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Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Sierra, M. C., Brunskog, J., & Marozeau, J. (2021). *An audio-tactile artinstallation for hearing impaired people*. Paper presented at 2nd Nordic Sound and Music Conference .

An Audio-tactile Art Installation for hearing impaired people

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ABSTRACT

This paper covers the design and development processes of a prototype for an audiotactile installation with the aim of enhancing the music experience of hearing impaired people. The prototype consists of a wooden structure with cantilevered beams globally excited with two tactile transducers, so that people lying on the prototype can feel different vibrating bars at different positions of their body. The installation was designed as a first prototype for an exhibition in the Museum of Art and History of Geneva, Switzerland. In order to optimize the music perception through vibration sensing, the frequency response of the prototype was designed using numerical simulation. Once the prototype was built, vibration measurements were performed in order to assess its behaviour. A perception test with participants was carried out to evaluate the efficiency of the structure. The evaluation shown that the music experience was enhanced in the participants, a well as significant body distribution-dependency in the frequency response of the structure vibration.

1. INTRODUCTION

Hearing plays a key role in people's lives. Through our auditory system, we are able to perceive sound waves arriving to our ear and interpret them as words, a saxophone playing a piece of music or a telephone ring. Among all the aspects hearing loss implies in everyday life, music is missed very much by hearing impaired people. Music is a very important element in people's lives: it helps to express feelings, communicate without words, or unwind ourselves. Everyone has experienced how it is possible to "feel the bass" when standing in a big concert or in a night club, and it is clear that this affects to the overall perception of the music we are hearing. Studies like [1] [2], have shown that tactile stimulation can improve the experience of music in deaf and hard of hearing people. The main goal of these audio-tactile devices is to allow people to feel the music through vibrations using the tactile receptors in the skin.

In 2020, the department of Hearing Systems at the Technical University of Denmark (DTU) started a collaboration with two Swiss musicians and artists from Geneva to create new forms of inclusive musical expressions, using new musical language accessible to people with different impairments. Within this collaboration, an audio-tactile art installation was developed to be presented as part of a temporary exhibition in the Museum of Art and History of Geneva (MAH) in October 2020, during the so-called 'Inclusion Week'. The installation was based on six wooden podiums that where excited with tactors (vibrating transducers) at the time different musicians were performing their pieces. The audience, that included people with different impairments, could lie on the vibrating platforms while listening to the music, that was sent through loudspeakers and partly through the tactors too. Due to the very positive response of the audience, the collaboration with the museum was extended, with the aim of taking the art installation to a next level. The project included the construction of two audiotactile chairs where people sitting could feel a combined perception of hearing and feeling music.

2. KALIMBA MODEL

2.1 Initial considerations

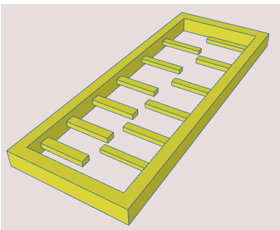
The strategy behind all the already existing audio-tactile installations involving chairs or beds analyzed, was to excite different positions of the body with vibratory sources. To induce the vibratory signal that would be felt by the user, surface speakers were used in the projects of Nanayakkara et al. [1] and Perini [3], while voice coils were used in the work of Karam et al. [4] .

Based on this analysis, it was decided to aim for a structure that could activate specific parts of the body at different frequencies when excited with an audio signal. Segregating the frequency spectrum of the input signal into different sections of the structure would provide a combined audio tactile perception in which different frequency components could be felt in different positions of the body.

Using several excitation points as in the cited examples was found to be not suitable for a permanent museum exhibition in terms of maintenance and interactivity with visitors. On the other hand, the structure was designed as a bench where people can lie on while different parts of their body are excited when the structure is globally excited with a shaking system. For this purpose, the shape of the structure was designed with *ad hoc* degrees of freedom, in order to control its vibration modes. This allowed to use only one or two audio-tactile transducers to induce the vibration of the whole system, getting rid of multi-channel processing devices.

