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Wearable sound: integrative design for hearing and feeling vibrations

Claire Richards

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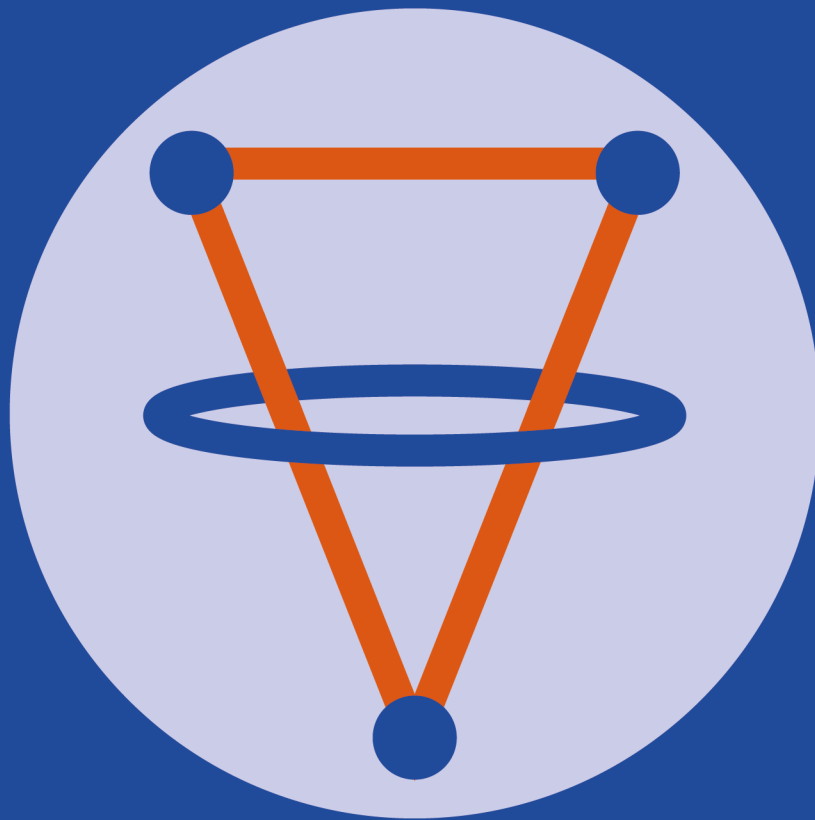
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Wearable Sound

*Integrative Design for Hearing
and Feeling Vibrations*



Claire Richards



DOCTORAL THESIS OF SORBONNE UNIVERSITY
Ecole doctorale 391: Sciences mécaniques, acoustique, électronique et robotique de
Paris (SMAER)

In affiliation with:
IRCAM / Perception and Sound Design Team
Le Centre de Recherche en Design ENSCI Les Ateliers - ENS Paris-Saclay

A CIFRE Partnership with:
Actronika SAS

Presented by:
Claire Richards

To obtain the grade of:
Doctor of Sorbonne University

Thesis subject:
**Wearable Sound: Integrative Design for Hearing
and Feeling Vibrations**

Supervised by Nicolas Misdariis and Roland Cahen

Members of the Jury:

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Prof. Bruce Walker	Georgia Institute of Technology	Reviewer
Dr. Jean-Loïc Le Carrou	Sorbonne University	Examiner
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Dr. Damien Faux	Actronika SAS	Invited
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Prof. Roland Cahen	Le Centre de Recherche en Design, ENSCI Les Ateliers, Ecole Normale Supérieure Paris-Saclay	Thesis Co-Director

Abstract

Apart from connecting us to our sensory environment, our skin and ears share the unique ability to detect and appreciate vibrations. A single stimulus can simultaneously excite both the inner ear and the surface of the skin, through bone conduction and vibrotactile sensation. Bone conduction propagates sound waves to the inner ear by traveling inside the body, along musculoskeletal structures and through bones, soft tissue and fluids. In our research, we referred to this manner of sound perception as *extra-tympanic conduction*: any auditory perception that does not depend on air-conducted sound waves. To elicit extra-tympanic sound perception, it is necessary to create contact between the skin and the source of vibration, which causes vibrotactile sensation within a specific frequency range. Assuming that it is not limited to the skull, we wondered how different points of stimulation on the torso (spine, clavicles, sternum, ribs) might influence the auditory, and mixed audio-tactile, perception of vibration. We first explored this by evaluating auditory detection thresholds of vibratory stimuli, and found that they depend on three signal parameters: frequency, intensity, and position on the body.

