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Multichannel Vibrotactile Glove: Validation of a new device designed to sense vibrations

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Abstract—There is a growing interest in using the tactile modality as a compensation or sensory augmentation tool in various fields. The Multichannel Vibrotactile Glove was designed to meet the needs of these diverse disciplines and overcome the limitations of current sound-to-touch technologies. Using 12 independent haptic exciters on each finger's back and on the palm, the device can convey acoustic information to cutaneous vibrotactile receptors with precise control of the location, frequency, timing, and intensity. A staircase method was used to model vibration detection thresholds at six frequencies (100, 200, 250, 500, 800, 1000 Hertz) for each actuator position (All, Thumb, Index, Major, Middle, Pinky, Palm) and both hands (Right, Left). No between hand difference was observed and all finger actuators provided consistent thresholds, except for the Palm which exhibited higher thresholds. Spatial summation effects were observed when all actuators were activated simultaneously. Detection thresholds significantly increased at 100 Hertz and above 500 Hertz. These findings confirm that the system provides uniform stimulation across hands and actuators. Overall, the Multichannel Vibrotactile Glove provides the freedom to send various acoustic features to individual actuators, providing a versatile tool for research and a potential technology to substitute, compensate, or extend sensory perception.

Index Terms—Assistive devices, human augmentation, haptic device, tactile perception, wearable technology.

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This work involved human subjects. Approval of all ethical and experimental procedures and protocols was granted by The Research Committee for sectorial research in neurosciences and mental health of the CIUSSS - Capitale Nationale under Application No. 2023-2695 and performed in line with relevant guidelines and regulations.

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I. INTRODUCTION

HUMANS are developing ways to extend their physical capabilities through machines that mechanically interface with the body to transcend existing limitations. Some of these emerging technologies aim to augment sensory processes such as hearing. Peripheral and central auditory systems are the primary structures associated with sound perception. However, Hermann von Helmholtz already observed more than a century ago that sound waves can also be felt through touch [1]. This idea was further developed by Georg von Békésy, whose experiments illustrated the striking similarities in the ways the tactile and the auditory systems perceive and process vibrations [2]. In several situations where auditory perception is limited or even impossible, the sense of touch can thus provide an alternative to substitute or augment normal hearing abilities [3], [4]. Humans are also looking for more immersive experiences, which can also be addressed by conveying sounds as vibrations to the tactile system [5]. Early work on auditory-to-tactile substitution focused on providing opportunities for deaf people to understand speech through touch [6], [7], [8], however this avenue of research fell out of favor with the advent of cochlear implants and modern hearing aids [9], [10]. These hearing devices drastically improve communication for people with hearing loss in many situations, but still struggle to restore many high-level auditory capabilities such as music perception, speech comprehension in noise and auditory discrimination in environments with competing sounds [11], [12], [13], [14]. As such, a renewed interest is growing for tactile devices as assistive tools to tackle these difficulties. To address these remaining challenges, we designed the Multichannel Vibrotactile Glove, a new wearable device to sense acoustic information as vibrations via the hands.

Previous experiments from our team with a first prototype which provided vibratory mechanical stimulation to the hands revealed that both individuals with normal-hearing and profound hearing loss can discriminate frequencies and identify emotions in music [15], [16] via the tactile modality solely. Furthermore, results from these previous studies suggested that individuals with extensive musical training have improved performance for tactile frequency discrimination in comparison to non-musicians [17]. Additionally, individuals with profound hearing loss were better at identifying happiness in music with tactile stimulation only [15]. These findings support the assumption that tactile perception of sound abilities is trainable and is also influenced by the amount of exposure.

The efficacy of auditory to vibrotactile sensory substitution relies on an adequate stimulation of the appropriate skin

mechanoreceptors [18]. In particular, the Pacinian corpuscles in the deep dermis of the skin offer an optimal target for vibrotactile perception. These mechanoreceptors are not interesting for spatial localization due to their large receptive field [19], however, they produce a high-fidelity neural image of transient and vibratory stimuli transmitted to the hand [20]. Their receptor potential rapidly adapts to mechanical stimulus with an extreme sensitivity to skin motion. This specialized frequency dependent-tuning of Pacinian corpuscles enables high-fidelity responses selectively to high-frequency stimuli [20], [21]. Their frequency responsiveness range for vibration (100 to 1000 Hz) overlaps with hearing (20 to 20000 Hz) [22]. All these characteristics make it not surprising that Pacinian corpuscles receptors evoke sensations that shares many properties with hearing [22], [23], such as the ability to generate the perception of pitch [24], [25], [26] and positions them as promising candidates for facilitating tactile perception of auditory information. The hands offer by far the best performance for tactile applications since they have the highest tactile innervation of the body [27] and contains the highest number of Pacinian corpuscles [28]. However, there exists to date very few haptic gloves transmitting acoustic information as vibrotactile stimulation specifically targeting these mechanoreceptors. Furthermore, all existing models offer limited versatility because they are unable to control frequency independently from intensity [29], [30], [31] or to send distinct vibrations to different locations on the hand [15], [16], [17].

These drawbacks are significant given that the tactile system can only feel mechanical vibrations in a limited frequency range compared to hearing [22], meaning that a combined use of spatial, frequency and intensity dimensions are needed to compensate for this lower bandwidth. Multichannel devices offer a clear opportunity for improvement by allowing the introduction of a spatial dimension to vibrotactile sound perception to substantially increase the amount of auditory information conveyed through touch. Some research has experimented with systems that could filter sounds into multiple spatially separated channels [32], [33], but the number of independent channels remains limited, far below the typical 12 to 22 channels used in modern sensory replacement technologies such as cochlear implants [34].

