INTERACTIVE PERFORMANCE FOR MUSICIANS WITH HEARING IMPAIRMENTS USING THE VIBROTACTILE MODE

C Hopkins Acoustics Research Unit, University of Liverpool, Liverpool, UK
J Ginsborg Royal Northern College of Music, Manchester, UK
S Maté-Cid Acoustics Research Unit, University of Liverpool, Liverpool, UK
R Fulford Royal Northern College of Music, Manchester, UK
G Seiffert Acoustics Research Unit, University of Liverpool, Liverpool, UK

1 INTRODUCTION

This paper presents findings from AHRC-funded research into the potential for vibrotactile technology to be used by musicians with a hearing impairment. The project was an interdisciplinary collaboration between acousticians in the Acoustics Research Unit at the University of Liverpool and music psychologists in the Centre for Music Performance Research at the Royal Northern College of Music. The intention of the research is to facilitate interaction with other musicians in group performance and open up new opportunities for people with a hearing impairment to become musicians and perform with other musicians. The inspiration for the project came from Dame Evelyn Glennie, the highly-renowned solo percussionist. She began to lose her hearing when she was eight years old and is classified as profoundly deaf with residual hearing at very high amplification [1]. Many percussion instruments that she plays cause the floor to vibrate and this vibration can be transmitted from the floor through her bare feet into her body. In these situations, the tactile feedback from the vibrating floor will be highly dependent upon the type of floor construction.

To facilitate group rehearsal, performance and musical improvisation for musicians with hearing impairments, versatile solutions are sought that can transmit different vibration signals to different musicians simultaneously. For singers there is the potential to use the fingertips whereas musicians playing an instrument are more likely to require some form of vibrating performance deck for the feet or vibration pads attached to the body. The basic concept is outlined in Figure 1.

In the majority of situations where vibrotactile feedback is used (e.g. warning systems) there is no need for the perception of pitch information. However, this is clearly necessary for musical applications and this paper focuses on three aspects of the research concerning pitch. The first aspect concerned establishing the limits for perceiving vibration (vibrotactile thresholds) on the glabrous skin of the fingertips and feet over a range of musical notes. The second aspect concerned the perception and learning of basic relative pitch through the skin. The third aspect provided ‘proof of principle’ through audio and video recording of a group musical performance using vibrotactile feedback.

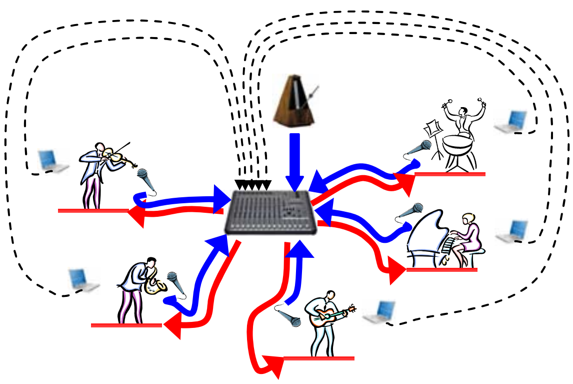

Figure 1. Concept for interactive performance using vibrotactile feedback.

2 ESTABLISHING VIBROTACTILE THRESHOLDS

When vibrotactile thresholds are measured for the diagnosis of sensorineural disorders at the fingertips using ISO 13091-1 [2] there are some aspects of the measurement method that make it less relevant to a singer or musician with a hearing impairment when (a) touching a vibrating surface with hands or feet that is excited by a music signal, or (b) feeling vibration on the surface of a musical instrument. For example, the use of very small contactors would be impractical for a musician to position on the body whilst playing. For this reason, the thresholds in this work were determined using an approach for the fingertip and the foot that is expected to be more representative of potential vibrotactile technology for the presentation of music.

