Effect of Frequency Level on Vibro-tactile Sound Detection

Abdikadirova Banu[1], Praliyev Nurgeldy[1] and Xydas Evagoras[2]
[1]*Department of Mechanical and Aerospace Engineering, Nazarbayev University, Astana, Kazakhstan*
[2]*IREROBOT LTD, Nicosia, Cyprus*

Keywords: Vibrotactile, Audio-tactile Integration, Touch.

Abstract: It has been shown that vibrotactile stimuli elicits sound perception either on their own or by enhancing otherwise inaudible sounds. For taking advantage of this phenomenon in the design of vibrotactile displays it is important to identify its properties with respect to the level of the excitation frequency. In this work, the effect of frequency levels on the ability of humans to perceive vibrotactile stimuli as sounds at the index fingertip is investigated. Eight subjects participated in the study which included comparison of sound and vibration versus sound only signals. It is shown that as hypothesized, there is a range of frequency in which the phenomenon under study seems to be most intense with maximum occurrence at 300 Hz.

1 INTRODUCTION

It has been established that integration of auditory and vibrotactile signals activates a larger volume of the auditory cortex than the auditory stimulus alone (Auer et al., 2007). This hypothesis is also demonstrated in monkeys by Kayser et al., (2015) who tested integration of auditory broad-band noise and tactile stimulus. By using fMRI (functional Magnetic Resonance Imaging) they detected that audio-tactile signal activated the posterior and lateral side of the auditory cortex of the animal. Given the continuous technological leaps in information and communication technology, interest in studying audio-tactile integration is increased and there are several works which demonstrate that human auditory cortex is activated through vibrotactile excitation at the hand. Schürmann et al. (2004) have established that audio-tactile stimulation activates the auditory cortical area in normal hearing participants. In the experiment, participants were asked to adjust the sound intensity at the same level as fixed-intensity vibration. With the presence of vibration, the participants perceived a higher intensity than the actual sound intensity, which satisfies the hypothesis that under certain circumstances vibration facilitates hearing. Further, by using whole-scalp magnetoencephalography (MEG) and analysing results, authors concluded that human auditory cortex can be activated by feeling fixed intensity vibration of 200-Hz at the fingertips. Also, Caetano et al., (2006) extended this study and demonstrated auditory cortex activation by vibrotactile stimulation alone. Both research experiments were conducted at fixed-frequency of 200-Hz vibrations, without providing level of frequency or location effects on this phenomenon. In another work researchers studied the perceptual integration of 50, 250, and 500-Hz vibrotactile and auditory tones in a detection experiment as a function of the relative phases of sound and vibration pulses (Ranjbar et al., 2016). The results did not establish significance regarding the effect of phase difference in sound detection performance. However, combination of 250-Hz and phase difference resulted significantly high scores in sound detection in contrast to other fixed-frequencies (e.g. 50-Hz and 500-Hz). The work suggests that auditory and vibrotactile signals can be effectively integrated without regard to phase difference and fine structure regulation. Also, it can be speculated that audio-tactile integration is more notable in some frequencies than in others. For effective design of vibrotactile interfaces it is important to establish further understanding of the range of frequencies in which audio-tactile integration is stronger. The main hypothesis of this work is that there is a specific range of vibration frequencies in which audio-tactile integration is most intense. When it comes to sensitivity to vibrotactile stimuli, it is known that the fingertips and hand have greater density and more sensitive regions compared to the rest of the body and are more appropriate for receiving tactile information than other regions (Bensmaïa, 2005; Kaczmarek et

