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Vibration Perception Thresholds on the Five Fingers of the Human Right Hand Among an Adult Population

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ABSTRACT

The goal of the present study was to assess vibration perception thresholds (VPT) for frequencies of 65, 300, and 500 Hz, at the finger pads of the five fingers of the human right hand, while also assessing potential differences between the fingers, and potential effects of the use of two similar psychophysical methods to measure VPT. A novel instrument, the Hand Vibration Threshold Mapper, was used in this study. 13 participants took part on this experiment. Significant differences were found between VPT scores obtained using the two methods. No significant differences were found between VPT scores obtained on the five fingers, when grouped by method. Significant differences were found between VPT scores obtained on the 3 frequencies, grouped by method. Design guideline recommendations aimed at haptic feedback developers were elaborated based on these results.

Keywords: Vibration perception thresholds, Fingers, Sensory perception, Vibration, Accessibility

INTRODUCTION

While several studies have been conducted to assess Vibration Perception Thresholds (VPTs) on several locations of the human body, when it comes to the human hand, research has mostly been towards accessing VPT on the finger pad of the index finger. However, while the results from some studies, such as Dahlin et al. (2015), report no significant differences between the mean VPT obtained at the finger pad of the index and little fingers at seven different frequencies, other studies, such as Ekman et al. (2021), report that differences can indeed be found between mean VPT obtained at the finger pad of the index and little fingers, albeit only at three of the seven frequencies they studied. While the VPT for a number of frequencies at the finger pads have been studied throughout the literature, according to Gandhi et al. (2011), the choice to test certain frequencies over others is usually done mainly because of hardware limitations, instead of due to scientific reasons. Furthermore, Gandhi et al. (2011) also note that hardware limitations have usually also affected the choice of testing protocols, with protocols for commercially available equipment usually being selected less due to their efficacy, and more due to their time efficiency. As an alternative to these issues, some researchers have resorted to developing their own proprietary haptic devices in order to study haptic feedback, by using and adapting commonly available parts, creating instruments that are more well suited for their needs (Culbertson et al. 2018). To provide some standardization to research conducted in the field of haptic feedback, the international standards for mechanical vibration provided recommendations for the assessment of VPT on the fingertip, focusing on the characteristics that a vibrometer should have, as well as characteristics for the experimental protocol to follow (International Organization for Standardization 2001; International Organization for Standardization 2003). According to Mirioka and Griffin (2002), the method used for psychophysical measurement of VPT has a significant effect on a participant's results, with intermittent stimulation (e.g., staircase algorithm) providing lower thresholds in comparison to those obtained with continuous stimulation (e.g., von Békésy algorithm), albeit only at 125 Hz.

Most common devices that exist today that have haptic feedback capabilities make use of vibrotactile stimuli to deliver information. These stimuli are usually generated through actuators, of which the most common are Eccentric Rotary Mass (ERM) motors. While ERM motors can generate high displacement outputs with a low power consumption, their other characteristics, such as low response time, low bandwidth, and bigger size when compared to other actuators, make them less well suited to be included in devices in certain settings. Alternatively, while not capable of generating displacement outputs as high as ERM motors, piezoelectric actuators might be more well fitted to be used in said other settings, due to their high response time, high bandwidth, and very small size (Basdogan et al. 2020; Culbertson et al. 2018; Kim et al. 2021). However, to effectively transmit information through vibrotactile stimuli generated by actuators such as piezoelectric, developers must first know which combinations of frequency and amplitude, from the entire range that these actuators can generate, can reach and/or surpass the VPT at the intended point of contact with the user's body, so that the generated stimuli is correctly perceived by users.

The main goal of the present study was to collect VPT data for three different frequencies on the finger pads of the five fingers of the human right hand, using two similar psychophysical methods, and to evaluate if said VPT data differed between the methods used, the fingers, and the frequencies. From this data, we aimed to elaborate a basis from which design guidelines for the implementation of vibrotactile haptic feedback, generated by piezoelectric actuators, could be written, with which developers can work with.