2.1 Experimental procedures

For fingertip measurements, the pad of the distal phalanx of the middle finger from the participant's dominant hand rested upon a vibrating contactor. This contactor was a circular aluminium disc with a diameter of 2cm as shown in Figure 2 (left). The fingertip was positioned such that the whorl, arch or loop of the fingerprint was positioned at the centre of the disc. Participants were instructed to relax their arm and hand on the foam-covered table and not to press down upon the contactor. The contactor height was such that the middle finger rested upon it naturally. For foot measurements, individual thresholds were measured for the forefoot (toes and ball of the foot) and the hindfoot (heel) using Perspex discs of 12cm and 10cm diameter respectively as shown in Figure 2. The participant was seated such that the leg was naturally supported by the contactors.

For diagnostic measurements, a much smaller contactor disc of approximately 4mm diameter is required; often with a contactor surround [2]. Touching such a small diameter contactor is not a feasible solution for a musician; hence larger contactors were used as a closer approximation to touching a vibrating surface. The reason for the surround is to minimize propagation of surface waves beyond the contactor [3,4]. This is ideal for investigating the role of mechanoreceptors as it prevents propagation of surface waves beyond the perimeter of the surround to other parts of the body. However, this is not the situation which is relevant to the vibrotactile solution envisaged in this project. For this reason, thresholds were measured without a contactor surround.

Vibrotactile thresholds were determined using an up/down algorithm by applying a sequence of stimuli with successively increasing intensity until the participant signals that a stimulus has been detected. The procedure was adapted from audiometric procedures to determine thresholds for air conduction and was based on the shortened version of the ascending method in ISO 8253-1 [5]. The audiometric procedure uses discrete steps to increase the level by 5dB HL but this was considered to be insufficient resolution for vibrotactile thresholds; hence a step of 2dBV was used. The procedure is described in more detail by the present authors in [6]. Skin temperature was monitored at ≈20 minute intervals using an infra-red thermometer. Based on the findings of Verrillo and Bolanowski [7] the acceptable temperature ranges for valid measurements were chosen to be 20 to 36ºC for notes C1 to G2 and 24 to 36ºC for notes C3 to C6. The signal was a continuous pure tone of 1s duration. The stimulus consisted of this 1s tone presented three times in a row, with each tone separated by a two second interval without any signal. Participants were instructed to press a response button whenever they felt a tone. Eleven tones were presented that corresponded to the musical notes C and G in the range from C1 to C6. Frequencies were calculated using the ratio $2^{1/12}$ in twelve-tone equal temperament to give the frequency of any note relative to A4. For example, C1 corresponded to 32.7Hz, C4 to 261.6Hz and C6 to 1046.5Hz. In audiometry, the starting tone is chosen as 1kHz which is in the frequency range of highest sensitivity for the human ear. Similarly, to determine vibrotactile thresholds, C4 was chosen because it approximately corresponds to the frequency of highest sensitivity for the Pacinian corpuscle [3]. Therefore, the order of presentation of tones began with C4 ascending up to C6, followed by tones descending from G3 to C1.

Figure 2. Left – pad of the distal phalanx of middle finger placed on the contactor. Right – forefoot and hindfoot supported on individual contactors.

2.2 Results

For the distal phalanx of the middle finger, Figure 3 shows the vibrotactile thresholds from participants with normal hearing and with a hearing impairment. The threshold curves all have the characteristic U-shape for the Pacinian corpuscle [3]. The lowest thresholds occur in the vicinity of musical notes between G3 and G4. No significant difference (Mann-Whitney, p > 0.05) was found between the mean values of thresholds for participants with normal hearing and participants with a severe/profound hearing impairment. The comparison of thresholds for these specific contactor areas shown in Figure 4 indicates that there is some potential to present notes below C2 and above C5 to the foot in order to maximize the available dynamic range.