Banu, A., Nurgeldy, P. and Evagoras, X.
Effect of Frequency Level on Vibro-tactile Sound Detection.
DOI: 10.5220/0007347100970102
In *Proceedings of the 14th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2019)*, pages 97-102
ISBN: 978-989-758-354-4

al., 1991). Tactile sensation can be caused by mechanical vibration of the skin at frequency ranges between 10 and 500-Hz (Johansson and Löfvenberg, 1984). When it comes to ability for frequency discrimination in vibrotactile stimuli, Mahns et al., (2006) have shown that at the fingertips the discriminative increment or Just Noticeable Difference (JND) for frequencies of 20, 50, 100 and 200-Hz are 0.32 ± 0.07%, 0.19 ± 0.07%, 0.21 ± 0.03% and 0.14 ± 0.04%, respectively. However, another work suggests that JND is constant across frequencies with a discriminate increment of 22 % (Johansson and Löfvenberg, 1984). This information is employed in experimental design in this work, namely for choosing the set of test frequencies shown in Table 2. More specifically, for lower frequencies, JND of 50, 100 and 200 Hz were used to choose the frequencies (Johansson and Löfvenberg, 1984; Mahns et al., 2016), while higher frequencies were incremented by 22 %. (Mahns et al., 2016).

Overall, the work is organized as follows: first a methods section describes the group of participants, equipment and experimental procedure. This is followed by the results sections and finally a discussion and conclusion sections elaborate on the results and investigation in general.

2 METHODS

2.1 Participants

Eight young adults participated in the experiments. Their age ranged between 19 and 21 years (mean 19.9, standard deviation 0.60). One of the persons participated in a similar experiment before, but he had no information regarding the primary aim of the investigation or details of the study. All other participants did not have any knowledge about the topic of the study and were not involved in vibrotactile experiments before. All of them signed an informed consent and were compensated for participation.

2.2 Experimental Setup

The vibrotactile testing apparatus consists of the following equipment: 1. PC. 2. External sound card. 3. A pair of headphones with active ambient noise and sound cancellation (Sony WH-1000XM2). These include automatic performance optimization given current environmental conditions. 4. A vibration generator with a vibrating probe (Frederiksen 2185.00). 5. Amplifier (L-Frank Audio PAA30USB). 6. Custom-made sound insulation box. The vibration generator was placed inside the insulation box with only the vibrating probe protruding, so that sound generated due to mechanical parts movement is isolated to the maximum possible extent. A cylindrical 4mm wooden interface with flat end is inserted in the centertap as the probe endpoint (which the user touches), so that it matches the dimensions used in research which was conducted by Kayser et al., (2005). The complete experimental setup is presented in Figure 1.

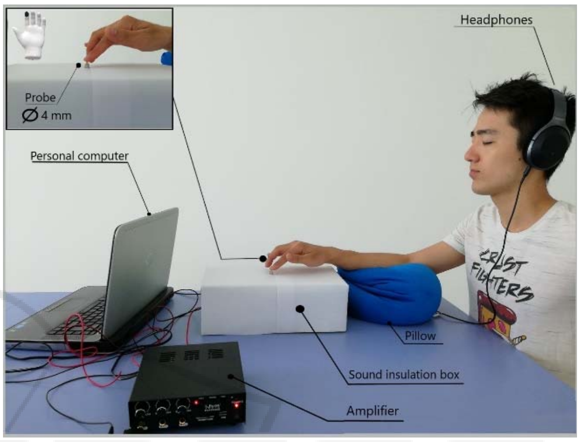

Figure 1: Experimental setup.

MPU6050 Accelerometer and Arduino Software are used to take sample acceleration measurements on the forearm of the participant to make sure vibration is not transferred through the body by conduction.

2.3 Experimental Procedure

At the beginning of the experiment, the participant seated in a relaxed position with the headphones on and the noise and ambient sound cancellation activated. The participant had the headphones on, throughout the duration of the experiment. The experiment consisted out of three stages: 1. Vibration intensity calibration. 2. Audio-tactile sensitivity test. 3. Control measurements. The third stage was performed only by two participants mainly for testing the sound shielding performance provided by the headphones. All three stages were performed 13 times, one for each of the frequencies shown in Table 2. Furthermore, during each experiment, sample sound and vibration frequency measurements were performed to ensure that the correct signals are delivered to the vibration generator. Also, sample acceleration measurements were taken on the user's forearm to ensure that vibrations did not transfer to the ears by conduction through the body.