2.2 Cantilever design

It is possible to introduce *ad hoc* degrees of freedom in a structure that can be independently controlled if their natural frequencies are known. An example of such behaviour are the sympathetic strings present in a lot of traditional music instruments, like the sitar, the sarangi or the hurdy-gurdy. A similar behaviour was aimed to build the prototype. The structure defined consisted of a rectangular frame with cantilevered wooden bars coming inwards. The beams would embedded into the frame, ensuring them to be fixed at the frame and free to move at the other end, see Figure 1a.
The project was named "*Kalimba chair*", after the african traditional instrument Kalimba, in which metal beams of different lengths clamped at one end are plucked producing different notes, see Figure 1b.



(a)

(b)

Figure 1. a) Schematic of the thought kalimba chair, consisting of a set of cantilevered bars attached to a common frame that would be excited with the audiotactile transducers. b) Picture of a Kalimba, an inspiration for the name of the prototype due to the similar configuration of cantilevered beams.

2.3 Tuning of the bars

When the frame is excited by a shaker from below with an audio signal, the whole structure is driven into vibration, and each cantilever vibrates presenting a resonance according to its geometrical and material properties, given by:

$$f_n = \frac{K_n}{2\pi L^2}\sqrt{\frac{EI}{m'}}, \tag{1}$$

where $K_n \simeq \pi^2(n-1/2)^2$, L is the length of the beam, E, I and m' are the Young's Modulus of the beam, its area's moment of inertia and its mass per unit length, respectively [5].

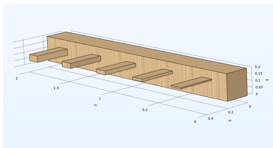
Equation (1) allows to tune the Kalimba chair to present a resonating beam at the desired position, so a person lying on it would be touched at a certain point of his/her back when a given frequency is in the signal.

It should be noticed that a person lying directly on the bars is expected to produce a shift downward in their resonance frequency, due to the addition of mass. To try to avoid this, the body should only gently touch the cantilevers, being his weight supported by other parts of the structure.

2.4 Numerical simulation

A numerical model was developed with the goal of verifying numerically the Eq. (1) in a system of cantilevers with different thicknesses, when excited with a shaker at a common frame that support them. The COMSOL 5.6 version was used [6] for this purpose. COMSOL is a solver and analysis software platform based on finite elements, with applications in different fields of physics and engineering. A 3D geometrical model was built using the COMSOL geometry framework, with five bars of $L = 28$ cm and width $w = 10$ cm but different thickness embedded in a common frame, so they stay clamped at one end and free to move at the other, see Fig. 2a. The bars had thicknesses between 1 and 5 cm. To simulate the action of a shaker, a boundary load was included in a circle with radius of 2 mm, located in the middle point of the wooden frame that supported the cantilevers. The assumption of small displacement from equilibrium position under excitation in the whole domain was made, allowing to use the Linear Elastic Material theory [7]. Besides, a spring foundation with high stiffness ($k = 10^8\ N/m$) was included in the whole bottom surface, to allow the system to move when excited by the shaker. The material used in the simulation was pine [8]. The orthotropy of the material was included with values of Young's modulus, shear modulus and Poisson's ratio in the three perpendicular directions L,T and R.

Three mechanical modes of the structure are presented in the Fig. 2, showing each of them a different resonating beam. This values are well explained by Eq. (1).



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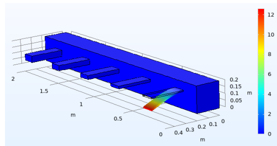

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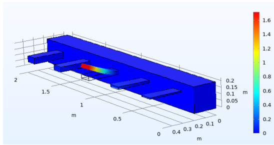

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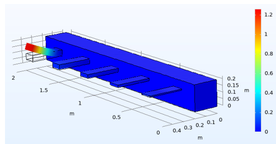


(d)

Figure 2. a) COMSOL model developed for verification of Kalimba model of cantilevers. The common frame is excited from below with a frequency dependent source. b-d) Bars of thickness $h = 1$, 3 and 5 cm showing a resonance at 20 Hz, 57 Hz and 99 Hz.