With up to 12 independent channels, the Multichannel Vibrotactile Glove allows the use of various mapping strategies to transmit the multiple features of sound to different places on the hand. A concrete example, not investigated in this study but highlighting future research possibilities, is the technology's potential to enable users to perceive a different instrument at each finger within a piece of music. The technology allows the unique instrumental lines of each instrument in a track to be conveyed through separate speakers, enabling distinct localization for each instrument and providing differentiated vibrotactile information. Another example is the possibility of doing frequency transposition, as the temporal envelopes of several higher frequency bands are typically not perceived by the skin. Therefore, these higher frequencies can be extracted, presented using lower frequency carriers, and organized across multiple fingers. Such signal processing strategies can thus reproduce a tonotopic mapping, similar to how sound is coded by the cochlea, on the skin [32], [33]. By shifting high-

frequency information to lower frequencies and distributing it across multiple sensory points, it is possible to increase total amount of information that can be perceived. However, this type of configuration requires investigating to understand the limits of tactile perception and measure the possible benefits. The versatility of our technology will allow researchers to explore these understudied elements of tactile perception.

The primary goal in developing the Multichannel Vibrotactile Glove was to address the limitations of existing sound-to-touch technologies by providing a tactile device capable of 1) efficiently stimulating the Pacinian corpuscles across their entire frequency range and 2) providing independent control over multiple spatially separated channels. The aim of the current study is to validate the Multichannel Vibrotactile Glove by evaluating its adequacy in fulfilling these design goals. In presenting the design and the validation of the device, we hope to provide useful proof of concept for a broad range of experimental designs in cognitive neuroscience, rehabilitation [35], and music [36] to explore new ways to augment performance, entertainment, and accessibility through multisensory or immersive experiences [4].

II. DESIGN OF THE MULTICHANNEL VIBROTACTILE GLOVE

The design philosophy of the Multichannel Vibrotactile Glove (Fig. 1(a)) was guided by the recent framework proposed by Sharp [37] in response to recent calls for a transdisciplinary approach in technology development to facilitate collaboration among disciplines traditionally operating in silos. The device thus aims to provide a versatile, accessible, and minimally invasive tool to fulfill the needs of different fields. The device, which is detailed in a pending patent [38], can transmit acoustic information through vibrotactile stimulation on the back of each finger and on the palm on one or both hands simultaneously, allowing for a total of 12 independently controlled haptic actuators. The choice and placement of the actuator, as well as the overall design, aimed to optimize vibrotactile sensitivity while minimizing physical invasiveness (Fig. 1(b)).

A. Tactile Simulation Techniques

Tactile stimulation techniques for replicating sensory experiences can generally be categorized into two main types: mechanical and electrical stimulation [39]. Due to their deep location in the skin and high sensitivity to mechanical movements, Pacinian corpuscles make electro-tactile actuators less practical. The need for high current levels poses safety risks, while continuous calibration is essential due to variations in skin properties across individuals [39]. Even if mechanical actuators tend to be bulkier, these challenges make electro-tactile stimulation less attractive for sending vibrations to the skin to elicit vibrotactile perception of sounds. Furthermore, Pacinian corpuscles have large receptive fields which greatly limit their spatial resolution. Due to this characteristic, the spatial discrimination of small actuators may be limited as they would only contribute to a summation effect within the receptive field.

B. Actuator position

Human hands are optimal for tactile applications, but haptic gloves need to be designed so that hand movement and grasping

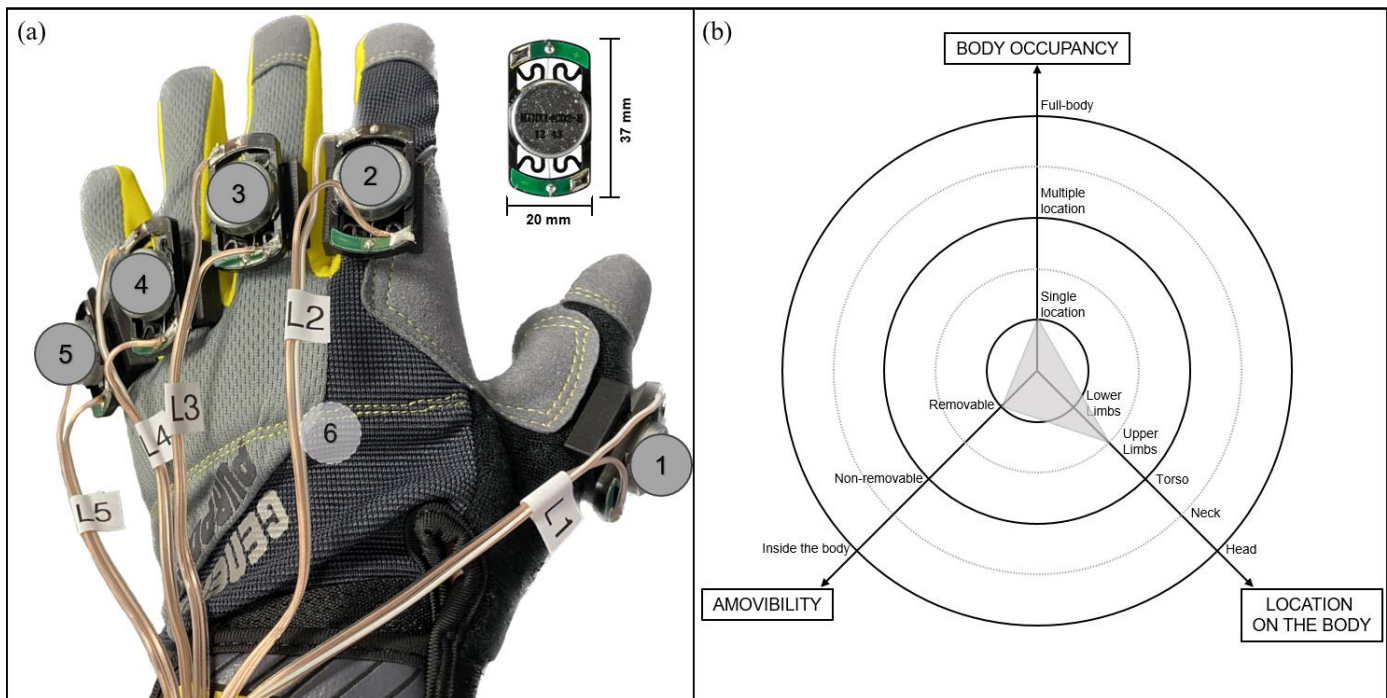


Fig. 1. (a) Picture of the left Multichannel Vibrotactile Glove. The actuator has size of 20 x 37 x 9.85 mm and weighs 12.8 g. (b) Representation of the degree of physical invasiveness of the technology in the proposed framework of Sharp [37].