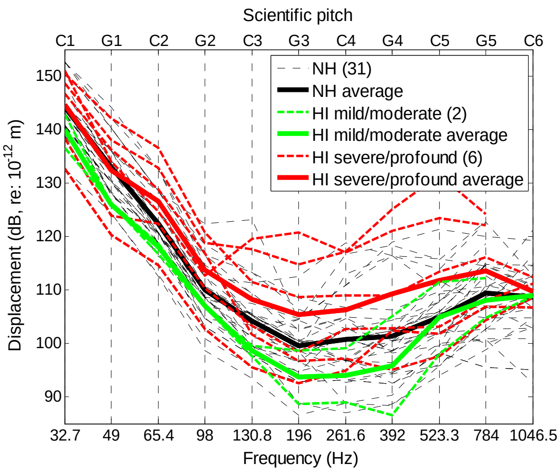

Figure 3. Vibrotactile thresholds obtained from the distal phalanx of the middle finger from participants with normal hearing (NH) and with a hearing impairment (HI). Numbers of participants are indicated in brackets.

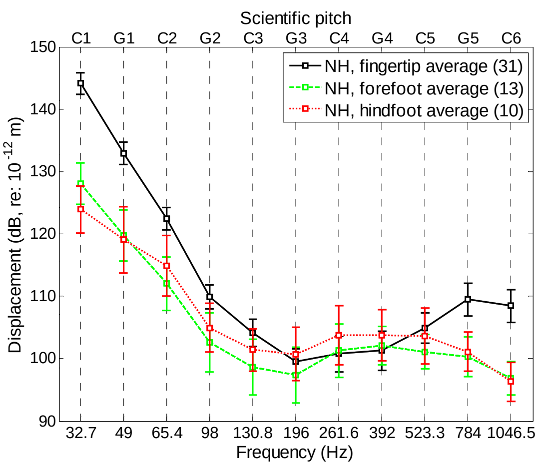

Figure 4. Comparison of average vibrotactile thresholds obtained from the distal phalanx of the middle finger with the forefoot (toes) and hindfoot (heel) from normal hearing (NH) participants. Data points shown with bars indicate one standard deviation.

3 USING VIBROTACTILE THRESHOLDS TO DEFINE THE AVAILABLE DYNAMIC RANGE

One of the challenges in presenting music as vibrotactile stimuli is that any device which exposes people to vibration must not cause vascular symptoms or discomfort. The threshold measurements have been used to assess the dynamic range that is potentially available if music were presented to a musician using vibration such that it was easily perceptible without causing vascular symptoms.

The thresholds in terms of displacement have been converted into frequency-weighted acceleration magnitudes [8] for comparison against a proposed upper limit for frequency-weighted acceleration of 1m/s^2 rms. This is based upon previous data cited by Griffin [9] suggesting that vascular symptoms would not usually occur below this value when considering normal usage of hand-tools. Figure 5 indicates that the available dynamic range between threshold and this upper limit for fingertips varies significantly but lies between approximately 10dB and 40dB for pitches between C1 and C6. However, feeling vibration at threshold is likely to require excessive concentration from a performer and be difficult in a performance situation where background vibration levels may not be low. These practical issues lead one to consider raising the lower limit of the dynamic range to at least 10dB above threshold. The implication is that notes below C2 and above C5 would have an available dynamic range of less than 10dB, and notes between G2 and G4 would have an available dynamic range of approximately 20dB. To put this in context it is necessary to consider the dynamic range typically produced by singers and musical instruments for different notes.