3. BUILDING PROCESS

A prototype for the installation was built based on the mentioned kalimba model, with the geometry shown in the Fig. 1a. The crafting was made applying carpentry techniques and tools, and good quality wood was acquired.
A frame of 175 cm x 80 cm was designed. In order to obtain a very tight connection between the beams and the frame to appear as much as possible to a cantilever condi-

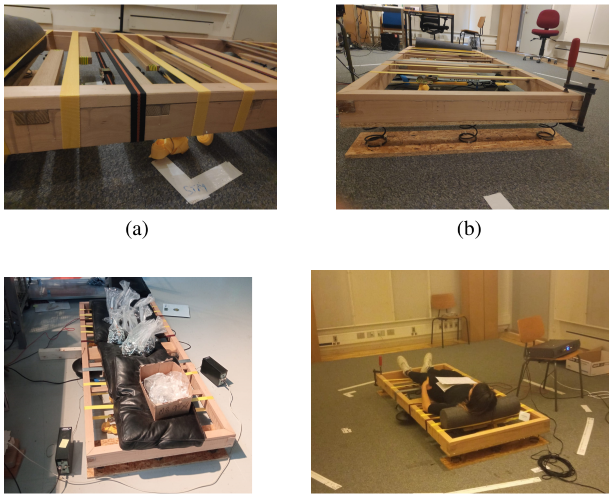
tion, the bars were crafted in a stepped shape. They were introduced into the frame along a certain length, and a second wooden plank was placed on top to ensure the clamping, see Fig. 3a. Both the frame and the top frame were made out of beech, whereas oak was used for the bars. Circular dowels and wood glue were used to reinforce the corner joints between the bars, in order to make them more solid and reduce the rocking movement.
Using a turret milling machine allowed to precisely craft the bars in a stepped shape and at the desired thickness. A length of 46 cm for the bars was chosen to increase the contact surface with the body. Ten bars were accounted to be a reasonable number of excitation positions. Six of them were placed on the upper part of the structure to excite the upper back, and the four remaining were placed to excite the legs. The final disposition and thicknesses of the bars, and their expected resonances based on Equation (1) are reported in the Table 1. The system of cantilevers was tuned using ten bars with equal length L and different thickness h. The tuning and disposition of each bar in the bed was designed considering two main references. First, the article of Brétéché Sylvain [9], in which four classifications of human resonance frequencies of different parts of the body, found in previous investigations, are reported. These classifications refers to the chest having a resonance frequency between 50 and 100 Hz, and the legs having a resonance frequency at around 20 Hz. The second reference was the Model Human Cochlea design by Karam et al. [10]. Here, different voice coils are placed in the back of a subject following a linear spatial order that tries to simulate the cochlea functionality. Following the natural spatial perception of pitch height [11], they placed the high frequencies in the upper back and the low frequencies in the lower back.
To reduce the shifting of the frequency downward due to the high contact of the body on the bars, very tight ratchet straps, commonly used in cars transportation, were placed surrounding the frame from left to right, in order to lift the body of the person. Besides, a thick bar was screwed in the middle on the frame in order to support the bottom of a lying person as well as reinforcing the structure from collapsing due to the shear load introduced by the straps.
Finally, the structure was mounted on a system of springs, see Fig. 3b. The goal of this was to boost the vertical movement of the frame and making it easier to achieve the resonances at frequencies predicted by Equation (1). The resonance frequency of the system of springs plus the structure should be very small in order to avoid potential motion out of the vertical axis when excited by the shaker. An estimation of the total mass of the structure with a lying person was done for this purpose, and the springs were specifically designed for this project.