freedom are not restricted [40], [41]. One option is to limit the stimulation area to the back of the hand. That’s why five of the six actuators were placed on the dorsal aspect of the proximal phalanges. Although the palm is more sensitive to tactile stimulation because it possesses specialized glabrous (i.e., non-hairy) skin instead of the hairy skin on the back of the hand [42], the ability to perform frequency analysis appears to be similar in both glabrous and hairy skin [43]. Next to the fingertips, the proximal phalanges and the metacarpophalangeal joints have the highest density of Pacinian corpuscles [27], [44], which may be able to be stimulated from the back of the finger due to the large receptive field of Pacinian corpuscles [19], [28]. An actuator was also placed on the palm to directly stimulate glabrous skin. Petry et al. [45] found that palm actuators performed better than wrist or forearm actuators, while still maintaining the user’s ability to grasp. For the Multichannel Vibrotactile Glove, the palm actuators were placed on the thenar eminence, which has been shown to yield similar sensitivity as the fingertip given a large enough contact area [46].

C. Choice of Actuator

The choice of actuators is of crucial importance for wearable devices since they need to account for the impedance introduced by the mounting mechanism and by the skin tissues themselves [47]. Choi and Kuchenbecker [48] describe the tradeoff between existing haptic actuator options. On one side, the popular ERM motors are an inexpensive and widely available option, but lack the precision and versatility required for the Multichannel Vibrotactile Glove. On the other side, piezoelectric actuators offer great expressiveness and customizability, but are more expensive and harder to work with. Instead, voice coil based electrodynamic loudspeakers were chosen because they offer great mechanical simplicity and

expressiveness while remaining very affordable. Specifically, audio exciters were selected, a type of electromagnetic voice coil that induces vibrations of the rigid surface to which they are fixed. Such exciters can induce vibrations with higher amplitudes over a larger area, which may be able to recruit more mechanoreceptors in the skin and provide a better vibrotactile stimulation [49], [50]. Because of this area of contact, these exciters may perform worse for spatial resolution, however placing actuators on different fingers may counteract this issue as there appear to be finger-specific representations in the somatosensory cortex [51], [52].

D. Hardware characterization

The TEAX14C02-8 actuators (Tectonic, New York, NY, USA) were mounted on synthetic General Purpose leather gloves (Firm Grip, Atlanta, GA, USA) using custom 3D printed mounting pieces (see Fig. 1(a)). They were connected to a 12-channel class D audio MA1260 power amplifier (DaytonAudio, Springboro, OH, USA) using copper wires. The amplifier was driven by an external ICUSBAUDIO7D sound card (StarTech.com Ltd., London, ON, Canada). The system was operated using a dedicated laptop running the Microsoft Windows 11 operating system (Redmond, WA, USA). The whole system fits on a 75x75 cm desk space, with most of the space taken up by the 43x35 cm amplifier. The length of the wires allowed the user around 1 m of movement around the amplifier.

III. METHODS

The proposed experiment aimed to model the detection thresholds that could be achieved with the Multichannel Vibrotactile Glove, assessing internal consistency of thresholds across both hands (Right, Left) and across each actuator position (referred to as “Thumb”, “Index”, “Middle”, “Major”,

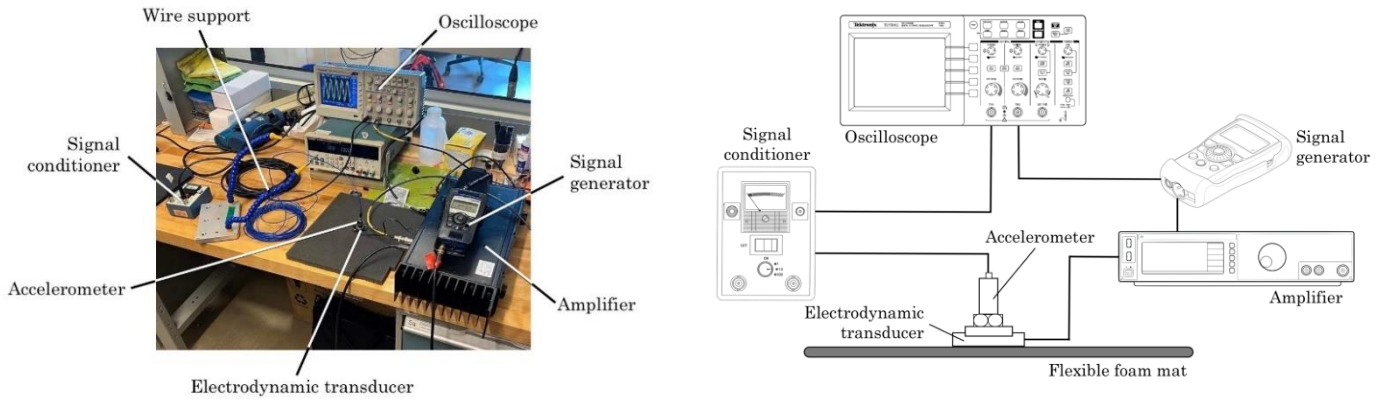


Fig. 2. Picture and diagram of the test setup for the sensitivity analysis

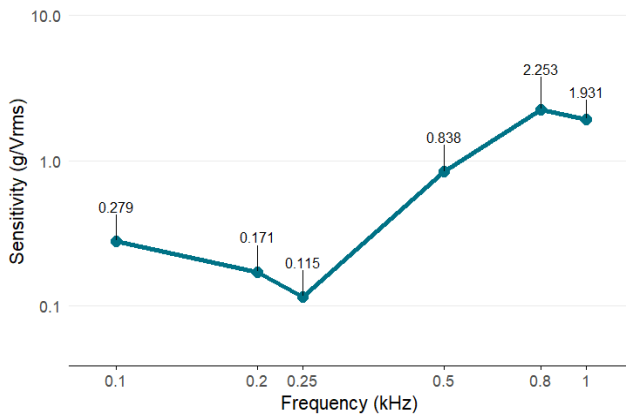


Fig. 3 Results of the sensitivity analysis

“Pinky”, “Palm”, and “All”). Considering that vibrotactile detection thresholds are highly dependent on stimulation frequency, a further aim was to assess the consistency across each actuator for six frequencies representative of the Pacinian corpuscle’s frequency response range (100, 200, 250, 500, 800, and 1000 Hz).