METHOD

Two tasks, Task A and Task B, were designed to assess VPT, for the three studied frequencies, at the finger pads of the five fingers. These tasks follow an adaptative procedure, the staircase algorithm, with a transformed 1 up /3 down rule. Participants completed the study over one session, in which they completed both tasks, assigned to participants in alternating order. Each session was composed of two phases: a training phase, and an experimental phase.

Participants

13 healthy participants aged 22 to 45 years (M = 30.08, SD = 7.5; 9 male, 4 female; 12 right-handed, 1 left-handed), took part in this study. Participant's self-reported height was between 1.60 m and 1.90 m (M =1.75, SD = 0.1), and self-reported weight was between 58 Kg and 85 Kg (M = 70.39, SD = 9.59). The average weight of the participant's right hand was between 104 grams and 620 grams (M = 385 grams, SD = 161.94). A written informed consent was obtained from all participants.

Research Design

Instruments. This study was conducted using the Hand Vibration Threshold Mapper (HaViThreMa) testing platform and its accompanying Graphical User Interface (GUI) (published elsewhere). Sessions were conducted on an open-spaced lab room of the building. This room was well-lit, with a room temperature that varied between 22°C and 22.5°C during sessions. The noise and traffic levels of the room varied throughout the day, as this room was also used as a passage point between two adjacent lab rooms. The HaViThreMa was placed on top of a table at a height slightly lower than the participant's chest while sitting. Participants were seated in a chair without armrest support. An ACM 60 Precision scale, with a square weighting pan of 145X160cm, was used to measure the weight of the participant's hand, while on a resting position, before they placed their hand on the testing platform. During the hand weight measuring and experimental procedure, the participant's lower right arm rested on top of an object with a foamy material, which resulted in their hand being at the same height as the metal platform of the HaViThreMa. Participants inputted their answers to each trial using a wireless keyboard with their left hand. Participants were required to wear a pair of Sony WH-1000XM4 noise-cancelling headphones during the experimental tasks, to mask out the noise of the actuators and the room.

Experimental Design. The vibration of the actuators was controlled through sinusoidal waves. Vibration stimuli with different frequencies were delivered to the finger pad of each of the 5 fingers of the participant's right hand. Each combination of frequency and finger was identified as one Subtask. Vibration amplitude was controlled through percentages of actuation. The amplitude of the stimulus varied between 0% and 100%. Depending on which frequency is being used, these amplitudes percentages correspond to different accelerations (g). Therefore, the relation between amplitude percentage inputted in the GUI, and acceleration outputted by the actuators, is unique for each vibration frequency. Other factors, such as how much pressure is exerted on top of the Piezo Cradle, or how the finger is placed on top of it, also affect the readings recorded by the accelerator. While the experiment was running, participants were instructed to let their hands rest on the HaViThreMa testing platform in a way that was natural to them, but that left the central area of their finger pads rest on top of their corresponding Piezo Cradle, while the palm of the hand rested on top of the metal structure of the testing platform.

Training Phase. Before starting the experimental tasks, participants were required to complete a short training, following the procedure of Task A, with vibrations of 250 Hz being delivered to the finger pad of the index finger.