4. RESULTS

An evaluation of the frequency response of the prototype was carried out. Besides, a perception test with subjects lying on the prototype to assess its behaviour was performed.

Bar	h (cm)	f_{cant} (Hz)
1	2	61
2	1.86	56
3	1.71	52
4	1.57	47
5	1.42	43
6	1.28	39
7	1.13	34
8	1	30
9	0.84	26
10	0.7	21

Table 1. Relation of bars and thicknesses, and expected resonance frequency according to Equation (1). The values and ρ =700 kg/m^3 and $E = 11$ GPa were assumed using the reference [8]. The numbering of the bars starts to count from the upper part of the bed.



(a) (b) (c) (d)

Figure 3. a) The bars were inserted in the frame, screwed and glued to ensure a tight clamping. b) The frame was mounted on a system of springs to boost the vertical movement and so the cantilever resonances. c) A mock body was made of cushions and loads to analyze the effect of a person's body on the bars behaviour. d) Participants subjectively assessed their experience in the Kalimba Bed while being excited with pure tones and audio signals.

4.1 Vibration Measurements

The response of the bars was measured in two situations: one with unloaded bars, and one with a mock body loading them, in order to analyze the effect of the person in the vibration of the bars. Two Clark Synthesis TS329 Gold audio-tactile transducers were connected in the middle point of each long side of the Kalimba bed's frame. These present a tactile frequency range from 10 Hz to 800 Hz, and an audible frequency range from 20 Hz to 17 kHz. Since the response of interest was in the low frequency range, low-pass filtered white noise was used as excitation ($f_l = 300$ Hz). The signal was sent to the shakers through a computer, and amplified using a SAMSON Servo 300 amplifier. A Matlab script controlled the measurement of

the transfer function between the two vibrational accelerations, as well as the FFT analysis.
The vibrational acceleration under excitation was measured using accelerometers, at two different positions: at the frame directly on top of one of the transducer, and at the tip of each cantilevered bar. The sensors were attached to the surface using bee wax. Each accelerometer was connected to a B&K charge amplifier Type 2635. The mock body was made with four cushions with heavy loads placed on top and equally distributed along the bars, see Fig. 3c. The total mass of the mock body was measured to be of 43 kg. In the loaded case, the accelerometer was placed in the lower side of the bars.
Fig. 4 shows the results of the vibrational measurements. The transfer accelerations between each bar tip and a point close to the frame are represented, measured with (blue) and without (red) mock body. The frequency range is 10 to 100 Hz.
A COMSOL model of the final prototype was developed as well in order to compare it with the vibrational behaviour of the prototype. However, it was found that experimental and simulation results did not match well. The main reason found for this was that the simplifications made in the COMSOL model, especially the description of the joints between wooden planks and the estimation of the mechanical parameters of the wood. Besides, an improved numerical model should take into account the effect of the straps in potentially bending the frame.

4.2 Perception Test

Two tests were conducted in which participants subjectively assessed their experience when lying on the bed, see Fig. 3d.
The participants were 3 women and 7 men between the ages of 23 and 50, with normal hearing and diverse musical background. In the first part, the bed was excited with pure tones at frequencies coincident with the resonance frequencies measured for each bar. The effect in the perception was compared when the signals of both shakers were presented in phase and out of phase. The participants were asked to indicate where in their body the stimulus was mainly felt. The body was separated in six regions: Head, Upper Back, Lower Back, Bottom, Upper Legs and Lower Legs.
In the second part, the bed was excited with two music pieces: *Sis Puella Magica!* of Yuki Kajiura [12], and *Also Sprach Zarathustra* of Deodato [13]. The participants were told to assess if they could feel different instruments of the track at different positions of their body. The idea behind the experiment comes from the difficulty that hearing impaired listeners find to identify different instruments in a track, mainly because of their difficulty to perceive timbre compared to normal hearing listeners, as it was stated in [14]. The two music tracks were chosen because both have an initial section with few instruments, and more are progressively joining to the piece. This was thought to be an easy way to segregate different instruments even for a participant with no musical knowledge.
The results of the first part of the perception test are