For individual choral singers singing the vowel /ah/, the average dynamic range between pianissimo and fortissimo has been measured to be approximately 10dB to 30dB for soprano, alto, and tenor singers (*n*=5 for each type) and approximately 25dB to 40dB for bass singers (*n*=5) [10]. In contrast to singing, the sound produced by orchestral string, woodwind and brass instruments (*n*=2 for each instrument) is less variable, the average dynamic range between pianissimo and fortissimo being approximately 12dB when playing scales, and between 2dB and 20dB for individual notes between C1 and C7 [11]. It is not possible to draw definitive conclusions based on these limited data. However, it is clear that practical implementation of vibrotactile technology will always require signal compression to increase the level of quiet signals (e.g. pianissimo) and decrease the level of loud signals (e.g. fortissimo). By compressing the dynamics of singing and classical instruments into a 10dB to 20dB dynamic range, it should be feasible to present music as a vibrotactile stimulus whilst avoiding vascular symptoms or discomfort. Using a relatively narrow dynamic range is likely to be beneficial because it should minimize issues with the signal intensity affecting pitch perception [12].

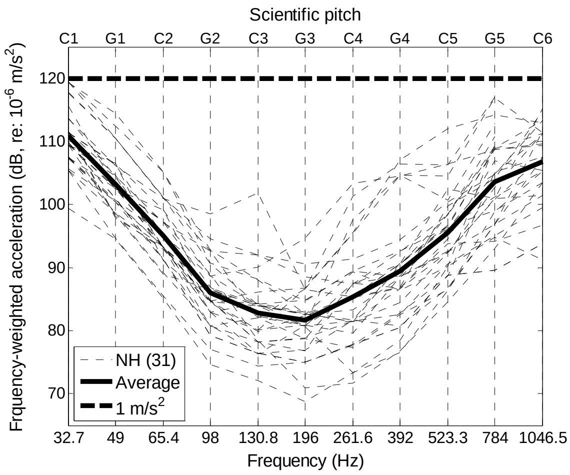

Figure 5. Measured vibrotactile thresholds in terms of frequency-weighted acceleration from the distal phalanx of the middle finger from participants with normal hearing (NH).

4 VIBROTACTILE PERCEPTION OF HIGH NOTES

During the threshold measurements on the fingertip, some participants with normal hearing commented that for the highest notes there were distinct differences in perceiving high notes compared to low notes. Each signal was a continuous pure tone of 1s duration. For this reason, a post-hoc experiment was carried out using 14 of the participants with normal hearing. These participants repeated the threshold experiment for the 11 white notes from G4 to C6. Once the threshold had been determined for a tone, the participant was again presented with the stimulus sequence at threshold level and asked using a two-alternative forced choice, a) whether they felt transient vibration at the beginning and/or end of any of the 1s tones in the sequence and (b) whether they felt continuous vibration during any of the 1s tones in the sequence. As noted previously, vibration would often need to be presented above threshold; hence the same stimulus sequence was then presented at 10dB above threshold and the questions were repeated before proceeding with the next tone.

Figure 6 shows that participants' awareness of the transient aspect increased with increasing pitch height, peaking at A5 and B5. Conversely, and therefore as expected, participants' awareness of the sustained vibration of tones was greatest for the lower pitches in the range, dropping off at A5 and B5 where transient awareness increased. Participants were more aware of sustain when presented 10dB above threshold compared to at threshold. For A5 to C6 this has implications for the perception of music using vibration because detecting only the transient at the beginning or end of a note will not give sufficient information to identify the note itself. These findings and those concerning the limited dynamic range available between G5 and G6 informed the authors' decision to omit notes at and above A5 from their experiments on relative and absolute vibrotactile pitch.

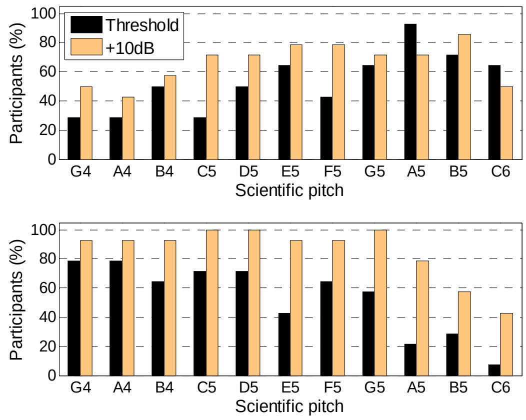

Figure 6. Percentage of participants indicating that the transient vibration at the beginning or end of the note could be felt (upper graph) and that sustain of the note could be felt (lower graph) when presented at threshold and 10dB above threshold.