This rather anatomical description of our research may feel slightly impersonal - why did we study this specific type of audio-tactile sensation, if not to learn more about its perceptual nuances? This experimental foundation ultimately served to support our design research methods, employed in order to build and study a novel wearable audio-tactile device: the multimodal harness. The device embodies an alternative listening experience, and challenges assumptions about which parts of the body can ‘hear’.

We developed a multidisciplinary approach to design research which we define as *integrative*, where diverse project elements each contribute to a cohesive whole. They correspond to methodologies and contributions from the sciences of perception (psychophysical, multimodal...) and design research (product, speculative, wearable...). Using the multimodal harness as a tool for creative exploration, we studied how the interaction between hearing and touch may inform how to compose spatialized vibrations for the surface and interior of the body. We also used it in two scientific experiments, which studied the perceived alignment between musical audio-tactile stimuli, and the ‘bimodal’ zone where auditory and tactile sensitivities overlap. The theoretical, experimental and creative outcomes, or *products*, generated by the multimodal harness carry variations of a central narrative, telling the story that *the experience of sound is about the experience of vibrations - something that everybody can perceive, and appreciate in their own way*. Together, they shed light on the possibility for a novel, *alternative* sensory experience of sound, independent of one’s capacity to hear.

Résumé

Au delà de nous lier à notre environnement sensoriel, notre peau et nos oreilles partagent une capacité unique : celle de détecter et d'apprécier les vibrations. Un même stimulus peut exciter simultanément l'oreille interne et la surface de la peau, par conduction osseuse et par sensation vibrotactile. La conduction osseuse propage les ondes sonores vers l'oreille interne en se déplaçant à l'intérieur du corps, le long des structures musculosquelettiques, à travers les os, les tissus mous et les fluides. Dans notre recherche, nous avons défini ce mode de perception du son comme "conduction extra-tympanique" : toute perception auditive qui ne dépend pas des ondes sonores propagées dans l'air. Pour activer la perception sonore extra-tympanique, il est nécessaire de créer un contact entre la peau et la source vibratoire, ce qui provoque une sensation vibrotactile dans une gamme de fréquences spécifique. En supposant qu'elle ne se limite pas au crâne, nous nous sommes demandés comment différents points de stimulation sur le torse (colonne vertébrale, clavicules, sternum, côtes) pouvaient influencer la perception auditive, et audio-tactile mixte, de la vibration. Nous avons d'abord exploré cette question en évaluant les seuils de détection auditive des stimuli vibratoires, et nous avons constaté qu'ils dépendent de trois paramètres du signal : la fréquence, l'intensité et la position sur le corps.

Cette description plutôt anatomique de notre recherche peut sembler légèrement impersonnelle - pourquoi avons-nous étudié ces sensations audio-tactiles, si ce n'était pour en apprendre davantage sur leurs nuances perceptives ? Cette base expérimentale a servi de socle pour nos méthodes de recherche en design, employées pour construire et étudier un nouveau dispositif audio-tactile portable : le harnais multimodal. Ce dispositif est l'incarnation d'une expérience d'écoute alternative et remet en question les préconceptions sur les parties du corps capables d'entendre.

Nous avons développé une approche multidisciplinaire de la recherche en conception que nous définissons comme *intégrative*, où divers éléments du projet contribuent chacun à un ensemble cohésif. Ces éléments participent des méthodologies et contributions des sciences de la perception (psychophysiques, multimodales...) et de la recherche en design (produit, spéculatif, portable...). En utilisant le harnais multimodal comme outil d'exploration créative, nous avons étudié comment l'interaction entre l'ouïe et le toucher peut informer sur la manière de composer des vibrations spatialisées pour la surface et l'intérieur du corps. Nous l'avons également utilisé pour deux expériences scientifiques, dans le but d'étudier l'alignement perçu entre les stimuli musicaux audio-tactiles, et la zone "bimodale" où les sensibilités auditives et tactiles se chevauchent. Chacun des résultats générés par le harnais multimodal apporte une contribution à la narration au coeur du projet : *l'expérience du son est une expérience de vibrations - quelque chose que chacun peut percevoir et apprécier à sa manière*. Ensemble, ils mettent en lumière la possibilité d'une expérience sonore *alternative*, indépendante des facultés auditives.