A. Participants

Five graduate students (2 males, 3 females) aged between 23 and 27 from the CERVO Brain Research Center participated in this experiment. Most participants were aware of or had interacted with the vibrotactile glove (or a previous prototype) before this experiment. Participants had no history of hearing loss, diabetes, or reduced tactile sensibility. The individuals selected exclusively self-reported as right-handed, as research on language and the motor system suggests that right-handedness provides more consistent behavioral and neurophysiological patterns, whereas left-handed individuals exhibit greater variability in lateralization [53], [54]. This methodological decision was made in order to ensure that any observed effects were attributable to the device rather than individual differences in handedness.

The Research Committee for sectorial research in neurosciences and mental health of the CIUSSS - Capitale Nationale approved all procedures and each participant provided written informed consent (Ethics approval number

2023-2695). All experiments were performed in accordance with relevant guidelines and regulations.

B. Stimuli and procedure

Sinusoidal pure-tone waveforms were created using the free and open-source software Audacity [55]. The generated tones were converted to waveform files and were played continuously from the soundcard of a dedicated laptop running Windows 11. The experimenter used a customized keystroke script [56] to control the start of the stimulus, the interstimulus duration, and to increase or lower the intensity by predetermined steps directly from the operating system’s sound interface. The method of estimating detection threshold by modulating the intensity of the stimuli is commonly used in experiments on vibrotactile sensitivity [42], [50], [57]. Thresholds were obtained for six frequency stimuli (conditions 100, 200, 250, 500, 800, and 1000 Hz) across seven actuators (conditions “Thumb”, “Index”, “Major”, “Middle”, “Pinky”, “Palm”, and “All”) and two hands (conditions “Right” and “Left”), for a total of 84 measurements per participants.

The stimuli were presented for 2 seconds with an interstimulus interval arbitrarily chosen by the experimenter from 2 to 10 seconds to reduce the risks of habituation effects biasing the results. A classical up-and-down staircase method [58] was selected due to its simplicity and high efficiency [59]. Up-down staircase methods have the advantage that most trials will be near the true thresholds and can show if a drift occurs in the response pattern during the test [60]. The initial stimulus intensity in effective voltage (Vrms) was first set at an undetectable level (either at 0 or well below known thresholds) and the intensity was increased in predetermined steps by the experimenter up to a possible maximum of 2.16 Vrms. Participants reported perceiving the stimulus by saying “Yes”, which was considered the first ascending reversal. The signal intensity was then decreased in fixed steps by the experimenter until the participant stopped perceiving the stimulus, which was considered the first descending reversal. This was repeated for a total of 8 reversals, 4 ascending and 4 descending [59], [61].

Participants were seated in a quiet room with participants seated facing away from the experimenter, and stimuli were presented via the Multichannel Vibrotactile Glove. To have reproducible conditions and avoid possible interference from self-generated tactile sensation, participants were instructed to

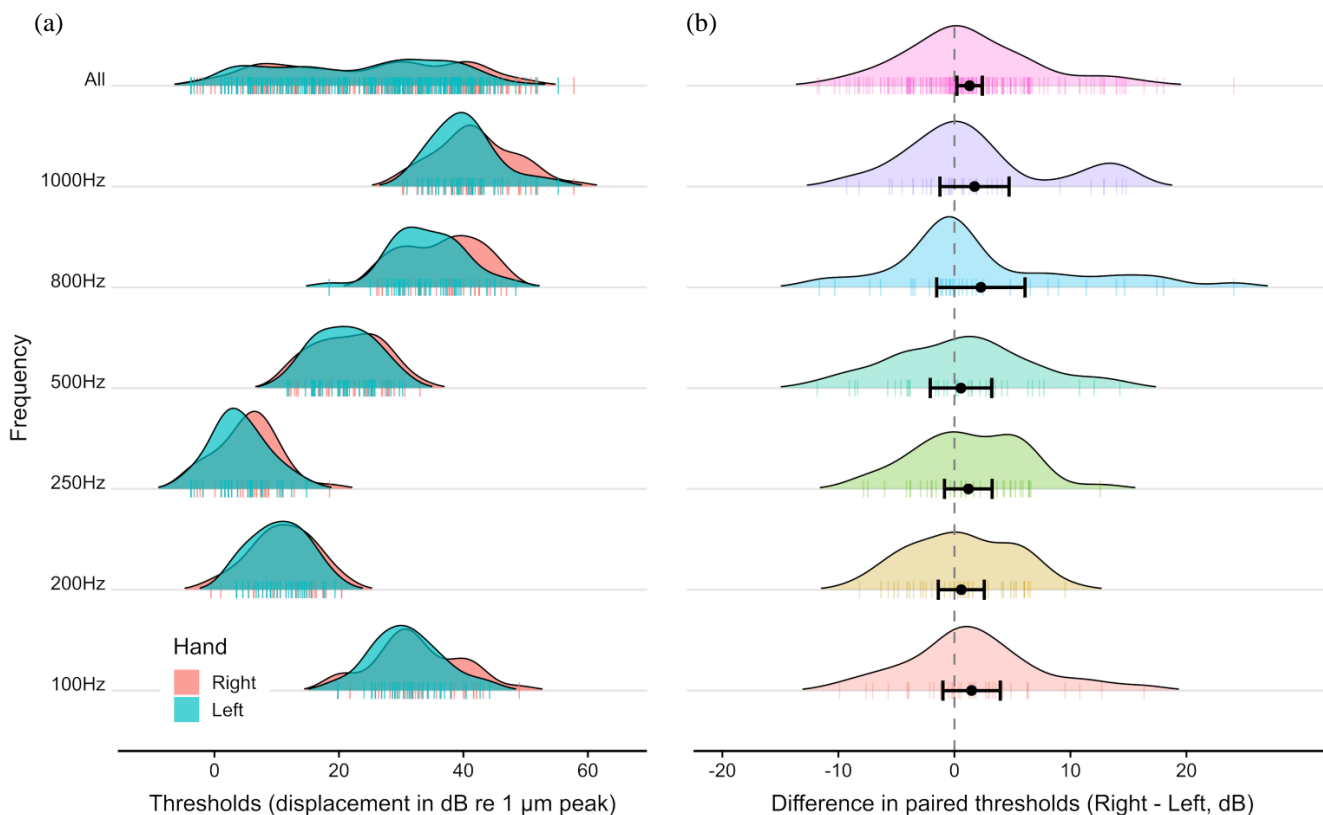


Fig 4. Comparison of thresholds between hands. (a) Distribution of thresholds for the right (red) and left (blue) hand for each frequency and for all frequencies together (topmost). (b) Difference in thresholds between paired comparisons (right minus left). Error bars are 95% confidence intervals (CI).