2.3.1 Vibration Intensity Measurement and Calibration

The first stage of the procedure for each frequency involves calibration of the vibration intensity. The purpose is to achieve minimization of the audible sound generated by the vibration generator, so that only controlled sounds through the headphones are delivered to the user. At this stage the user is not touching the probe. Vibration signals are generated and the user is asked to tap whenever he listens to a tone. The vibration intensity is reduced after each signal until the user does not respond to the tone. The resulting sound intensity is used for the subsequent stage of the study.

2.3.2 Audio-tactile Sensitivity Test

In the second part of the procedure, the participant touched the probe with the index fingertip. The participant was asked not to exert intense pressure on the probe, rather just rest the centre of the fingertip on the probe end. A pillow was placed under the participant's forearm to keep the wrist and arm relaxed. Three types of sinusoidal signals were generated at this stage. 1. Sound only (SO). 2. Sound and vibration (SV). 3. Vibration only (VO). Frequency steps were chosen by considering JND suggested by literature as described in the introduction.

In total, 25 tones were delivered to the user for each of the test frequencies. 10 sound tones, 10 sound and vibration tones (Sound through the headphones and Vibration at the fingertip) and 5 vibration only tones. All 25 tones were generated in a random order. The amplitude of vibratory stimulation remained the same in all 15 stimuli (5 vibration and 10 sound and vibration). Auditory stimuli had 10 different intensities and they contained both normally audible and nonaudible tones which were calibrated based on experiments with two young adults for each frequency. As in the calibration stage, whenever the user heard the tone, he tapped on the workbench. The number of positive responses (taps) for each user in each frequency are counted, then the median as well as boxplots for all users in each frequency are calculated. This is done for positive responses in Sound only (SO) and Sound plus Vibration (SV) signals. Also, a further criterion is considered for testing the audio-tactile integration: If the user cannot hear a specific sound intensity played on its own (SO), but can hear it when it is combined with a vibration (SV), then this is a valid case where it is shown that vibration enhances hearing. All such cases are counted and statistically analysed. This group of results is termed SVS as it is a comparison between Sound and Vibration versus Sound only. Vibration only (VO) signals were generated for randomization purposes of SV and SO signals. Providing a third option (VO) alongside the signals that are under investigation (SV and SO) reduces the possibility that the user will become biased towards either SO or SV signals. Only five VO signals are provided since firstly this option does not presently involve any investigation and secondly due to duration limitations. They are not used in the analysis for the test group. They are only considered in the analysis when it comes to the control test.

As an example, Table 1 illustrates sample results of the experiment for one specific frequency, for a specific participant. The last column of Table 1 shows the responses of users for vibration only stimuli.

Table 1: Sample results of specific participant.

Sound loudness level	SVS		Test result	VO
	SV	**SO**		
1	Yes	Yes	Inconclusive	No
2	Yes	Yes	Inconclusive	No
3	Yes	Yes	Inconclusive	No
4	Yes	Yes	Inconclusive	Yes
5	Yes	Yes	Inconclusive	No
6	Yes	Yes	Inconclusive	
7	No	No	Inconclusive	
8	Yes	No	Valid	
9	No	No	Inconclusive	
10	No	No	Inconclusive	

2.3.3 Control Test

In contrast to sound tests, in vibrotactile tests it is nearly impossible to completely isolate the user acoustically from the vibration source. It is expected that despite isolating the vibration generator in a box and using specialized sound-cancelling headphones, still some sounds coming from the vibration generator will reach the participant. To get an idea for this unwanted sound detection it was requested from two of the participants to perform the whole experiment again, but in this case, they were not touching the vibration probe. They assumed the same posture and had the headphones on as before. They were also asked to tap whenever they heard a tone. The results of these controlled tests were compared to the results of the tests that included touch and are shown in the results section. In this case the results are described with the letters VONT (Vibration Only, No Touch) and SVNT (Sound and Vibration, No Touch).

3 RESULTS

Figure 2 represents the percentage of positive responses in sound only (SO) test. Figure 3 demonstrates similar data for sound and vibration (SV) test.