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Chapter I: Thesis Introduction and State-of-the-Art

Thesis Introduction

In the human body, every functional process is part of a whole, integrated system. Each organ has its own, essential function and yet produces a cascading multitude of effects throughout the body. Our perceptual senses work in quite the same way. Although each sense fulfills a specific role in the perception of the surrounding environment, they are all interconnected, and in constant reaction to each other. When I smell the scent of pine, I can close my eyes and see the forest. I can hear the crackling of the leaves under my feet, and I can almost feel the texture of the tree, smell the smoke coming from the campfire. When I hear someone bite into an apple, I can feel the moisture and freshness of the fruit. I can imagine if it is crisp or tender. I remember the fermenting scent of the orchard, I see the mottled color of the apple's skin, I feel the give of its bruises, the slickness of its skin. All of the senses are integrated, their constant interaction stirs up memories, emotions, and desires; none is isolated.

This thesis deals with the integration of two perceptual senses and several domains of research: the senses of hearing and touch, and the domains of haptics, sound design, the science of design, and the science of perception. It is multimodal and multidisciplinary: hearing and touch co-exist at all phases of the project, and the research that we have employed to intertwine them is rooted in the coordination of separate domains of expertise. Design research methods have acted as binding matter in this integrative process. They served as the guiding hand while developing devices to stimulate both the senses of hearing and touch, and it has brought together contributors whose expertises would have otherwise kept them separate. Its principles give cause to learn not only from the resulting sensory experiences created by these audio-tactile devices, but also from the working processes and interactions that enabled us to create them.

Beyond figurative terms, the experience of sound is as much about feeling as it is about listening. In our research, we therefore approached sound through the focus of vibrations. While design research methods have brought together separate domains of expertise, vibration has been the binding matter connecting the senses of hearing and touch. Though it is the driving source behind auditory perception, vibration is not exclusively associated with hearing, nor is its experience exclusively reserved for those who can hear. The incredible thing about vibration is its ability to penetrate and affect every inch of the body. As described by Laurent de Wilde, "*It is not only through the ears that we hear sound. It passes through us like water through blotting paper, through the feet, the back, the stomach, the head...*" (De Wilde, 2016, p. 8)¹. To de Wilde, bodies are only "*passing obstacles on [the path of sound], the auditory witnesses of its propagation*" (ibid., p. 9)².

¹ « Il n'y a pas que par les oreilles qu'on entend le son. Il passe en nous comme l'eau dans un buvard, par les pieds, le dos, le ventre, la tête ... »

² Pour de Wilde, les corps ne seraient que « des obstacles passagers sur [la route du son], les témoins auditifs de sa propagation. »

“An Inspiring Letter”

In a letter written by Helen Keller to the New York Symphony Orchestra in 1924, she beautifully articulates the power of vibration, perceived via the sense of touch, to elicit a musical experience. The next passage contains the full letter, which she wrote after having “listened” to Beethoven’s *9th Symphony* by touching the surface of a loudspeaker with her hands (Keller, 1924).

Miss Helen Keller

to: New York Symphony Orchestra, New York City.

Dear Friends:

I have the joy of being able to tell you that, though deaf and blind, I spent a glorious hour last night listening over the radio to Beethoven’s “Ninth Symphony.” I do not mean to say that I “heard” the music in the sense that other people heard it; and I do not know whether I can make you understand how it was possible for me to derive pleasure from the symphony. It was a great surprise to myself. I had been reading in my magazine for the blind of the happiness that the radio was bringing to the sightless everywhere. I was delighted to know that the blind had gained a new source of enjoyment; but I did not dream that I could have any part in their joy. Last night, when the family was listening to your wonderful rendering of the immortal symphony someone suggested that I put my hand on the receiver and see if I could get any of the vibrations. He unscrewed the cap, and I lightly touched the sensitive diaphragm. What was my amazement to discover that I could feel, not only the vibration, but also the impassioned rhythm, the throb and the urge of the music! The intertwined and interwingling vibrations from different instruments enchanted me. I could actually distinguish the cornets, the roil of the drums, deeptoned violas and violins singing in exquisite unison. How the lovely speech of the violins flowed and plowed over the deepest tones of the other instruments! When the human voices leaped up thrilling from the surge of harmony, I recognized them instantly as voices. I felt the chorus grow more exultant, more ecstatic, upcurving swift and flamelike, until my heart almost stood still. The women’s voices seemed an embodiment of all the angelic voices rushing in a harmonious flood of beautiful and inspiring sound. The great chorus [sic.] throbbed against my fingers with poignant pause and flow. Then all the instruments and voices together burst forth—an ocean of heavenly vibration—and died away like winds when the atom is spent, ending in a delicate shower of sweet notes.

