Palm-area sensitivity to vibrotactile stimuli above 1 kHz

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ABSTRACT
The upper limit of frequency sensitivity for vibrotactile stimulation of the fingers and hand is commonly accepted as 1 kHz. However, during the course of our research to develop a full-hand vibrotactile musical communication device for the hearing-impaired, we repeatedly found evidence suggesting sensitivity to higher frequencies. Most of the studies on which vibrotactile sensitivity are based have been conducted using sine tones delivered by point-contact actuators. The current study was designed to investigate vibrotactile sensitivity using complex signals and full, open-hand contact with a flat vibrating surface representing more natural environmental conditions. Sensitivity to frequencies considerably higher than previously reported was demonstrated for all the signal types tested. Furthermore, complex signals seem to be more easily detected than sine tones, especially at low frequencies. Our findings are applicable to a general understanding of sensory physiology, and to the development of new vibrotactile display devices for music and other applications.

Keywords
Haptic Sensitivity, Hearing-impaired, Vibrotactile Threshold

1. INTRODUCTION
We experience sound and music not just with our ears, but our whole body. The hands are particularly sensitive to vibrotactile feedback which appears to be an important component of musical instrument interaction (see for example [1]). Thorough reviews of functionality of haptic perception [2] and fundamental aspects of tactile psychophysics [3] are available, and often quoted studies of the human tactile system report frequency sensitivity up to approximately 1000 Hz [4], [5], [6].

Most of the research on this topic has been conducted using simple sine tones as test stimuli, but responses to more complex and dynamic signals characteristic of natural environmental stimuli might not be predictable from responses to sine tones alone. From early single cell studies [7], [8] to more recent studies of auditory cortex and belt regions [9], it is clear that many auditory neurons respond preferentially to specific complex signals such as clicks, noise bursts, sounds with specific band-widths, or frequency modulated signals. Complex signals are qualitatively more than the sum of their parts. For example, harmonic components with properly constructed amplitude and phase relationships can create signals with nearly instantaneous pressure variations (approaching square waves) with steeper slopes than those in any of the constituent sinusoidal components alone, and these fast pressure variations could conceivably play a role in signal detection. Similarly in the haptic domain, Verrillo [6] has reported that intensity discrimination is better for pulsed and amplitude modulated tones than for pure tones. With the dearth of relevant literature on the topic, we believe that the role played by higher frequencies in tactile perception is still an open question.

Previous studies have examined how various parameters of vibrotactile signals can be combined to produce tactile icons or tactons [10], [11], [12]. However, frequency responses of subjects to sine tones reported in the literature have typically been measured using contact areas of 1 cm^2 or less on the skin [5], [6], [13]. Interaction with vibrotactile stimuli in everyday life is very different from that used in these controlled laboratory experiments. Brisben et al. [14] have reported lower thresholds for vibrotactile stimuli transmitted through a cylinder grasped in the hand. Lower thresholds may have resulted from differences in contact area, direction of vibration, contact force and the shape of the stimulus probe. Our experiment grew out of research aimed at enhancing the experience of music for the hearing-impaired. That research resulted in the development of a 'Haptic Chair' which delivers vibrotactile stimulation to several parts of the body including the palms of the hands, and has been shown to have a significant positive effect on musical enjoyment even for the profoundly deaf [15]. The current study was designed to determine thresholds of detection for hearing-impaired subjects for a variety of complex stimuli and full-hand contact with the vibrotactile display we developed. Details of the vibrotactile display are given in Section 2.

2. METHOD
2.1 Participants
Twelve hearing-impaired participants (five male subjects and seven female subjects; median age 24 years ranging from 16 to 31 years) took part in the study. Out of the 12 participants, nine were profoundly deaf (six born deaf, one from the age of 1 year, two from the age of 2 years) and three were partially deaf. All participants had normal vision. A person experienced in using and interpreting sign language for the deaf was present to help explain, when necessary, the purpose of the study, the procedure, and to answer any questions subjects might have. The study was conducted in accordance with the ethical research guidelines provided by the Internal Review Board (IRB) of the National University of Singapore and with IRB approval.