rest their forearms on the armrest, with their hands suspended in the air. The method employed for masking the sound produced by the gloves was the same as in prior studies [15], [16], [17]. A white noise was presented via attenuating circumaural headphones (10 S/DC, David Clark, Worcester, MA, USA) and the participant also wore earplugs. The volume of the white noise was adjusted so that the participant could not hear the sound produced by the gloves. Data acquisition lasted around 4 hours for each participant and took place over 2 to 4 sessions. To avoid fatigue bias, participants were advised to take breaks every 30 minutes.

C. System characterization and sensitivity tests

A digital oscilloscope model TBS1052B-EDU (Tektronix, Beaverton, OR, United States) was used to measure the electrical input signal delivered by the audio power amplifier to the haptic audio exciters. The high frequency noise introduced by the Class D power amplifier was filtered out using a Sallen-Key second-order active low pass filter with a cut-off frequency of 4954 Hz. Changing the signal frequency had no effect on the measured voltage sent to the activators (linearity of the electrical chain) and both left-hand and right-hand gloves received the same driving voltages for the same stimuli intensity. Furthermore, the electrical signal sent to the electrodynamic actuators was also monitored to ensure that the signal was not distorted, clipped or noisy.

Sensitivity tests were conducted to measure the performance of the electrodynamic actuators as a function of the excitation

frequency. The test setup (Fig. 2) was composed of an analog signal generator model MR2 Minirator (NTi Audio, Schwab, Liechtenstein), an amplifier model RA-100 (ALESIS, Cumberland, USA), an oscilloscope, an accelerometer model PCB352C34, and its signal conditioner model 480E09 (PCB Piezotronics Inc., New York, USA). To simulate free-free boundary conditions, the driving mechanisms were laid down on a flexible foam mat. The driving voltage signal was a pure sine wave and the Root Mean Square (RMS) of the signals were calculated for both induced acceleration and driving voltage. The sensitivity is defined as the output acceleration normalized with respect to the effective electrical driving voltage, measured in g/V_{rms} where g is the gravitational acceleration (9.81 m/s^2). The excitation frequencies were the same as the frequency conditions used in the experiment. The results of the sensitivity tests are reported in Fig. 3. Additional measurements that were recorded with a constant frequency of 500 Hz for different driving voltage levels showed that sensitivity was mostly level independent, only slightly increasing with the input voltage.

D. Analyses

To estimate the thresholds, the driving voltage obtained at all 8 reversals was first averaged. This averaging method is a type of mid-run estimate, which is robust threshold estimation methods for staircase procedures that have a high precision even with smaller numbers of trials [60]. The driving voltage was then converted to acceleration based on the measured sensitivity of the actuators (Fig. 3) and subsequently integrated

twice with respect to frequency to yield thresholds expressed in terms of displacement, in decibels, with a reference value of 1 micron. Statistical analyses (analysis of variance, paired t tests) were conducted to assess if there were significant differences in threshold values between the levels of each condition (Hands (x2), Actuators (x6), Frequencies (x7)). Data processing and analysis was conducted using statistical computing software R version 2.4.4 [62] and the rstatix package version 0.7.2 [63].

IV. RESULTS

A three-way repeated measures analysis of variance (ANOVA) was conducted to determine the effects of *Hands*, *Actuators*, and *Frequencies* on thresholds. Results showed a significant two-way interaction between *Frequencies* and *Actuators*, $F(30, 120) = 3.131, p < .001$. Furthermore, there was no statistically significant main effect or interaction effect with *Hands* (all $p > 0.1$), suggesting no differences in thresholds between the right and left hand conditions (Fig. 4). Paired t -tests with Bonferroni correction were conducted to compare thresholds between consecutive frequencies in each *Actuator* condition (Fig. 5) and to compare thresholds between every actuator in each *Frequency* condition (illustrated in Fig. 6 and detailed in Table I).

In summary, the thresholds significantly differed across most consecutive *Frequency* conditions in each actuator, except for 200 compared to 250 Hz in the Thumb actuator and for 800 compared to 1000 Hz in the Thumb, Middle and Ring actuators (Fig 5). The “All” Actuator condition consistently showed lower thresholds compared to individual actuators, with significant differences observed compared to least two and up to five actuators in each *Frequency* condition (Table 1). Additionally, the Palm Actuator condition showed significantly higher threshold compared to the Thumb and Index at 100 Hz, and compared to the Index, Middle and Ring at 1000 Hz (Table 1).

To validate the estimated thresholds, they were compared to additional measurements conducted in 10 additional participants for frequencies 100, 250, 500 and 800 Hz in the “All” actuator condition. For these validation thresholds, participants were now asked to respond by pressing on a keyboard key to assess the vibrotactile sensitivity with some added hand movement. Results of t -tests showed no statistically significant difference between the original thresholds and the validation thresholds at 100, 250, 500 and 800 Hz (all $p > 0.1$).

V. DISCUSSION

The main goal in designing the Multichannel Vibrotactile Glove was to enable tactile stimulation with a high-fidelity acoustic representation while allowing for independent control of each vibrotactile actuator. Measurements of the resulting input driving to the haptic audio excitors with a digital oscilloscope allowed to validate that the signal was not noisy, clipped, or distorted. Furthermore, to validate the functionality of the gloves, vibration detection thresholds were measured on human subjects at different frequencies to compare them across hands and actuators.