5 PERCEPTION AND LEARNING OF BASIC RELATIVE PITCH

Relative pitch (RP), the ability to recognize that one note is higher or lower than another, is important for musicians. Psychophysical experiments were used to investigate relative pitch using vibrotactile instead of auditory stimuli: specifically, to identify the smallest musical interval that can be perceived in this way, to find out if a hearing impairment affects relative pitch for vibrotactile stimuli and if vibrotactile relative pitch can be improved with training.

Subjective experiments have been carried out with the aim of determining the extent to which participants can correctly identify and learn to distinguish the basic RP of two tones presented consecutively via vibration to the fingertip. It was hoped that the study would show the range of musical intervals for which RP can consistently be identified. It was hypothesized that basic RP can be learnt and improved through training.

5.1 Experimental procedures

The experiment was carried out in a quiet room without visual distractions for the participants. The pad of the distal phalanx of the middle finger from the participant's dominant hand rested upon a vibrating contactor. This contactor was an aluminium disc (diameter: 2cm) driven by an LDS V200 electrodynamic shaker. The whorl, arch or loop of the fingerprint was positioned at the centre of the disc. Participants were instructed to relax and not to press down upon the contactor. The contactor height was such that the middle finger rested upon it naturally. White noise was presented as masking noise using headphones at a level of 78 dB L_{Aeq} to avoid unwanted audio cues caused by sound radiated by the shaker and contactor.

A total of 24 notes were used to cover the entire range of notes between C3 (130.8Hz) and B4 (493.9Hz). This range represents one octave below and one octave above Middle C (C4). The reason for choosing this range of notes is that the vibrotactile threshold is relatively flat. Considering that the final application of vibrotactile technology is for performing musicians, it would be impractical for them to assess relative pitch at threshold values of vibration. Therefore the presentation level for stimuli was 15dB above the average vibrotactile threshold between C3 and B4. This was considered to be a comfortable level that avoids adverse effects from high vibration levels [9], and avoids the confounding factor of intensity affecting pitch perception [13].

Participants were asked 'Is the second tone higher or lower than the first tone?' in a two-alternative forced choice design in order to establish the participants' ability to discriminate basic RP. Both pre-training and post-training tests were administered without feedback as to whether the participants' responses were correct or incorrect. A total of 420 interval pairs (i.e. two tones) were presented to the participant in random order. Each tone lasted for 1s with a time between them of 1s. These interval pairs were ascending and descending in pitch and covered all 12 intervals ranging from a semi-tone to an octave over the frequency range C3 to B4. After completing the pre-training test, participants completed 16 training sessions (one session per day) over a period of five to six weeks. In each training session 72 interval pairs were presented from the complete set of 420, comprising 6 permutations chosen randomly from each of the 12 possible intervals. However, once an interval pair was presented it was not used again in the same session or any following session until all possible pairs for that particular interval had been exhausted. To facilitate learning, feedback was given to the participant as to whether each answer was correct or incorrect. At the end of each training session, the participant was informed of the percentage answers that were correct, incorrect or unanswered.

Seventeen participants with normal hearing were recruited. All participants were healthy with no self-reported impairment of sensation in their hands. All participants were right handed, and carried out the experiment using the middle finger of the right-hand. Participants consisted of 13 males and 4 females with an age range of 18 to 50 (μ: 27.7, σ: 9.5). The temperature of the fingertip was measured before and after each training session and each test using an infra-red thermometer. Based on the findings of Verrillo and Bolanowski [7], the acceptable temperature range for valid measurements was chosen to be 24 to 36ºC.