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2.2 Apparatus

The mechanism used to generate the vibrotactile stimulation, haptic display, was developed based on the hand stimulation component of the 'Haptic Chair' [15]. The haptic display consisted of a vibrating wooden surface (Figure 1) with four supports that were attached to the panel with epoxy glue and attached to the ground with double-sided tape. The wooden surface was a densely laminated rectangular wooden panel (surface area 33 cm x 23.5 cm, thickness 0.25 cm) similar to the densely laminated wooden frame of the 'Haptic Chair'. This surface was directly driven by a contact speaker, SolidDrive™ (SD1sm, MSE Audio), which was mounted on the under-surface of the wooden panel using special adhesive glue provided by the manufacturer. The contact speaker was driven by an amplifier (SA 202, MSE Audio) connected to a computer running customized software written in LabVIEW™. We have examined the response of this apparatus and believe the amplitude levels we worked with did not trigger any non-linear vibration modes.

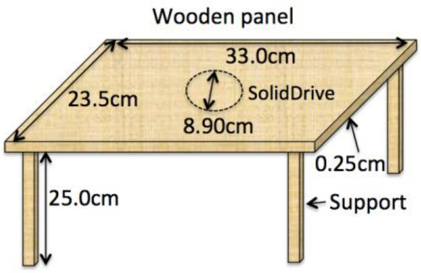

Figure 1. Schematic of the vibrating wooden surface.

Subjects were seated throughout the experiment and the vibrating surface was positioned so that subjects could rest their hands comfortably without the need to tense the muscles of the arm, the elbow being slightly extended (Figure 2). Before each experiment, subjects were given the opportunity to ensure they were seated comfortably and that the vibrating wooden surface was at an appropriate height and position relative to the subject's body. This configuration enables the findings of this research study to be directly applied to our work with the 'Haptic Chair'. Subjects were instructed to use their dominant hand and to remove watches and jewelry.

2.2.1 Response of the haptic display

We used a frequency sweep (sweeping from 50 Hz to 5000 Hz in 3 seconds) to characterize the response of the haptic display at locations L1 to L4 (Figure 3). During the study, a member of the research team kept his hand lightly resting on the surface imposing a loading effect with the palm and fingers similar to the experimental condition. The frequency sweeps were delivered through the SolidDrive™ (SD1sm, MSE Audio) speaker and the response was measured at all four locations. Vibration strength was measured using an accelerometer (3041A4, Dytran Instruments, Inc., U.S.A.). The accelerometer was connected to a signal conditioner and the output of this device to a data acquisition module (USB-6251, National Instruments). The data were then collected and processed on a computer running customized software written in Matlab™. This process was repeated 20 times for five different signal amplitude levels covering the range used in the experiments. Thus, for each location, 100 responses were recorded corresponding to five different amplitude levels (1, 2, 3, 4 and 5 times the initial amplitude) with 20 repetitions per given amplitude. This would correspond to approximately 0, 6, 10, 12, 14 dB increase in the power spectral density (PSD.)

Figure 2. Experimental setup: relaxed placement of the hand and position of the arm assumed by the subjects.

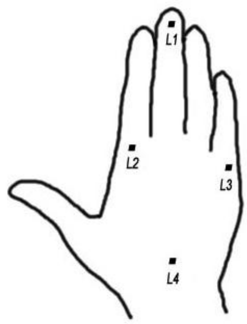

Figure 3. Locations on the hand where accelerometer measurements were made.

Figure 4 shows the PSD of the response measured at location L4, which agreed with the expected dB levels. Other locations L1, L2, and L3 showed similar results; thus we conclude that

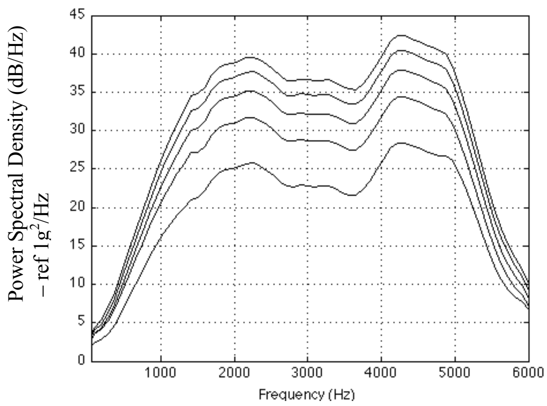

Figure 4. Response of the wooden panel at location L4 for five different amplitudes. For each amplitude level, the plot corresponds to the mean value of 20 measurements.