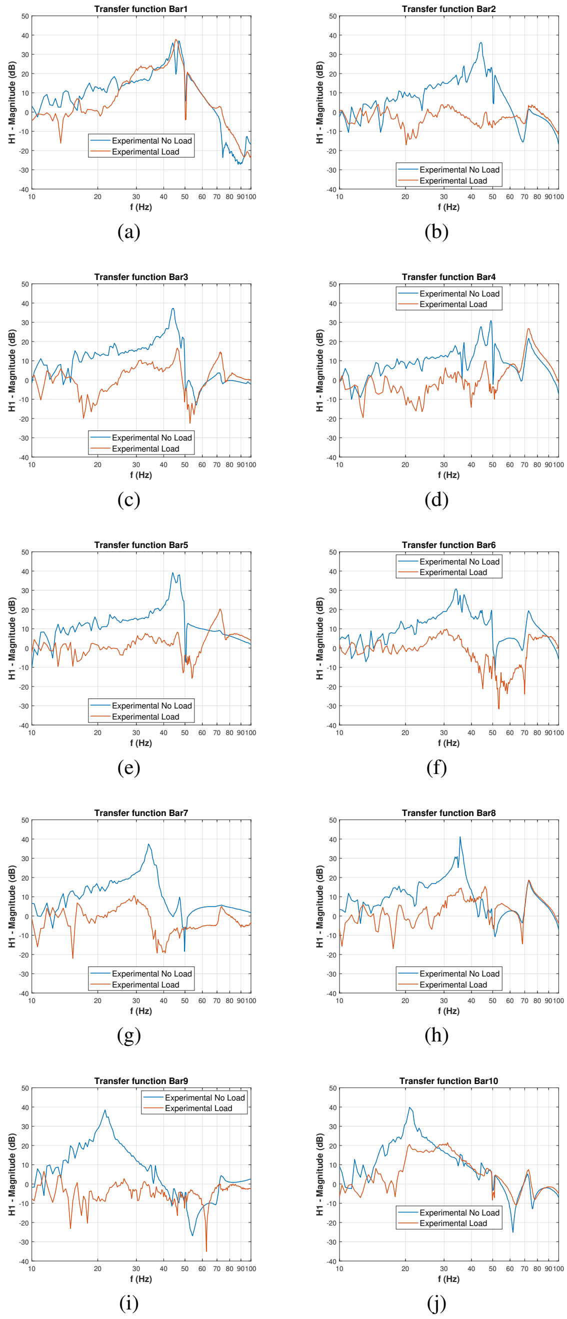


Figure 4. Transfer accelerations between the input position of the transducer and each bar. The numbering of the bars starts to count from the upper part of the bed.

shown in Fig. 5. The answers of the participants are collected in histograms for the excitation of each bar. The blue and pink histograms correspond to the experiments where the left and right histograms where presented in phase and out of phase, respectively. This graphs show that the participants find it difficult to perceive the local vibration of each beam segregated from the global vibration of the structure.
Finally, the second part of the experiment was qualitatively analyzed by the comments of the different participants. Table 2 summarizes the different instruments that were identified by the participants, and the positions where they could feel them.