5.2 Results

Figure 7 shows the percentage of correct responses from individual intervals for both pre-training and post-training. For intervals of 5 to 12 semitones, the results indicate high success rates (>75%) with or without the 16 training sessions. As expected, the larger intervals were easier to identify correctly than smaller intervals. For individual intervals between 9 and 12 semitones, there was a significant improvement from pre- to post-training tests (Wilcoxon, $p<0.05$). In both pre- and post-training tests there was a significant ($p<0.001$) positive correlation between interval size and correct responses: as the interval size increased, the number of correct answers increased. The Spearman correlation coefficient between these variables increased from 0.664 in the pre-training test to 0.842 in the post-training test. This confirms that larger intervals are easier to distinguish than smaller intervals.

Results for the post-training test had a narrower spread of results than the pre-training test except for the interval of two semitones. The whisker for the interval of one semitone extends to include chance performance (i.e. 50%), although the median increased notably up to 8.7% from the pre- to the post-training test. Hence training helps bring participants up to a similar level for all intervals except for one semitone and one tone. Grouping the smaller intervals between 1 and 6 semitones also shows a significant improvement between pre- and post-training tests (dependent *t*-test, p=0.001) as does grouping larger intervals between 7 and 12 semitones (Wilcoxon, p<0.001). This indicates that significant improvements in RP can be obtained as a result of training.

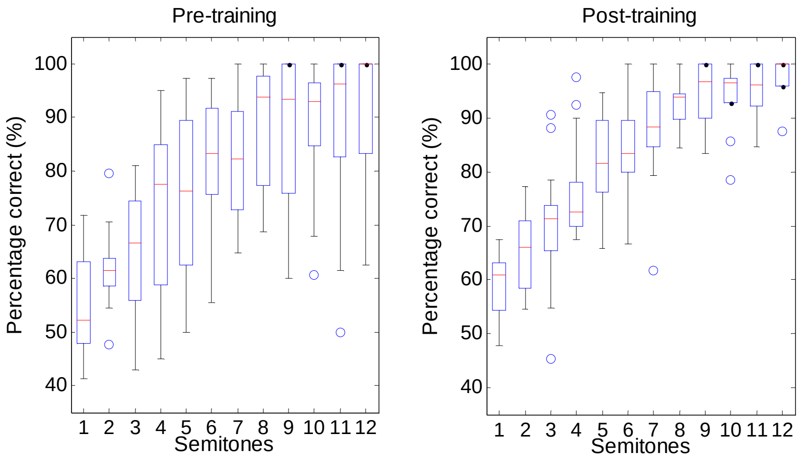

Figure 7. Mean percentage of correct responses using the middle fingertip from all 17 participants. Whisker marks indicate the extreme scores. The 25th and 75th percentiles form the edges of each box that contains the middle 50% of scores. The median is the red line. Circles represent outliers. Black dots indicate the absence of whiskers.

6 PROOF OF PRINCIPLE

The third component provided 'proof of principle' through audio and video recording of a group musical performance using vibrotactile feedback. For this performance, the acoustic laboratories were used to ensure that all auditory cues from other musicians were removed and there was no visual contact between the musicians. The video promoted the research findings to a much wider audience than would ever be reached through academic publications and it had more than 1000 views in its first week online (https://stream.liv.ac.uk/kgfymdz4).

Three musicians played electric guitar, bass guitar and drums. As they had normal hearing, they all wore earplugs and hearing defenders. The two guitarists were also played high levels of masking noise (white noise) through loudspeakers to ensure there were no auditory cues from their own instrument, the other instruments and the vibration equipment providing the vibrotactile feedback. The drummer was isolated in an anechoic chamber in the laboratory. Due to the high levels of sound produced by the drums, the drummer could hear them directly even when wearing earplugs and hearing defenders; however, he received no auditory feedback from the two guitarists. In a semi-anechoic chamber in another part of the laboratory, the two guitarists were seated at opposite ends of the chamber, facing away from each other. This ensured there was no visual contact between all three musicians. Vibrotactile feedback was delivered via electrodynamic shakers. Using the foot, each guitarist was able to feel the drums through the hindfoot and the guitar played by the other musician on the forefoot. Using the drum stool, the drummer was also able to feel the guitar.