the amplitude levels used during the experiment would not trigger any non-linear modes. We also compared the response of the panel at different locations L1, L2, L3 and L4 for given amplitude levels. Figure 5 shows the responses corresponding to one amplitude level. As shown in Figure 5, the response at different locations differs by at most 2 dB over most of the frequency range of interest, with a maximum difference of 5 dB between two of the sensors at 3600 Hz. We observed similar results for the other amplitude levels. Therefore, to monitor the response of the board during the experiments, we chose one location, L1.

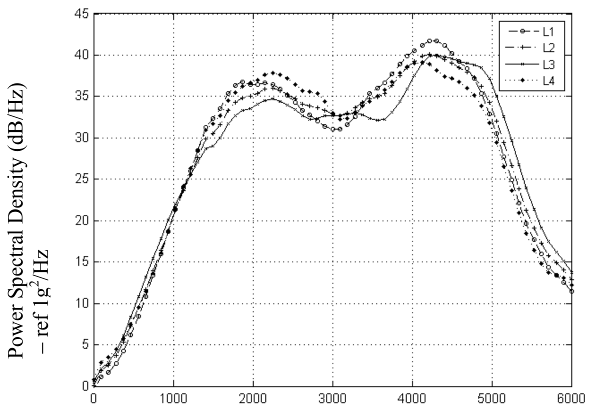

Figure 5. Response of the haptic display at locations L1, L2, L3, and L4 at one amplitude level.

2.3 Stimuli

Five different signal types were used in this study: sinusoidal, square wave, amplitude-modulated (AM), frequency-modulated (FM), and upward frequency sweeping signals. For each signal type, five stimuli were created for five different frequencies: 250, 500, 1000, 2000 and 4000 Hz. All the signals were normalized to have equal average power. Specifications of the signals are given in Table 1. A computer running LabVIEW™ 8.2 was used to control the intensity of the input signals. From the researchers' own observations, the perception of even the highest presentation amplitudes for stimuli above 1 kHz was never far above the threshold of detection.

To avoid the possibility of fatigue which might result from testing all five signal types at all five frequencies, we divided the subjects into four groups, and each group was tested with three different frequencies: Group (1) 250, 500, 2000 Hz; Group (2) 250, 500, 4000 Hz; Group (3) 250, 1000, 2000 Hz; Group (4) 250, 1000, 4000 Hz, and with all signal types for a given frequency.

2.4 Procedure

Before each experiment, subjects were given at least 10 minutes to rest and become accustomed to their new surroundings before they took part in the experiment. The study was conducted in a sound-isolated audio recording studio, at a comfortable temperature of 24^{o} C. During the initial rest period, subjects read the information sheet prepared for participants and were given the opportunity to sign the consent form or to not take part, as they wished. Each subject was asked to rest their dominant hand lightly on the vibrating surface and indicate when they could feel the surface vibrating. A short trial run was conducted before the actual experiment to make sure the subjects understood the instructions and to familiarize them with the experimental procedure.

Table 1. Specifications of the signal types used in the experiments.

Signal Type	Specifications
Sinusoidal	Sine tones at frequencies: 250, 500, 1000, 2000 and 4000 Hz
Square wave	Square waves at frequencies: 250, 500, 1000, 2000 and 4000 Hz
Frequency sweep	Frequency sweeps at starting frequencies: 250, 500, 1000, 2000 and 4000 Hz Upward frequency sweeps based on $f*2^t$; for t in [0, 1] seconds where f is the starting frequency (f = 250, 500, 1000, 2000 and 4000 Hz)
FM	Frequency modulated sine tones at carrier frequencies: 250, 500, 1000, 2000 and 4000 Hz Frequencies varied between ±10% of the carrier frequency at a rate of 2 Hz
AM	Amplitude modulated sine tones at carrier frequencies: 250, 500, 1000, 2000 and 4000 Hz Modulated with a 2 Hz tone Modulation depth = 100%