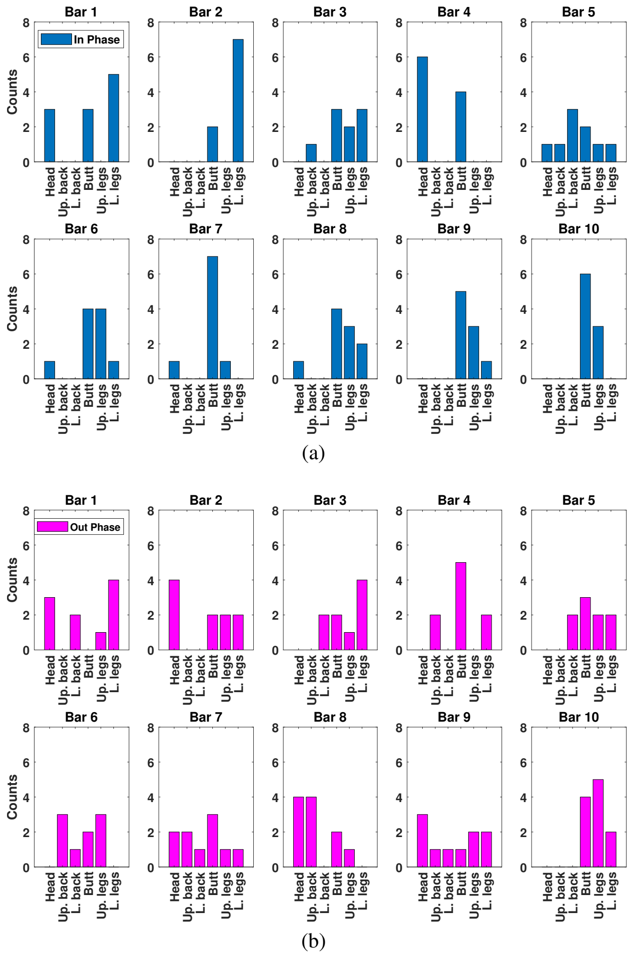


Figure 5. Results summarized of the first part of the perception test. The title of each bar plot indicates wich bar of the bed was excited. The y-axis shows the number of times the participants drew a circle in one of the six divisions of the body: *Head*, *Upper back*, *Lower back*, *bottom*, *Upper legs* and *Lower legs*. (a) Signals from transducers in phase. (b) Signals from transducers out of phase.

5. DISCUSSION

5.1 Vibration measurements

A dip at 50 Hz can be seen in all the bars' response, which can be related to electric noise. In the unloaded case, clear peaks can be seen in each bar response, showing a general agreement in the bars from 4 to 10, where an increase of the resonance frequency can be seen with thicker bars in the range of the expected values from the theory. However, the first three bars show lower values than those predicted. This was related with a discrepancy between the values of density and elasticity used to tune the bars and the real values of the wood, as it was found through measurements later. Furthermore, other factors like the effect of the straps in the structure were considered for further analysis. Above 70 Hz the effect of the load seems to disappear, and the behaviour of the bars is similar. This can be related with the modal behaviour of the frame, that seems to be not affected by the load. This implies that at high frequencies the structure will present modes that can be potentially felt and so can affect the vibration perception.

Instruments	Position
Bass	Strongly felt in the bottom
Drums	Back. Shoulders. Arms. Head
Horns	Felt in the upper back. Feeling of playback.
Tambourine	Travelling along the spine.
Cymbals	Behind the head.
Guitar	Upper back. Head. Chest.
Keys	Upper part
Voice	Feet

Table 2. Instruments identified by the participants and summarized positions where they could be felt.

In the loaded situation (red) the resonance behaviour seems to be reduced in the majority of the bars. In contrast, bar 1 presents almost the same response than in the unloaded situation. In a similar way, bar 10 shows a slightly lower reduction effect than the rest of the bars. This can be explained by the disposition of the loads of the mock body, affecting less to both ends of the bed.

5.2 Perception test

In the first part, when the signals are presented *in phase* it can be seen that the majority of the stimulus were felt in the bottom by at least one participant. This indicates that the stimulus is felt mainly through the frame instead of the beam excited. Two reasons can be argued in this respect. First, the dimensions of the subject could have avoided the contact with the bar. Second, the contact existed but was too strong that the bar motion was damped by the presence of the body.