Experimental Phase. On each task, vibrotactile stimuli were individually delivered to the finger pads of the 5 fingers of the participant's right hand. Vibrations were generated through sinusoidal waves, with fixed frequencies of either 65, 300, or 500 Hz, depending on the subtask. Each task was composed of 15 total subtasks (3 frequencies x 5 fingers). During each subtask, vibration amplitude would increase or decrease depending on the participants answers of "detected" or "not detected", in pre-defined step sizes and in accordance with the transformed 1 up / 3 down rule. A *reversal* occurred whenever a change from a decrease to increase, or vice-versa, occurred. On Task A, stimulus intensity for each subtask began at the upper limit of 100%, above expected threshold levels. On Task B, stimulus intensity for each subtask began at the lower limit of 0%, below expected threshold levels. To speed up the experimental procedure of Task A, a 1 up / 1 down rule was implemented before the first reversal occurred, after which a 1 up / 3 down rule was used. After a task had been started, all subtasks on that task had to be completed before the next task could begin. The initial step size of 10% was reduced to 5% after the first 4 reversals. After a subtask was started, it had to be completed before the next subtask could begin. Each subtask ran until either a total of 8 reversals had occurred, ending on the trial whose response led to the 8th reversal, or three "detected" responses were inputted while the amplitude was at 0%, or three "not detected" responses were inputted while the amplitude was at 100%. Vibration stimulus for each trial started when the trial began and ended after an answer had been inputted. A 1s delay was implemented between the end of a trial and the start of the next trial. After 0.5 seconds had passed since the beginning of a trial, a LED light, placed in front of the participant, was turned on, indicating to participants that they should input their answer.

Procedure. At the beginning of the session, the experimental setup and main objectives of the study were explained to participants. Following this, participants were asked to give their consent and fill out a sociodemographic characteristic's questionnaire. Afterwards, participants were asked to sit at the prepared table and to place their lower arm on the foam material object. Next, their right hand was first weighted using the scale, and, following this, participants were asked to place their hand on top of the HaViThreMa metal structure, with the researcher placing each Piezo Cradle under the center of the finger pad of its intended finger. Task instructions were then given to participants, alongside the wireless keyboard with which to input their answers. Next, participants completed the training phase. After this training, participants were free to either repeat it again, or to move on to the first experimental task. After the first experimental task was concluded, participants were incentivized to take a short break while the next task was prepared. After concluding the second experimental task, the session was concluded.

Table 1. Mean vibration perception threshold (standard deviation) in dB (relative to 10^{-6}m/s^2).

Frequency	Task	Thumb	Index	Middle	Ring	Little	Total Mean
65 Hz	A	101.31 (4.65)	105.26 (4.07)	103.71 (3.43)	104.7 (3.24)	105.6 (2.54)	104.36 (3.67)
	B	103.04 (5.69)	104.75 (5.13)	102.68 (4.67)	103.63 (4.31)	105.25 (1.43)	103.85 (4.48)
300 Hz	A	117.01 (5.61)	119.48 (8.73)	119.92 (8.84)	115.93 (8.8)	119.16 (4.41)	118.25 (7.49)
	B	115.61 (6.68)	115.93 (9.87)	118.59 (6.84)	111.1 (10.58)	114.83 (7.46)	115.21 (8.57)
500 Hz	A	125.99 (4.02)	126.93 (8.47)	127.65 (8.93)	127.12 (7.86)	128 (7.03)	127.09 (7.26)
	B	123.46 (9.39)	124.76 (12.47)	124.98 (9.36)	124.03 (13.39)	122.37 (8.46)	123.99 (10.63)
Total Mean	A	118.81 (9.42)	117.54 (11.58)	118.16 (12.39)	115.92 (11.47)	121.15 (9.06)	118.07 (11.02)
	B	115.98 (10.62)	115.42 (12.55)	116.23 (11.56)	113.17 (13.13)	115.47 (9.38)	115.18 (11.61)

Analysis. All acceleration (g) data acquired from the accelerometer allocated to each actuator was first transformed from acceleration g to amplitude dB relative to 10^{-6}m/s^2. The vibration perception threshold (VPT) was assessed for each participant and each task's subtasks, by calculating the average stimulus intensity across the last 4 trials in which reversals occurred, prior to the subtask's conclusion, for subtasks on which participants completed 8 total reversals. Afterwards, an analysis following a repeated-measures design was performed. All analysis were conducted using IBM SPSS Statistics Version 21.

RESULTS

The mean VPT (dB) levels obtained on Tasks A and B are presented in Table 1, organized by *Frequency*, *Task*, and *Finger*. While all participants were presented with all 15 subtasks assigned to each Task, not all managed to achieve 8 total reversals on each subtask. Information regarding the number of completed subtasks, for each combination of *Task*, *Finger*, and *Frequency*, as well as the percentage of completed subtasks overall for each said combination, is presented on Table 2. Mean VPT levels were calculated based on data acquired from completed subtasks.