- The duration of each of the 25 tones (5 signal types and 5 frequencies of each type) was 1 second
- A 10 ms ramp up at the beginning and down at the end of each tone was imposed to avoid clicks and distortion of the endpoints
- All tones were normalised to have equal average power

The standard psychoacoustic 'up-down staircase' method described in [16] was used to determine the threshold of detection. For a given stimulus, the intensity level was decreased by a step of 1 dB after a positive response or increased by a step of 1 dB after a negative response. In order to avoid the situation of a participant anticipating a trial, there were checks for false positives –i.e. trials without stimuli were presented and a 'yes' would be counted as a false response. This procedure was carried out until six reversals in response were obtained. A trial between two reversals is a 'run'. Two members of the research team independently handled stimulus intensity control and data recording. Following the method described in [16], we used the midpoints of runs 2, 4 and 6 to calculate the threshold. Figure 6 illustrates the 1-up 1-down staircase procedure. Participants were given a break of one minute between trials to avoid adaptation to the various stimuli.

3. RESULTS

3.1 Detection of High Frequency Signals

We defined a given stimulus as 'undetected' if a subject could not detect it before the maximum intensity level was reached, or if the stimulus was found to be corrupted by low frequency noise or sub-harmonics when the subjects reported detection. Thus the stimulus was considered to have been detected only if the subject reported detection and the signal was measured to be free of possibly detectable subharmonics.

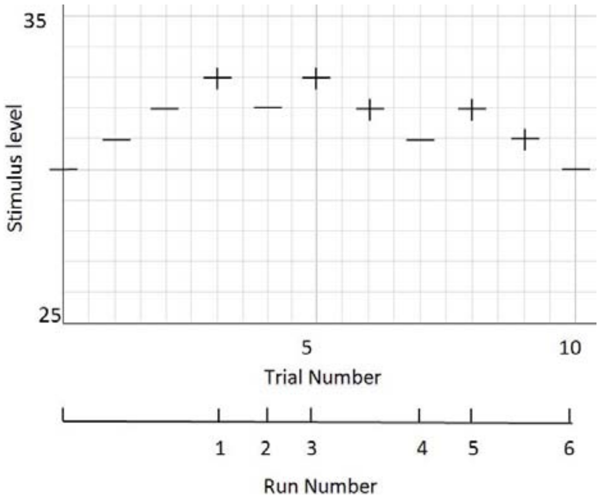

Figure 6. A sequence of stimulus level reversals during a 1-up 1-down staircase method. The initial value is typically determined based on preliminary experiments. The threshold of detection is calculated as the average of runs 2, 4 and 6 [16].

All five signal types at frequencies of 250, 500 and 1000 Hz were detected by all subjects. In addition, all the subjects were able to detect sine and square tones, and frequency sweeps at 2000 Hz. Five out of six subjects detected the 2000 Hz AM tone. At 4000 Hz, all the subjects were able to detect FM tones and frequency sweeps. The majority of the subjects were also able to detect sine and square tones at 4000 Hz.

3.2 Thresholds of Detection

Figure 7 shows the thresholds of tactile sensitivity for the different signal types at different frequencies. In agreement with [5], we found that sensitivity is greatest to tones at 250 Hz. We also found that signals with complex waveforms (AM, FM, square waves, and frequency sweeps) generally have lower thresholds than sine tones at the same frequency.