Of course this was not “hearing,” but I do know that the tones and harmonies conveyed to me moods of great beauty and majesty. I also sensed, or thought I did, the tender sounds of nature that sing into my hand-swaying reeds and winds and the murmur of streams. I have never been so enraptured before by a multitude of tone-vibrations.

As I listened, with darkness and melody, shadow and sound filling all the room, I could not help remembering that the great composer who poured forth such a flood of sweetness into the world was deaf like myself. I marvelled at the power of his quenchless spirit by which out of his pain he wrought such joy for others—and there I sat, feeling with my hand the magnificent symphony which broke like a sea upon the silent shores of his soul and mine.

Research Objective and Thesis Structure

The main, guiding objective of this research is to develop novel wearable technology and interfaces which make use of the whole body's ability to detect and appreciate vibrations: on the skin as vibrotactile sensation, and in the inner ear via extra-tympanic (aka bone) conduction sound transmission. The development of the audio-tactile technology has resulted in several branches of the doctoral project structure. We conducted *experimental* studies both prior to and post development of the main wearable device, the multimodal harness. Reflection about the different design processes that led to their creation brought in aspects of *theoretical* inquiry. The *creative* exploration of the associated multimodal experiences brought a compositional approach to the forefront of our research. While formulating our research approach, we certainly drew inspiration and meaning from the experience of sound as vibrations by those who are hard-of-hearing or deaf (the author herself has a sensorineural hearing impairment). However, we feel it is important to clarify that this project did not aim to target one specific group according to their sensory capacities. Rather, by advocating for a multimodal experience of sound, we hope to reach anyone who might be interested in shifting their assumptions about the divisions between our senses, and about which parts of our body are receptive to vibration as an aesthetic, even musical, medium.

This thesis is structured according to three main organizational axes: the *purpose*, the *process*, and the *outputs* of our research. We will present each of the three audio-tactile devices that we have developed throughout the thesis according to these terms, in order to trace the full story of their meaning, their creation and the results that they each generated. We will explain this structure in greater detail in the next chapter (Chapter II, section 1). First, during the following State-of-the-art, we will examine the scope of our research which deals with auditory, tactile and multimodal perception, design research methods, a survey of audio-tactile devices, and methods for audio-tactile sensory effect design. To close this chapter, we will resume the key findings of the State-of-the-art. In Chapter II, we will present the purpose, process and outputs of the first audio-tactile device developed during this doctoral research: the monopoint module. Then, we will also describe the purpose and process of conceiving the two iterations of the second, wearable audio-tactile device: the multimodal harness. From Chapter III on, we delve into the outputs of the multimodal harness. In Chapter III, we will elaborate the outputs of the multimodal harness that most relate to the project's industrial environment, and how it has allowed us to develop our theoretical approach to design research. Chapter IV deals with the products of the multimodal harness generated by its use as an experimental tool. Chapter V examines how we used the multimodal harness for creative exploration of audio-tactile sensations as a means for aesthetic expression. Finally, we will present the main conclusions resulting from this research, along with some perspectives for its continuation.

State of the Art

1. Human Perception of Vibration

1.1. Comparison of Auditory and Tactile Perception

Beginning the state-of-the-art with a comparative analysis of auditory and vibrotactile perception sets the stage for the rest of this thesis, of which one main recurring theme is the interaction between these two modalities. In the next sections, we will describe the two sensory systems separately and in greater detail, followed by a more complete overview of multimodal processing and a glimpse into other connections between our senses.

1.1.1. Anatomical Comparison

This research was fundamentally inspired by the multisensory experience of listening to music, a demonstration of how the sense of touch is intrinsically coupled to the sense of hearing. When listening to or creating music, mechanical waves reach our ears by means of air-conducted sound perception, but in certain cases these same oscillations are also sensed inside and on the surface of the whole body. Georg Von Békésy was a pioneer in the field of acoustics, having discovered the manner of excitation of the basilar membrane that leads to perception and auditory sensation of sound waves: surface wave transmission. He also conducted research about the many similarities between the auditory and tactile modalities, emphasizing the importance of taking both of these senses into account when considering the perception of vibrations. While there are similarities between the sensations of touch and hearing in certain conditions, there are differences between the sensory organs of the skin and the ear. Von Békésy (1959) lists the many ways that the ear can be stimulated: “*air-borne sound, mechanical vibrations touching the skull (bone conduction), electrical stimulation of the ear [(cochlear implants)], electrical stimulation of the acoustic nerve, electrical stimulation of the cortex, and hearing without any stimulation (tinnitus)*” (Von Békésy, 1959, p. 3). There are also many distinguishable qualities of the perceived sound “*pitch, loudness, volume, roughness (modulation, tremolo), direction, distance, on-and-off effects (important for the discrimination of speech and music), and rhythm*” (ibid.). For each of these acoustic parameters for sensing sound, there is a tactile counterpart for sensing deformation of the skin.