Influence of *Task* on Threshold Levels

A Shapiro-Wilk test, conducted with VPT data grouped only by *Task*, revealed a departure from normality for both Task A (W (164) $= .97, p < .001$) and Task B (W (168) $= .97, p < .001$). To test the influence of *Task* on threshold levels, Wilcoxon's Signed Rank Test was used. VPT (dB) scores significantly differed between Task A and Task B (Wilcoxon, $z = -4.86, p < .001$), with lower thresholds being obtained with Task B ($Mdn = 115.90$ dB) than with

Table 2. Number of completed subtasks (8 total reversals achieved) on each *Task* (percentage of completed subtasks overall).

Frequency	Task	Thumb	Index	Middle	Ring	Little	Total
65 Hz	A	4 (30.77)	12 (92.31)	10 (76.92)	12 (92.31)	3 (23.08)	41 (63.08)
	B	6 (46.15)	12 (92.31)	10 (76.92)	12 (92.31)	6 (46.15)	46 (70.77)
300 Hz	A	13 (100)	13 (100)	12 (92.31)	13 (100)	11 (84.62)	62 (95.38)
	B	12 (92.31)	13 (100)	13 (100)	13 (100)	12 (92.31)	63 (96.92)
500 Hz	A	13 (100)	13 (100)	13 (100)	12 (92.31)	10 (76.92)	61 (93.85)
	B	11 (84.62)	13 (100)	12 (92.31)	13 (100)	10 (76.92)	59 (90.77)

Task A (*Mdn* = 119.60 dB). As a significant difference was found between the vibrotactile threshold (dB) scores of these two tasks, statistical tests regarding the effects of *Finger* on vibrotactile thresholds (dB) were conducted grouped by *Task*.

Influence of *Finger* on Threshold Levels

A Shapiro-Wilk test, conducted with VPT data obtained for each *Finger*, grouped by Task A, revealed a departure from normality for the Thumb (W (30) = .93, p = .038), the Index Finger (W (38) = .93, p < .024), and the Ring finger (W (37) = .92, p < .012). When running the same test, grouping the data by Task B, the test revealed a departure from normality for the Ring Finger (W (38) = .87, p < .001). Friedman Test was used to test the effect of *Finger*, grouped by Task, on threshold levels. Friedman Test showed that vibrotactile thresholds (dB) scores did not significantly differ between the different fingers, grouped by Task A (X^2 (4) = 7.93, p > .094). The same result was obtained when analysing *Finger*, grouped by Task B (X^2 (4) = 5.18, p > .269). As no significant differences were found between the different fingers on each task, data from *Finger* was combined when analysing the effect of *Frequency* on threshold levels, grouped by *Task*.

Influence of *Frequency* on Threshold Levels

A Shapiro-Wilk test, conducted with VPT data obtained for each *Frequency*, grouped by Task A, revealed a departure from normality for the 65 Hz (W (41) = .94, p = .028) and 500 Hz (W (61) = .91, p < .001) frequencies. When running the same test, grouping the data by Task B, the test revealed a departure from normality for the 300 Hz (W (63) = .93, p = .001) and 500 Hz (W (59) = .94, p = .006) frequencies. To test the effect of *Frequency*, grouped by *Task*, on threshold levels, a Friedman Test was used.

Friedman Test showed that VPT (dB) scores significantly differed between the different frequencies, X^2 (40) = 78.05, p < .001, on Task A.