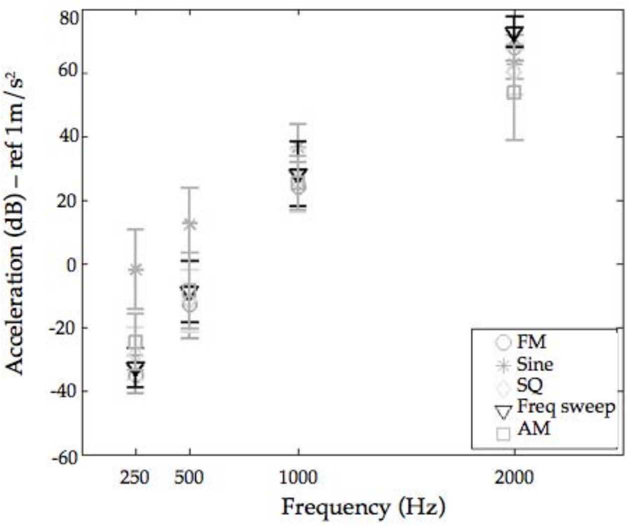

Figure 7. Threshold of vibration sensitivity to different signal types at different frequencies with 95% confidence intervals. (Note: The threshold for the AM tone at 2000 Hz was calculated with five data points because one subject could not detect that stimulus.)

3.3 Effect of Different Signal Types

A one way repeated measures ANOVA analysis was carried out to compare the sensitivity to different signal types at a given frequency. ANOVA reveals a significant difference between the thresholds to different signal types for most of the frequency points we tested: 250 Hz ($F(4,55) = 21.733$, $p<0.0001$), 500 Hz ($F(4,25) = 20.312$, $p<0.0001$), 1000 Hz ($F(4,25) = 6.374$, $p=0.001$), 2000Hz ($F(4,24) = 5.366$, $p=0.01$). Some subjects could not detect some of the stimuli at 4000 Hz so there were not enough data points to calculate statistics at this frequency. Based on Tukey's Honest Significant Test (HSD), at 250 Hz and 500 Hz, the sine tone has a significantly higher threshold compared to all other signal types at the same frequencies ($p<0.01$). At 2000 Hz, both FM tones and frequency sweeps showed significantly higher thresholds ($p<0.01$) compared to other signal types.

4. DISCUSSION

4.1 Data Validation

We identified that there were many potential confounding variables such as auditory cues, low frequency noise, visual cues, and perception of sound *via* bone conduction that could have accounted for our observations. In this section we discuss how these confounding effects were avoided.

4.1.1 Auditory cues

Although some of our subjects were profoundly deaf, all the subjects wore soft foam 'ear-plugs' (3M™ Foam Ear Plug 1100, rated to attenuate sound by a minimum of 29 dB in our experimental frequency range) and also ear-defenders that cupped the pinnae (H540A-411-SV, rated to attenuate sound by a minimum of 20 dB in our experimental frequency range) to further minimize the possibility of detecting any audible sound generated by the test stimuli. All subjects reported that no sound was audible during the experiment.

4.1.2 Presence of low-frequency noise

Another possible confounding factor of vibrotactile stimuli over 1000Hz was the presence of low frequency noise that might be caused by non-linearities in the response of the wooden board. If low frequency noise were present, subjects might have detected and responded to it rather than to stimuli at the frequency of the input signal. Therefore, we examined the response of the wooden panel (recorded at location L1 and shown in Figure 4) during every trial for each of the subjects. For every 'detected' high frequency stimulus, we checked its power spectral density (PSD) against PSDs of lowest detected stimuli at lower frequencies. If the low frequency components of the 'detected' high frequency stimulus were at least 10dB below the lowest detectable level by a subject, the high frequency stimulus was considered as free of detectable low frequency noise. Otherwise the stimulus was considered to be distorted and the entire staircase was discarded from the analysis.

Most of our high frequency stimuli were free of low frequency noise. However, there were seven data points (out of 180) corrupted with detectable low frequency noise. Amplitude levels of these seven stimuli were almost reaching the maximum level and such amplitude levels might have caused the non-linear response. Figure 8(a) shows the 2000 Hz stimulus sine tone without detectable low frequency noise and Figure 8(b) shows a 2000Hz FM tone stimulus with detectable low frequency noise.

4.1.3 *Visual cues*

To prevent any visual cues being available, subjects faced the person who recorded the responses, while the experimenter who controlled the stimuli *via* the computer was not in the subjects' field of view. The vibrations of the board at the amplitudes and frequencies used in the experiment were not visible to the naked eye.