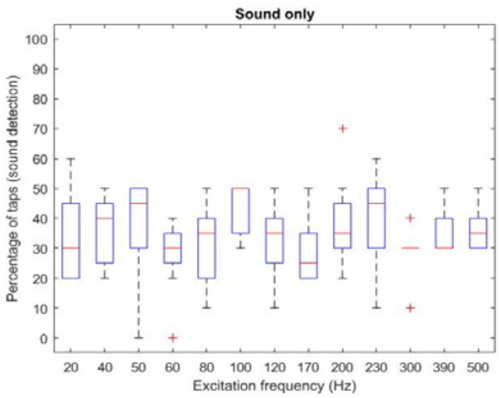

Figure 2: Boxplots of positive responses in sound only test (SO).

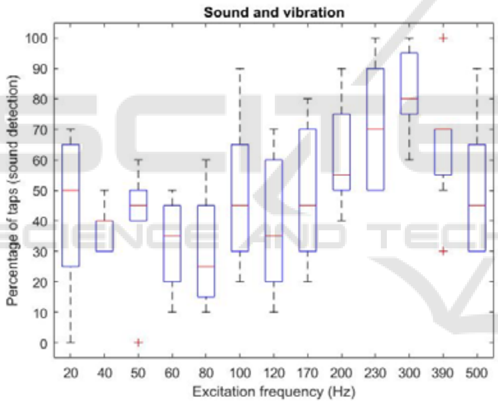

Figure 3: Boxplots of positive responses in sound and vibration test (SV).

Table 2: Hypothesis testing for sound only versus sound and vibration tones.

Test Number	Test Frequency (Hertz)	P-Value	H/H0
1	20	0.3248	false
2	40	0.9902	false
3	50	0.6171	false
4	60	0.5496	false
5	80	0.8517	false
6	100	0.8455	false
7	120	0.6912	false
8	170	0.0716	false
9	**200**	**0.0144**	**true**
10	**230**	**0.0095**	**true**
11	**300**	**0.0001**	**true**
12	**390**	**0.0047**	**true**
13	500	0.2657	false

Table 3 shows the results of Hypothesis testing between sound only and sound and vibration tests.

Figure 4 illustrates boxplots for all 13 frequencies, comparing sound and vibration versus sound only positive responses. The graph indicates the percentage of valid cases. The blue boxes contain 50% of the cases and the red lines the medians. The red crosses represent the outliers. Black dotted lines include the rest of the results.

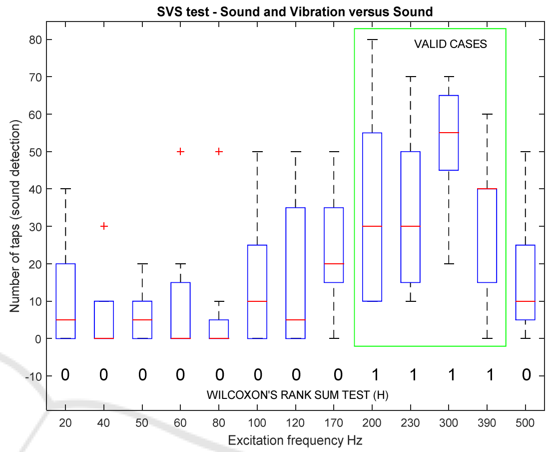

Figure 4: Boxplots of valid cases in SVS test.

Figure 5 shows boxplots of positive responses in SVNT and SV tests for Participant 7 and 8 for 200 Hz, 230 Hz, 300 Hz and 390 Hz.

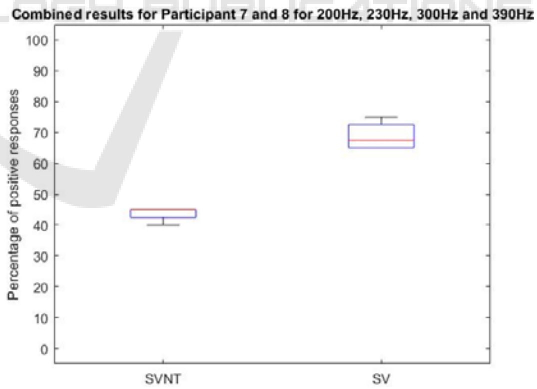

Figure 5: Boxplots of positive responses in SV and SVNT tests.