TABLE I
PAIRWISE PAIRED SAMPLES T-TESTS BETWEEN
ACTUATORS FOR EACH FREQUENCY

Freq (Hz)	Actuator 1	Actuator 2	$t(9)$	p
100	Thumb	All	7.987	<.001
	Middle	All	7.938	<.001
	Ring	All	7.396	<.001
	Palm	All	7.708	<.001
	Thumb	Palm	-4.588	.028
	Index	Palm	-4.241	.046
200z	Index	All	5.243	.011
	Middle	All	9.864	<.001
	Ring	All	9.544	<.001
	Pinky	All	7.884	<.001
	Palm	All	5.058	.014
250	Index	All	4.268	.044
	Middle	All	6.667	.002
	Ring	All	7.122	.001
	Pinky	All	4.543	.029
	Palm	All	5.660	.007
500	Index	Ring	-4.241	.046
	Middle	All	4.801	.020
800	Palm	All	5.404	.009
	Thumb	All	4.879	.018
1000	Index	All	6.592	.002
	Middle	All	4.540	.030
	Thumb	All	5.035	.015
	Index	All	5.311	.010
	Palm	All	8.095	<.001
1000	Index	Palm	-4.286	.043
	Middle	Palm	-4.281	.043
	Ring	Palm	-7.845	<.001

The p values are with Bonferroni correction. Only significant contrasts are shown.

A. Detection Thresholds as a function of frequency

Thresholds were significantly lower at 250 Hz, which is known to be the point of highest vibrotactile sensitivity [64], and significantly increased with each lowering and increasing frequencies. Overall, the measured thresholds produce a U-shape as a function of frequency (Fig. 6), which is consistent with previously measured thresholds for Pacinian corpuscle afferents of the electrical driving input (see electrodynamic transducer frequency response in Table I). The lowest sensitivity of $0.115 g/V_{rms}$ was at 250 Hz, but, despite this, 250 Hz is still the frequency where thresholds were the lowest. Actuator sensitivity was higher at lower frequencies, with values of 0.300 and $0.171 g/V_{rms}$ at 100 and 200 Hz, and at higher frequencies, reaching values of 0.838 , 2.253 and $1.931 g/V_{rms}$ at 500, 800, and 1000 Hz, meaning that the selected actuators are able to efficiently at stimulating frequencies that are typically harder for the tactile system to perceive. Nonetheless, thresholds still formed a U-shape as a function of frequency, which is then attributable to Pacinian corpuscles activation and not to actuators characteristics. Similarly, the significantly higher thresholds at 800 and 1000 Hz reflect the known limitations of the tactile system. Overall, these results suggest that the Multichannel Vibrotactile Glove can efficiently excite tactile receptors in a broad frequency range, with an

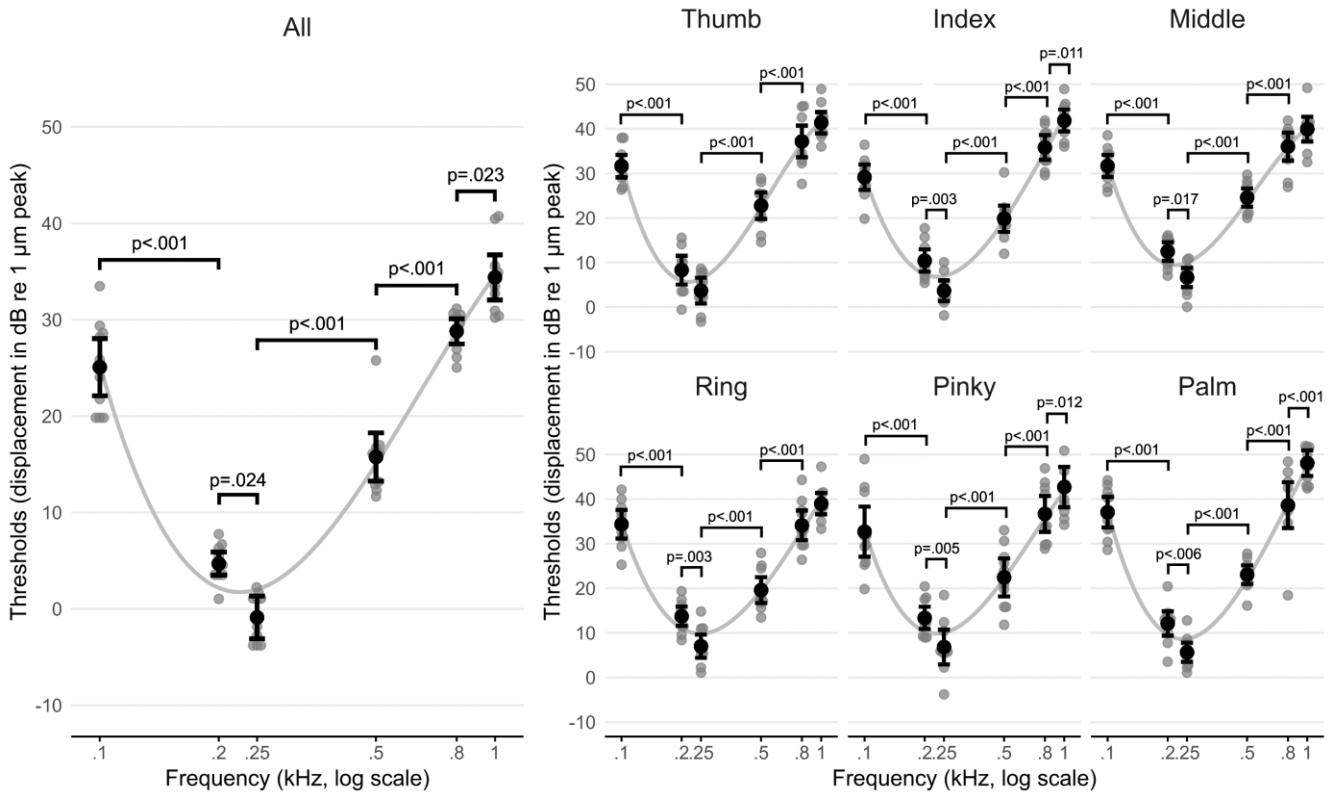


Fig. 5. Comparison of thresholds between consecutive frequencies for each actuator. Error bars are 95% confidence intervals (CI), p values are with Bonferroni correction.