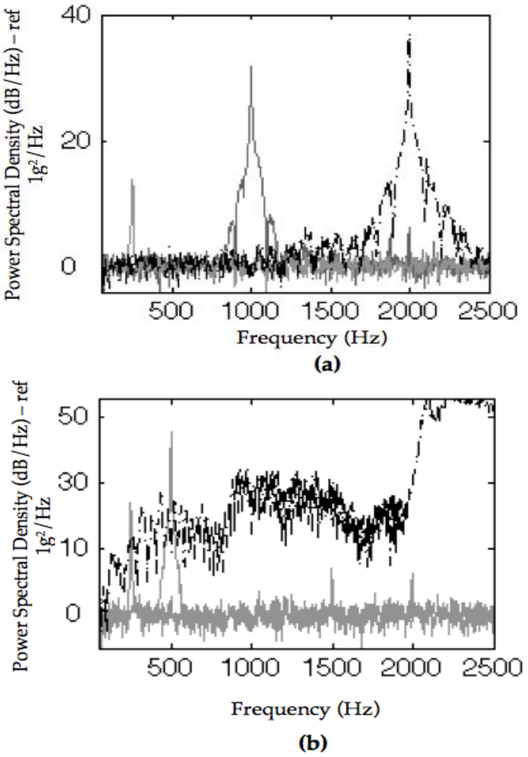

Figure 8. Image (a), shows a valid trial. In this case, the Power Spectral Density (PSD) of the 'detected' stimuli (sine tone) at 2000 Hz (dashed black line with a peak at 2000 Hz) is more than 15 dB below the lowest threshold of detectability (solid grey lines): sine tone at 1000 Hz and sine tone at 250 Hz for the same subject. Image (b) shows an invalid trial due to the presence of subharmonics. In this case, the PSD of the 'detected' stimuli (FM tone) at 2000 Hz (dashed black line) produces low frequency components within 10 dB of the lowest detectable thresholds (grey lines): sine tone at 500 Hz and sine tone at 250 Hz for the same subject.

4.1.4 *Bone conduction of sound*

We conducted an analysis similar to [17] to rule out the possibility that bone conducted sound from the vibrotactile stimuli could have influenced detection of vibrotactile stimuli. Dirks et al. [18] reported mastoid bone conduction thresholds (using the Radioear B-72 bone vibrator) of -9 dB at 250 Hz, -7 dB at 500 Hz, -13 dB at 1000 Hz, -14 dB at 2000 Hz and -15 dB at 4000 Hz re 1 m/s^2 (converting from the original reference of re. 1 cm/s^2). However, there is a significant energy loss before tactile stimulation of the fingers or palm of the hand reaches the skull bones due to dissipation and impedance mismatches between bones and tissue along the pathway. The bone conduction loss from forearm to mastoid has been reported by Lamoré [19] to be 35 dB at 250 Hz, 49 dB at 500 Hz, 80 dB at 1000 Hz and 98 dB at 2000 Hz re $1m/s^2$. Although conduction loss value at 4000 Hz was not reported, the trend in these data suggests that it would be higher than 98 dB. The highest stimuli strengths used in our study were 10 dB at 250 Hz, 24 dB at 500 Hz, 44 dB at 1000 Hz, 78 dB at 2000 Hz and 80 dB at 4000 Hz re $1m/s^2$. The forearm attenuation would thus result in a signal at the skull bones of at least 20 dB below the mastoid thresholds reported by Dirks et al. [18] at all frequencies. Bone conduction thresholds at the forehead are even higher [20]. It is therefore unlikely that bone conduction could have influenced our results.