Table 3 shows the results of Hypothesis Testing for SVNT versus SV. Separate Hypothesis Testing was performed for valid frequencies (200 Hz, 230 Hz, 300Hz and 390 Hz) and for the remaining frequencies.

Table 3: Hypothesis testing for SV and SVNT for 8 frequencies.

Participants 7&8	Frequencies (Hz): 100, 120, 170, 500 (Non-valid)		Frequencies (Hz): 200, 230, 300, 390 (Valid)	
	H/H_0	p – value	H/H_0	p - value
SVNT SV	false	0.6571	true	0.0286

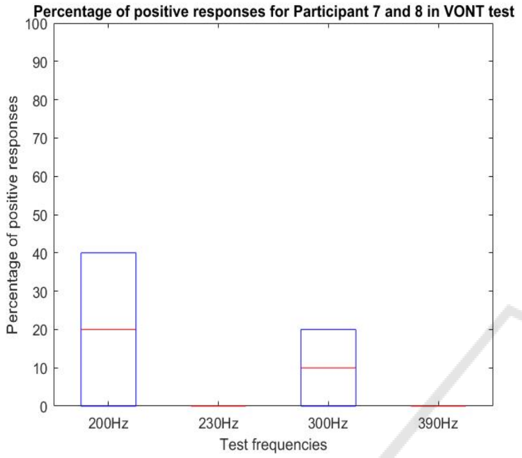

Figure 6: Number of positive responses in VONT test for participants 7 & 8.

4 DISCUSSION

In Figure 2, it can be seen that the median percentage of positive responses is roughly constant in SO test among all frequencies. This is reasonable, since, sound intensities were specifically chosen to have half audible and half inaudible sounds. Figure 3 demonstrates that the median percentage of positive responses is relatively low in SV test at frequencies of 20-170 Hz. With further increase of frequency, the percentage of sound detection increases, reaching its peak at 300 Hz. There is a sharp decrease in sound detection performance of users for frequencies higher than 300 Hz. As it was reported by one of the participants, the vibration was less sensible at 500 Hz, as it was naturally expected. The calibration stage might have contributed to this fact since the gradual reduction of the vibration intensity (for sound isolation purposes) might have led to undetectable amplitudes in certain frequencies in which hearing is more sensitive. This is believed to be the case in some of the instances of 500 Hz generation.

Comparing the results of SO and SV tests, it is seen that vibration has no significant effect on enhancement of sound detection at 20-170 Hz, since there is no significant difference in number of positive responses. At higher frequencies starting from 200 Hz, sound detection performance of participants in SV test becomes significantly better compared to their performance in the SO test. It can be noticed in Figure 2 and Figure 3 that the percentage of positive responses is significantly higher in SV test at 200 – 390 Hz. Also, according to the results of statistical comparison between SO and SV in Table 2, the hypothesis is valid at test frequencies of 200Hz, 230Hz, 300Hz and 390Hz in contrast to the rest of the frequencies. This shows that vibration can elicit tactile sound perception or enhance inaudible sound detection at this particular range of frequencies. Besides that, Table 2 shows that the biggest effect on sound detection performance is at 300 Hz with negligible p-value of 0.0001, and additionally, sound detection is also high at 200 Hz, 230 Hz, 390 Hz with p-values of 0.0144, 0.0095 and 0.0047, respectively. Figure 4 shows a similar trend to SV results in Figure 3. This graph confirms previous claims and shows that there is almost no audio-tactile exc~\\itation at 20-170 Hz. Starting from 200 Hz, the percentage of tactile sound perception increases. As it was already mentioned above, audio-tactile feedback is highest at 200-390 Hz having a peak at 300 Hz. This roughly agrees with (Ranjbar et al., 2016), where the respective frequency was 250 Hertz. Furthermore, 300 Hz coincides to the frequency at which maximum tactile sensitivity with respect to amplitude of excitation is located (Gescheider et al., 2002 cited in Jones and Sarter, 2008).