Dunn-Bonferroni post hoc tests were carried out and, after Bonferroni adjustments, there were significant differences between the thresholds obtained for 65 Hz and 300 Hz ($p < .001$), with higher thresholds obtained at 300 Hz (Mdn = 118.70) than at 65 Hz (Mdn = 105.18), the thresholds obtained for 65 Hz and 500 Hz ($p < .001$), with higher thresholds obtained at 500 Hz (Mdn = 126.96) than at 65 Hz (Mdn = 105.18), and the thresholds obtained for the 300 Hz and 500 Hz frequencies ($p < .001$), with higher thresholds obtained at 500 Hz (Mdn = 126.96) than at 300 Hz (Mdn = 118.70). Similarly, on Task B, Friedman Test showed that VPT (dB) scores significantly differed between the different frequencies, X^2 (42) = 58.48, $p < .001$. Dunn-Bonferroni post hoc tests were carried out and there were significant differences between the thresholds obtained for 65 Hz and 300 Hz ($p < .001$), with higher thresholds obtained at 300 Hz (Mdn = 116.45) than at 65 Hz (Mdn = 104.55), the thresholds obtained for 65 Hz and 500 Hz ($p < .001$), with higher thresholds obtained at 500 Hz (Mdn = 125.77) than at 65 Hz (Mdn = 104.55), and the thresholds obtained for the 300 Hz and 500 Hz frequencies ($p = .001$), with higher thresholds obtained at 500 Hz (Mdn = 125.77) than at 300 Hz (Mdn = 116.45), after Bonferroni adjustments.

CONCLUSION

The choice of whether to start delivering stimulus above (Task A) or below (Task B) expected threshold levels, when using similar psychophysical measurement methods, was shown to have an influence on participant's VPT, with the overall VPT obtained from Task A being statistically higher than those obtained from Task B. These differences should be considered when selecting a method to gauge user's VPT at the finger pads of the fingers of the hand. While VPT results obtained from Task B were lower (that is, less amplitude was needed for participants to detect the stimulus) than on Task A, we recommend developers that want to measure users' VPTs to calibrate interactions with a device, to use a method that first delivers stimulus above expected threshold levels, as was used in Task A. This recommendation is made with the reasoning that programming vibrotactile stimulus to be just above the VPT results obtained with the method of Task B might, depending on the context and the environment surrounding the interaction, cause said vibrotactile stimulus to not be perceived by a subset of users, since interactions with devices are not usually conducted in a sensory vacuum.

Regarding the statistically non-significance of *Finger* on VPT, our results are in line with those reported by Dahlin et al. (2015). However, it should be kept in mind that the frequencies reported by Ekman et al. (2021) as resulting in statistically significant differences between mean VPT obtained on the finger pads of the index and little fingers, namely 16, 32, and 64 Hz, where not use in this study.

As for the significant differences found between VPT for the different frequencies that were used in this study, these results are in line with those obtained by the overall literature regarding the topic of VPT on the finger pads of the right hand, namely that the VPT for lower frequencies is lower than the VPT for higher frequencies. Another important information resulting from this study which we consider should be given attention to is the fact that the % of completed subtasks overall was much lower for those subtasks using a frequency of 65 Hz than for those using 300 or 500 Hz. Therefore, we recommend that, when setting up important information to be delivered to users through vibrotactile stimuli, generated from piezoelectric actuators with similar capabilities to those that were used in this study, said stimuli should be generated with frequencies above 65 Hz, especially when delivered to the thumb and little finger, as lower frequencies might be harder for users to perceive even without the influence of external distractors, especially at these two fingers. We also recommend that, when delivering information deemed important or urgent to users, vibration frequencies around 300 Hz should be used, as this frequency was the one with the highest rate of completed subtasks, which might translate to this frequency being the easiest to correctly perceive out of the three that were studied.

While the results obtained from this study seem to be in line with those obtained by the overall literature regarding VPT on the human hand, indicating that the HaViThreMa testing platform can be used in this line of research, we are aware of areas on which it could be improved for future uses, through the inclusion of other features, such as a native hand weight or finger pressure sensor that can continuously track this information, or a thermometer that can continuously track hand temperature data. The inclusion of piezoelectric actuators capable of generating stronger amplitudes at lower frequencies than currently possible is also desirable, so that this platform can be used to gather data from said lower frequencies, such as those bellow 65 Hz.

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