The answers are more spread when the signals are presented *out of phase*. Although the frequency is the same for each stimulus, the two situations were clearly felt as different. This shows that the effect of the phase introduces a cue in the perception of the vibratory signals.

Regarding the second part of the perception test, overall, all the participants could separate different instruments at different positions. Mainly all found the bass line being stronger in the bottom, and the rest of instruments with more high frequency components were felt in the upper part of the body. The low frequency components, as it was seen in the first part of the experiment, are mainly felt in the bottom, which could explain the strong perception of the bass line there. Some participants argued that they could hear some instruments, especially horns, coming from different positions, even as if they were playbacked. This could suggest that some sound is radiated from the structure, and could explain that this happens for instruments with strong high frequency components.

6. CONCLUSIONS

In this project, an audiotactile installation was built, the so-called Kalimba bed, based on the analysis of the local

frequency selectivity of a system of cantilevers with different geometries.
The measurement of the mechanical properties of the materials used before the building of the prototype would have helped to develop a tuned system with a higher degree of agreement with the theory of beams. An evaluation based on vibration frequency response of the bars and a perception test with normal hearing participants showed that the effect of the body shape of the subject has a big effect in the frequency response of some bars, compromising the performance of the structure built at the affected bars. Besides, the participants could assess the perception of different musical instruments at different positions of their body when the structure was excited with music tracks. Larger samples of participants would help to obtain more robust conclusions.
Further investigations should focus on reducing this dependency of the body shape of the subject, in order to build an audiotactile installation inclusive and reliable for everyone. Besides, the development of simulations should be used as a tool to make decisions in the design and building process.

7. REFERENCES

[1] S. Nanayakkara, L. Wyse, S. Ong, and E. Taylor, "Enhancing musical experience for the hearing-impaired using visual and haptic displays," *Human-computer Interaction*, vol. 28, 01 2012.

[2] A. Baijal, J. Kim, C. Branje, F. Russo, and D. Fels, "Composing vibrotactile music: A multisensory experience with the emoti-chair," 03 2012.

[3] A. Perini. [Online]. Available: https://alessandroperini.com/2014/08/06/audiotactile-chair/

[4] M. Karam, C. Branje, G. Nespoli, N. Thompson, F. A. Russo, and D. I. Fels, "The emoti-chair: An interactive tactile music exhibit," *Conference on Human Factors in Computing Systems - Proceedings*, no. January, pp. 3069–3074, 2010.

[5] R. J. Roark and A. M. Sadegh, *Roarks formulas for stress and strain*. McGraw-Hill Education, 2020.

[6] C. Inc., "Comsol," 2020. [Online]. Available: http://www.comsol.com/products/multiphysics/

[7] S. Timoshenko and J. N. Goodier, "Theory of Elasticity," p. 376, 1967.

[8] *Wood handbook:*. U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, 2010.

[9] B. Sylvain, *The Deaf Musical Experience.: Bodily And Visual Specificities: Corpaurality And Vusicality.*, 01 2021.

[10] M. Karam, F. A. Russo, and D. I. Fels, "Designing the model human cochlea: An ambient crossmodal audiotactile display," vol. 2, no. 3, pp. 160–169, 2009.

[11] E. Rusconi, B. Kwan, B. L. Giordano, C. Umiltà, and B. Butterworth, "Spatial representation of pitch height: the smarc effect," *Cognition*, vol. 99, no. 2, pp. 113–129, 2006.

[12] Y. Kajiura, "Sis puella magica!" 2011.

[13] E. Deodato, "Also sprach zarathustra," 1973.

[14] H. Innes-Brown, A. Au, C. Stevens, E. Schubert, and J. Marozeau, "New music for the Bionic Ear: An assessment of the enjoyment of six new works composed for cochlear implant recipients," no. May 2014, pp. 482–491, 2012.