Since, it is hard to completely isolate the sound coming from the vibration generator, the results of SV and SVNT tests need to be compared to ensure that the leaked sound is significantly low. From the statistical comparison between SV and SO, valid frequencies are determined to be 200Hz, 230 Hz, 300Hz and 390 Hz. Thus, hypothesis testing of SV versus SVNT was performed for the valid frequencies and for the remaining frequencies separately. For valid frequencies, as is seen from Figure 5, the percentage of positive responses is relatively higher in the SV test as compared to SVNT test. Therefore, it can be safely concluded that the trend observed in Figure 3 and Figure 4 is potentially a result of audio-tactile excitation. Hypothesis testing results also show the validity of tactile sound perception with p-value of 0.0286. For the remaining 4 frequencies, hypothesis testing result indicates that SV and SVNT results are not significantly different with p – value of 0.6571.

Figure 6 further establishes that the trend shown in Figure 3 and Figure 4 is not a result of unwanted sound detection (as a response to sound coming from the vibration generator and reaching the user through the headphones). Further it is noted that the sample acceleration measurements did not detect transfer of the generated vibration through conduction since throughout the experiments the generated frequencies were not present in the measured signals.

5 CONCLUSIONS

The results further support existing research regarding perception of vibrotactile stimuli as sounds. The hypothesis that there is a frequency range in which the phenomenon under study is most intense, is validated, with the optimal audio-tactile integration frequency range being at 200-390 Hz. Given the results presented in this work, further tests that accurately address hardware issues, including response curve of hardware to frequency, sound isolation, absolute values of vibration and sound intensities and other issues should be designed so that a more precise understanding of the audio-tactile integration is achieved.

REFERENCES

Auer Jr, E. T., Bernstein, L. E., Sungkarat, W., & Singh, M. (2007). Vibrotactile activation of the auditory cortices in deaf versus hearing adults. *Neuroreport*, 18(7), 645.

Bensmaïa, S., Hollins, M., & Yau, J. (2005). Vibrotactile intensity and frequency information in the Pacinian system: *A Psychophysical Model. Perception & psychophysics*, 67(5), 828-841.

Caetano, G., Jousmäki, V. (2006). Evidence of vibrotactile input to human auditory cortex. *Neuroimag*e, 29(1), 15-28.

Johansson, R. S & Löfvenberg, J., (1984). Regional differences and interindividual variability in sensitivity to vibration in the glabrous skin of the human hand. *Brain Res*, 301(1), 65-72.

Kaczmarek, K. A., Webster, J. G., Bach-y-Rita, P., & Tompkins, W. J. (1991). Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Transactions on Biomedical Engineering*, 38(1), 1-16.

Kayser, C., Petkov, C. I., Augath, M., & Logothetis, N. K. (2005). Integration of touch and sound in auditory cortex. *Neuron*, 48(2), 373-384.

Mahns, D. A., Perkins, N. M., Sahai, V., Robinson, L., & Rowe, M. J. (2006). Vibrotactile frequency discrimination in human hairy skin. *Journal of neurophysiology*, 95(3), 1442-1450.

Ranjbar, P., Wilson, E. C., Reed, C. M., & Braida, L. D. (2016). Auditory-Tactile integration: Effects of Phase of Sinusoidal Stimulation at 50 and 250 Hz. *International Journal of Engineering Technology and Scientific Innovation*, 1(2), 209.

Schürmann, M., Caetano, G., Jousmäki, V., & Hari, R. (2004). Hands help hearing: facilitatory audiotactile interaction at low sound-intensity levels. *The Journal of the Acoustical Society of America*, 115(2), 830-832.

Gescheider, G. A., Bolanowski, S. J., Pope, J. V., & Verrillo, R. T. (2002). A four-channel analysis of the tactile sensitivity of the fingertip: Frequency selectivity, spatial summation, and temporal summation. *Somatosensory and Motor Research*, 19, 114–124.

Jones, L. A., & Sarter, N. B. (2008). Tactile Displays: Guidance for Their Design and Application. *Human Factors*, 50(1), 90–111.