4.2 Interpretation of Results

The primary results of this study suggest that hearing-impaired subjects were sensitive to vibrations at frequencies of 2000 Hz and 4000 Hz, although amplitudes required for detection were 30-40 dB higher than at a frequency of 250 Hz. This frequency is two octaves higher than the limiting frequency of 1000 Hz for tactile sensitivity reported in other studies [5], [6]. The mechanoreceptors in the human skin are believed to integrate energy spatially [21], [22]. It is therefore reasonable to assume that the relatively large contact area of the whole hand (palm and fingers) used in our experiments would have facilitated spatial integration of vibrotactile stimuli, leading to lower detection thresholds for higher frequencies. Because the contact area of the entire ventral surface of the hand (approximately 50-80 cm^2) is much larger than the contact area used in research work previously reported (0.01-10 cm^2) [22], absolute detection thresholds obtained in the study described here cannot be directly compared with those found in previous literature. For example, a point-source stimulus applied to a very small area of glabrous skin might by-pass or increase desensitisation of important channels of vibrotactile stimuli. We believe larger contact areas are important to understand because they are more applicable to sensing vibration in everyday environments.

The second finding of this study is that the complex signals we used have lower thresholds of detection than the sine tones. Some of the participants reported that they could "feel something moving" when sensing the vibrations corresponding to a FM tone and thus easily detected the stimulus compared to that produced by a static sine tone. This is reminiscent of reported observations of visual perception where a flashing source of light is more easily detectable than a constant source. We observed that increased sensitivity to complex signals is most significant at 250 Hz: at this frequency, both FM and square tones resulted in a decrease of approximately 5 dB in threshold compared with a pure sine tone. This occurred despite the complex tones having lower amplitude at the fundamental frequency compared to the sine tone, since all stimuli were normalized to have equal average power. This result suggests an explanation beyond simple integration across frequency, and points to the possibility that the temporal dynamics of complex signals could play a role in detecting vibrotactile stimulation. A separate series of studies would be needed to validate this hypothesis.

Although the focus of this research was on the hearing-impaired and profoundly deaf, there is no reason to expect that palm-area vibrotactile sensitivity would be different for hearing subjects. In fact, our pilot studies of people with normal hearing showed broad agreement with the findings reported here. However, the interpretation of this data was confounded by the fact that our study conditions did not consistently prevent louder signals from being heard by this group. Further studies would be necessary to provide conclusive results.

5. FUTURE DIRECTIONS

Speech information is carried primarily in the frequency region from 300 to 3000 Hz [23] which corresponds to the range of sensitivity found in our study using complex signals and full-hand vibrotactile stimulation. Gault [24] proposed a method of presenting speech signals via a vibrator on the skin. This and our pilot studies provide motivation for further exploration using this kind of vibrotactile feedback for speech therapy and education. The 'Haptic Chair' [15] is being further developed so that users will be able to sense amplified vibrations produced by their own voice as well as others such as teachers or therapists. Preliminary results suggest that this kind of display can to some extent function as an effective substitute for the traditional 'Tadoma' [24, 25] method of speech instruction wherein students touch the throat or lips of their teachers.

Another possible future study would be to determine the amount of information deliverable with vibrotactile stimuli using frequencies greater than 1000 Hz. One open question in particular is the extent to which detectable high frequencies can be discriminated. Frequency discrimination would have a bearing on, for example, the ability to identify multiple sound sources (e.g. speakers or musical instruments) based on spectral information, as well as whether multiple sources can be detected or identified when delivered through a single channel of vibrotactile stimulation. We hope that future work will lead to more effective uses of the vibrotactile channel for communication in speech and music.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] S. Sinclair, J.-L. Florens, and M. M.Wanderley. A haptic simulator for gestural interaction with the bowed string. In *10ème Congrès Français d'Acoustique*, Lyon, France, Apr. 2010.

[2] S. J. Lederman, and R. L. Klatzky. "Haptic perception: a tutorial," *Attention Perception and Psychophysics*, vol. 7, pp. 1439-1459, 2009.

[3] H. Burton, and R. Sinclair. "The Psychophysics of Tactile Perception and Its Peripheral Physiological Basis," in *Pain and Touch,* L. Kruger, Ed. San Diego: Academic Press, 1996, pp. 25-103.

[4] C. E. Sherrick. "Variables affecting sensitivity of the human skin to mechanical vibration," *Journal of Experimental Psychology,* vol. 45, pp. 273-282, 1953.

[5] R. T. Verrillo. "Investigation of some parameters of the cutaneous threshold for vibration," *J. Acoust. Soc. Amer.*, vol. 34, pp. 1768-1773, 1962.

