with non-musicians. The data gathered from this experiment supports a theoretical operation of combined critical band filtering that may be carried out by the sensory receptor arrays within human glabrous skin; specifically, in the ventral portion the fingers and the palmer surfaces of the hand at a fixed fundamental of 160 Hz. We predict that the stimulus of the four main types of mechanoreceptors outlined earlier, and their individual responses to mechanical displacement, function as frequency-tuned filters whilst experiencing complex tones. This filtering of complex tonality into component frequencies, with relative intensities, contributes to our tactile perception of differing timbres.

Studying the subjective, contextual, and physiological gestural characteristics of musical instrument interactions, highlights the importance of feedback via primary, secondary, and other lesser pathways from instrument to musician. The tactile component of haptic feedback, which is considered in this research, provides an insight into the complexity of primary/secondary and passive/active feedback in multimodal communications. During the playing of musical instruments, the auditory system takes on the role of primary feedback processor. In this context, the role of the visual and haptic senses operates on the secondary feedback signals, primarily relating to the instrument’s physical response to gestural inputs. Also worthy of note is the difference between active and passive feedback, as passive feedback was solely applied in our experiments. Passive feedback relates to the feedback provided through the physical characteristics of the system in use, i.e. the manner in which the system input responds when affected. Active feedback is produced by the system in response to a specific user action, a sound produced within for example. Further

	Response		Same-Different (Independent Observation)				
Stimulus Pair	Different	Same	Hit	False-alarm	z(H) - z(F)	p (c)$_{unb}$	d`
S_1- S_2 or S_2- S_1	0.89	0.11	0.89	0.07	2.67	0.91	3.33
S_1- S_1	0.07	0.93	0.93	0.11			
S_2 - S_3 or S_3 - S_2	0.96	0.04	0.96	0.04	3.57	0.96	4.16
S_2 - S_2	0.04	0.96	0.96	0.04			
S_1- S_3 or S_3 - S_1	0.81	0.19	0.81	0.07	2.34	0.88	3.03
S_3 - S_3	0.07	0.93	0.93	0.19			

Table 1: Proportion correct for independent observations of same-different experiment.

experimentation may reveal supplementary information about the role of active feedback in musical performance.

6. CONCLUSIONS

We have concluded from our experiments that humans possess the ability to distinguish between different waveforms via vibrotactile stimulation alone when presented asynchronously at a fundamental frequency of 160 Hz. We conducted an experiment to confirm that humans are capable of distinguishing between pure sinusoidal and complex waveforms with non-sinusoidal periodic shape containing odd only (square) and odd and even (saw) harmonic content at f_0. Our experiment yielded positive results, with 92% of participants successfully identifying waveforms when presented asynchronously. From this, it can be argued that the adoption of a combined psychophysical approach is required to reinforce the role of somatosensory integration in timbral discrimination tasks that are carried out on digital devices. This will hopefully allow researchers and DMI designers to combine multisensory interfaces that are transparent and intuitive to operate during musical tasks. The linking of tactile feedback to audio output can also assist in reducing computer-processing power that may be required in outputting extra channels of feedback in haptic systems.

7. REFERENCES

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