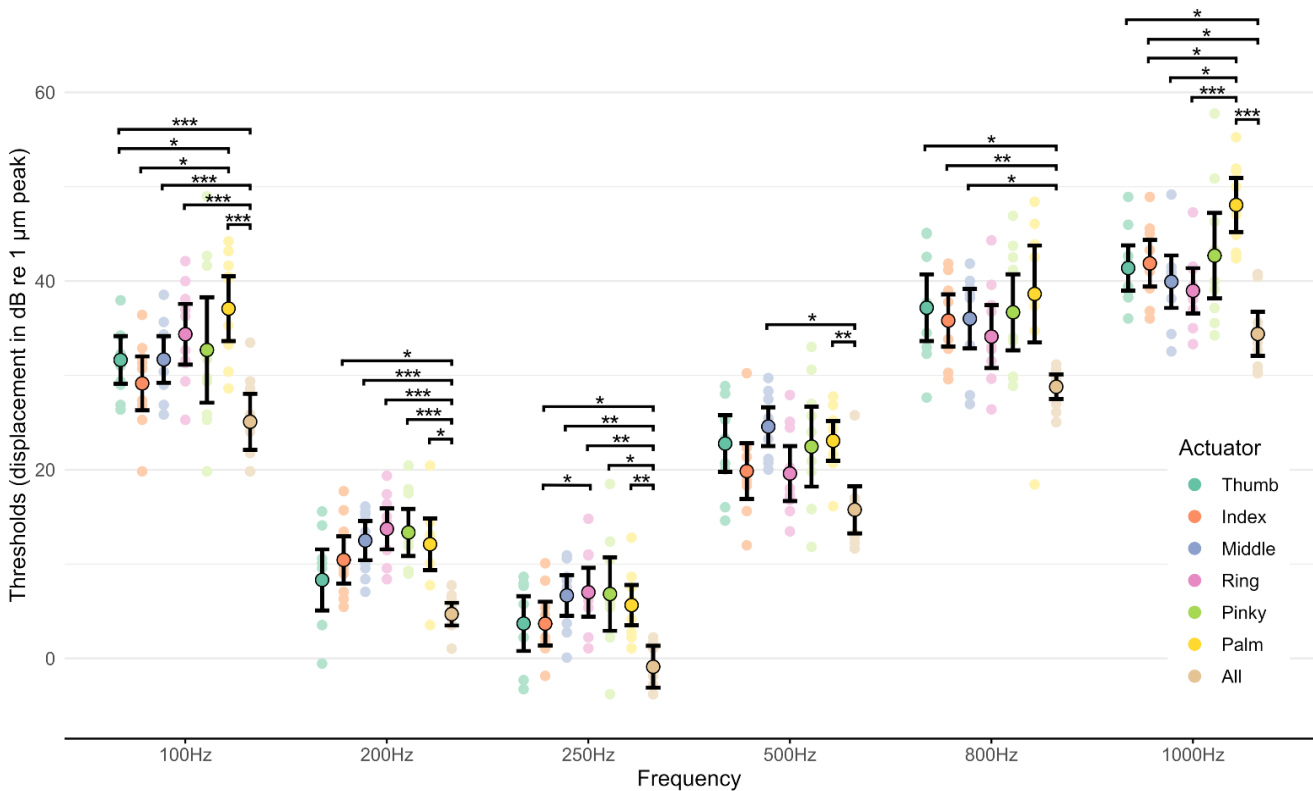


Fig. 6. Comparison of thresholds between actuators for each frequency. Error bars represent the 95% confidence intervals (CI). (* $p < .05$, ** $p < .01$, *** $p < .001$, after Bonferroni correction)

important involvement from Pacinian corpuscles. However, since these mechanoreceptors are mostly thought to be exclusive to glabrous skin, it's worth exploring the mechanisms by which the gloves can efficiently solicit Pacinian corpuscles afferent via the back of the finger.

A first hypothesis could be that hairy skin actually contains some Pacinian corpuscles. This hypothesis is supported by electrophysiological evidence. Notably, Järvillehto et al. [65] observed a fast-adapting mechanoreceptor on the back of the human hand capable of phase-locking to vibrations up to 400 Hz. Later, Vallbo et al. [66] found what they believe to be Pacinian corpuscle afferents in the hairy skin of the forearm based on the characteristics of their receptive fields. There is also a possibility that hair follicles mechanoreceptors may contribute to the response at lower frequencies [67].

A second hypothesis could be that the gloves are primarily stimulating Pacinian corpuscles from the palmar aspect of the hand. This could occur via transmission of the vibrations through either the soft tissue or the bone of the phalanges [68], [69]. Indeed, since Pacinian corpuscles are found deeper in the skin or near joints and ligament, they are characterized by large receptive field [19], [28], [44] that may reach the lateral and the dorsal aspects of the fingers [19], [70]. Mahns et al. [43] obtained detection thresholds on the hairy skin of the forearm and hypothesized that these responses were mediated by vibration transmission to remote Pacinian corpuscles at the wrist and elbow joint. The Multichannel Vibrotactile Glove instead transmit vibrations to the dorsal aspect of the proximal phalanges, which may be optimal to remotely stimulate Pacinian corpuscles because of the proximity to areas where their density is the highest, such as the palmar aspect of the proximal phalanges and metacarpophalangeal joints [27], [44]. Overall, these hypotheses support that more investigations are required to better understand the underlying physiological mechanisms of tactile perception of sound.

B. Thresholds as a function of actuator position

The detection thresholds measured in this study were not significantly different between the right and left hands. This result is coherent with previous literature showing either no between-hands differences [71] or a very small difference in favor of the left hand [72], [73] in mixed samples of right-handed and left-handed participants. In the present study, we exclusively tested right-handed participants to ensure homogeneity and reduce variability since our aim was to validate the technology rather than assess handedness effects. However, since our study exclusively involved participants who expressed a right-hand preference, the findings may not be directly generalizable to left-handed or ambidextrous individuals. Nonetheless, existing research on vibrotactile perception generally indicates that hand preference does not significantly affect absolute sensitivity between hands [64], [74]. Future research should investigate the impact of handedness more thoroughly.