[6] R. T. Verrillo. "Vibration sensing in humans," *Music Perception,* vol. 9, pp. 281-302, 1992.

[7] E. F. Evans. "Cortical representation," in *Hearing Mechanisms in Vertebrates,* A.V.S. de Reuck and J. Knight, Ed. Churchill London, 1968.

[8] I. C. Whitfield, and E. F. Evans. "Responses of auditory cortical neurons to stimuli of changing frequency," *Journal Sound and Vibration*, vol. 21, pp. 431-448, 1965.

[9] J. P. Rauschecker. "Cortical processing of complex sounds," *Current Opinion in Neurobiology*, vol. 8, pp. 516-521, 1998.

[10] I. R. Summers, P. G. Cooper, P. Wright, D. A. Gratton, P. Milnes, and B. H. Brown. "Information from time-varying vibrotactile stimuli," *J. Acoust. Soc. Amer.*, vol. 102, no. 6, pp. 3686-3696, Dec. 1997.

[11] S. Brewster, and L. M. Brown. "Tactons: structured tactile messages for non-visual information display," in *Proc. AUIC'04,* 2004, pp. 15-23.

[12] K. MacLean, and M. Enriquez. "Perceptual Design of Haptic Icons," in *Proc*. Eurohaptics, 2003, pp. 351-363.

[13] L. Pawson, C. M. Checkosky, A. K. Pack, and S. J. Bolanowski. "Mesenteric and tactile Pacinian corpuscles are anatomically and physiologically comparable", *Somatosens Mot Res, vol. 25, no. 3, pp.194-206, 2008.*

[14] A. J. Brisben, S. S. Hsiao, and K. O. Johnson. "Detection of vibration transmitted through an object grasped in the hand," *J Neurophysiology*, vol. 81, pp. 1548-1558, 1999.

[15] S. C. Nanayakkara, E. A. Taylor, L. Wyse, S. H. Ong. "An enhanced musical experience for the deaf: design and evaluation of a music display and a haptic chair," in *Proc. CHI '09,* 2009, pp. 337-346.

[16] H. Levitt. "Transformed Up-Down Methods in Psychoacoustics," *J. Acoust. Soc. Amer.*, vol. 49, pp. 467-477, 1971.

[17] E. C. Wilson, C. M. Reed, and L. D. Braida. "Integration of auditory and vibrotactile stimuli: effects of phase and stimulus-onset asynchrony," *J. Acoust. Soc. Amer.*, vol.126, pp. 1960-1974, 2009.

[18] D. Dirks, C. Kamm, and S. Gilman. "Bone conduction thresholds for normal listeners in force and acceleration units," *Journal of Speech and Hearing Research,* vol.19, pp. 181-186, 1976.

[19] P. J. Lamoré. "Vibrotactile threshold for hairy skin and its transformation into equivalent bone-conduction loss for the mastoid," *Audiology,* vol. 23, pp. 537-551, 1984.

[20] T. Frank. "Forehead versus mastoid threshold differences with a circular tipped Vibrator," *Ear and Hearing*, vol. 3, pp.91-92, 1982.

[21] G. A. Gescheider, B. GüÇlü, J. L. Sexton, S. Karalunas, and A. Fontana. "Spatial summation in the tactile sensory system: Probability summation and neural integration," *Somatosensory and Motor Research*, vol. 22, pp. 255-268, 2005.

[22] R. T. Verrillo. "Effect of Contactor Area on the Vibrotactile Threshold," *J. Acoust. Soc. Amer.*, vol. 12, pp. 1962-1966, 1963.

[23] T. R. Rossing. *The Science of Sound (2nd Ed.)*, San Francisco: Addison-Wesley, 1990.

[24] R. H. Gault . "Touch as a substitute for hearing in the interpretation and control of speech," *Arch. Otolaryngol*, vol **3**, pp. 121-135, 1926.

[25] C. M. Reed, M. J. Doherty, L. D. Braida, and N. I. Durlach. "Analytic study of the Tadoma method: Further experiments with inexperienced observers," *Journal of Speech and Hearing Research*, vol. 25, pp. 216-223, 1982.