The song chosen for the group performance was 'Day Tripper' by The Beatles because the song contains lots of opportunities to demonstrate aspects of timing, pitch awareness and ensemble playing. During the rehearsal the musicians commented that they did not feel any sense of isolation due to the presence of vibrotactile feedback; for example, they noticed that it was immediately apparent if the bass or guitar played the A riff instead of the E riff by mistake in the verse.

7 CONCLUSIONS

This paper reviews recent research by the authors on the potential for using vibrotactile feedback to facilitate interactive musical performance for deaf musicians. Limits have been established for perceiving musical notes via vibration on the fingertips and feet. This has defined the usable dynamic range and a pitch range that can reliably be perceived. Perception and learning of basic relative pitch at the fingertips was investigated with normal and hearing impaired participants. This indicated a high success rate with and without training which implies that everyone has a basic ability to perceive relative pitch although it is difficult to distinguish intervals smaller than three semitones. Using basic training it has been shown to be possible to achieve significant improvements in the assessment of relative pitch. To promote the research aims of social inclusion and to challenge public perceptions of what is possible with a hearing impairment; public engagement activities have taken place with the deaf community through a one-day dissemination conference and a video on the internet.

8 ACKNOWLEDGEMENTS

Research project No. AH/H008926/1 ‘Interactive performance for musicians with a hearing impairment’ was funded by the UK Arts and Humanities Research Council (AHRC). Approval for the subjective tests was given by the Ethics Committee at the University of Liverpool and the Royal Northern College of Music.

9 REFERENCES

1. C. Cleall. Notes on a young deaf musician. Psychology of Music 11, 101-102, 1983.
2. ISO 13091-1:2001 Mechanical vibrations – Vibrotactile perception thresholds for the assessment of nerve dysfunction – Part 1: Methods of measurement at the fingertips.
3. R.T. Verrillo. Effect of contactor area on the vibrotactile threshold. Journal of the Acoustical Society of America 35(12) 1962-1966, 1963.
4. M. Morioka. and M.J. Griffin. Thresholds for the perception of hand-transmitted vibration: Dependence on contact area and contact location. Somatosensory and Motor Research 22(4) 281-297, 2005.
5. ISO 8253-1:2010 Acoustics – Audiometric test methods. Part 1: Pure-tone air and bone conduction audiometry.
6. C. Hopkins, S. Maté-Cid, G. Seiffert, R. Fulford, J. Ginsborg. Measurement of vibrotactile thresholds on the fingertip to assess vibrotactile presentation of musical notes to people with and without a hearing impairment. Proceedings of Internoise 2012, USA, 2012.
7. R.T. Verrillo and S.J. Bolanowski. The effects of skin temperature on the psychophysical responses to vibration on glabrous and hairy skin. Journal of the Acoustical Society of America 80(2) 528-532, 1986.
8. ISO 5349-1:2001 Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements.
9. M.J. Griffin. Handbook of human vibration. Elsevier. ISBN 0-12-303041-2, 1996.
10. R.F. Coleman. Dynamic intensity variations of individual choral singers. Journal of Voice 8(3), 196-201, 1994.
11. M. Clark and D. Luce. Intensities of orchestral instrument scales played at prescribed dynamic markings. Journal of the Audio Engineering Society, 13(2), 151-157, 1965.
12. F.A. Geldard. Some neglected possibilities of communication. Science 131(3413), 1583-1588, 1960.
13. G. Von Békésy. Neural volleys and the similarity between some sensations produced by tones and skin vibrations, Journal of the Acoustical Society of America, 29(10), 1059-1069, 1957.