The actuators that were positioned on the dorsal aspect of the Thumb, Index, Major, Ring, and Pinky did not produce significantly different thresholds between each other at any frequency, except from the Index-Ring contrast at 250 Hz, which also supports that a homogeneous stimulation can be

provided to all fingers. However, significantly higher thresholds were consistently measured for the palm at the lowest (100 Hz) and highest frequency conditions (1000 Hz), where it performed significantly worse than the Index and Middle fingers respectively even if the palm is made of highly sensitive glabrous skin. Numerous explanations can account for this performance, but this discrepancy is unlikely to be caused by differences in skin thickness as there appears to be no relationship between epidermis thickness and vibrotactile sensitivity [75]. However, a physiological hypothesis could be that the underlying tissue may play a more important role, as vibrations are better transmitted over bone than soft tissue [68], particularly at higher frequencies [69]. This would mean that the Multichannel Vibrotactile Glove can efficiently transmit vibrations to the population of Pacinian corpuscles concentrated in the connective tissues near the joints and bones of the proximal phalanges [44], [76].

Another hypothesis is that there was a sufficient difference in the tightness of the gloves at the palm in comparison to the other stimulation sites to cause differences in performance. A looser fit around the palm than around the fingers, particularly for individuals with smaller hands, could have been exacerbated by the fact that the experiment was conducted palm side down with the hand hanging, meaning that gravity would have been pulling the palm actuators away from the skin. Improving the performance of the palm actuators would then require ensuring greater pressure against the skin or using larger actuators [50]. However, this may risk impairing the user's freedom of movement and grasping ability. Finally, it should be noted that actuators on the palm also limit the user's ability to rest their hand on a surface, which could be problematic for extended use. Overall, these results suggest that the choice of including a palm actuator on similar designs requires careful consideration.

C. Spatial summation

Sending stimuli through all actuators simultaneously consistently produced better thresholds than using any individual actuator. This spatial summation effect on detection thresholds provides further evidence that the Multichannel Vibrotactile Glove is indeed effectively stimulating Pacinian corpuscles. Indeed, these are the only fast adapting mechanoreceptors that appear to be sensitive to spatial and temporal summation effects [77]. This characteristic has led researchers to propose that Pacinian corpuscles act as a tactile analog to auditory critical bands [78], [79], further reinforcing psychophysical similarities between hearing and touch. For a single actuator, Verrillo [50] found that doubling the actuator area resulted in a 3 dB lowering of the detection thresholds for frequencies above 80 Hz. Craig [80] obtained similar results for multiple actuators positions, showing that using two actors instead of one lowers detection thresholds by 2 dB regardless of the distance between them. However, the author also found that spatial summation only occurred for stimuli of the same frequency and disappeared with stimuli too far apart spectrally (i.e., 160 and 360 Hz). These spatial summation effects are not only relevant for detection threshold since they can also be observed for supra-threshold stimuli. Indeed, Craig [81] also found that increasing the number of actuators from 1 to 5, as was the case for the "All" actuator condition in the present

study, roughly produced a doubling of the subjective loudness. The results also support that tactile receptors are solicited, with Pacinian corpuscles specifically being involved.

VI. CONCLUSIONS

The study demonstrates that the Multichannel Vibrotactile Glove can efficiently convey vibrations to the tactile system. The gloves showed a good internal consistency, as the vibrotactile detection thresholds were similar across both hands and all finger actuators. The palm actuators showed a lower performance at the lowest and highest frequencies tested, which could be explained by differences in physiology and/or glove fitting. The general U-shape of the responses as a function of frequency and the observed spatial summation effect support the hypothesis that the gloves are indeed stimulating Pacinian corpuscles.

To date, the ability to perceive complex vibrotactile stimuli through the tactile system is still an area with significant potential for exploration and development. In order to effectively configure vibrotactile technologies for various applications, such as allowing deaf older singers to synchronize with each other and with a piano in a choir context, more investigations are required. By having up to 12 independent channels, the device allows researchers from diverse fields to transmit vibrotactile information that can differ in amplitude, frequency, or timing by distributing these different physical attributes of the vibrations in a diverse manner over the multiple locations on both hands. This is a significant advantage of the device since it allows researchers to compare multiple signal processing strategies to convey complex vibrotactile information (e.g. harmonics, timbre, rhythm, melodies, ...) through the tactile system which will help to uncover the possibilities of vibrotactile technologies to support auditory perception in a noise context, to perceive music for hard of hearing people, to help musicians to synchronize with each other or to offer an immersive experience in an entertainment context [37]. The technology will therefore enable investigations across a continuum, from fundamental research to ecological and clinical studies.

The measured thresholds can be used by future studies to make sure they are transmitting supra-threshold vibrations through the whole frequency response range of the Pacinian corpuscle mechanoreceptors. Studies using the glove or similar device may indeed need to increase stimulation intensity at higher frequencies to compensate for rapidly decreasing vibrotactile sensitivity after 500 Hz. However, the current measurements were conducted in young and healthy participants, which limits the generalization to older individuals who are known to have lower Pacinian corpuscles mediated vibrotactile sensitivity [64]. Further normalization may thus be required if the device is to be used in studies with older participants or with participants who present characteristics known to affect vibrotactile sensitivity [82].

Finally, the current version of the Multichannel Vibrotactile Glove has some limitations, notably the relatively important size of the system which limits its use for applications where the user is not sitting close to a desk. While this current validation study has focused only on exploring a fundamental psychophysical attribute of our technology, namely the

detection thresholds at different frequencies. We recognize the importance of conducting future research to validate the glove's functionality in dynamic real-world scenarios where users may be subjected to movement and external vibrations (e.g., the ability to discriminate instruments among an orchestra in a real concert hall). To do this kind of experiment, improvements to the current prototype are required. The device already provides a versatile interface for static experimental design, but improvements such as self-powering and wireless connectivity will improve the portability of the technology and allows investigation in more ecologically valid contexts. Furthermore, familiarity with auditory stimuli patterns (e.g. Happy birthday song) may facilitate association with the modality converted pattern (vibrotactile) over novel patterns. Further research into the memorability and perceptual associations of these converted patterns could provide useful information about their usability and effectiveness in practical applications.

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