Keidel (1956) observed that the extent to which mechanical waves travel in the body is not limited to the specific zone of sensation (as cited in Von Békésy 1959). He used stroboscopic measurements of the skin’s surface to measure the transmission of waves across the skin’s surface, observing concentric circles radiating much farther into the body than the point of sensation. More recently, surface wave propagation across the skin was described by Manfredi et al. (2012): the propagation and decay of waves depends on frequency, as decay happens faster at low (20 Hz) and high (1000 Hz) frequencies in comparison to mid-range frequencies. Much like the way waves travel inside of and across the body, they also travel across the entire basilar membrane. However, as Von Békésy points out, the skin and ear capture and



process those traveling waves in different ways. While the skin perceives the maximum amplitude of the vibratory stimulus at the locus of excitation, the basilar membrane of the inner ear processes the maximum amplitude of the vibratory signal at different points along its length in terms of its frequency: a phenomenon called tonotopic coding.

Despite their mutual ability to process mechanical waves, the two sensory organs do not process vibrations in the same way; this leads to distinct perceptual differences. For example, when digitizing audio signals, a high level of quantification (16, 24, or 32 bits) is required in order to limit the perceptibility of digitization. However, when working with vibratory signals destined for the sense of touch, which are essentially comparable to audio signals, it has been demonstrated that the level of quantification during the digitization process can be drastically lowered (to 8 or even 4 bits), without affecting the quality of signal perception (Consigny et al., 2022). In the following section, the reasons for these perceptual differences will be elaborated in terms of a psychophysical comparison between hearing and touch.

1.1.2. Psychophysical Comparison

In a detailed survey of the similarities in perception between hearing and touch, Merchel and Altinsoy (2020) compare the psychophysical abilities and limitations of the two sensory systems in terms of age, energy adaptation, masking and adaptation. (We will provide only a brief review of their findings.)

Reviewing psychophysical data in terms of absolute sensitivity and discrimination thresholds, the authors give special attention to a specific zone of overlap between the two modalities: between approximately 20 and 1000 Hz, vibrations can be sensed via both auditory and tactile perception. While auditory perception is centralized to the head, tactile perception is decentralized all over the surface of the body. The mechanoreceptors responsible for vibratory perception in the skin are dispersed throughout the skin in varying densities, accounting for the variations in vibrotactile sensitivity between different regions of the body (refer to section 1.2.1 for a detailed review of mechanoreceptors). The auditory system can detect sound (through air- or bone-conducted vibrations) between frequencies of approximately 20 Hz and 20 kHz, while the skin can detect contact-based vibrations between approximately 20 and 1000 Hz. The ears are most sensitive to frequencies between 300 and 7000 Hz (Merchel & Altinsoy, 2020), while the skin's mechanoreceptors responsible for vibrotactile sensation are sensitive to frequencies between 20 and 1000 Hz, with their peak of sensitivity at approximately 250 Hz (ibid.).

As we age, we lose sensitivity in both auditory and vibrotactile perception. This decrease in sensitivity, called “presbycusis” in terms of hearing loss, primarily affects the perception of high frequencies in both modalities. The two sensory organs also both lose sensitivity as a function of stimulus duration: a phenomenon called sensory adaptation, or fatigue. Generally, the tactile modality experiences sensory fatigue more quickly, and more easily than the auditory modality.

In terms of differential sensitivity, the auditory and tactile modalities have clear differences in terms of discrimination between different stimulus intensities, frequencies, temporal characteristics, and locations. The just-noticeable differences (JNDs) vary according to each sensory system: while the ear can discriminate

frequencies with a difference of only 1 Hz, the skin has a very limited ability to differentiate between frequencies, requiring up to 100 Hz to be able to tell two frequencies apart (ibid.).

1.2. Tactile Perception

The basic purpose of the somatosensory system is to inform the brain of the mechanical state of the body it inhabits (Hayward, 2018). The human body's sensitivity to mechanical stimulation is essential to its ability to regulate its internal functions and respond to external information from the surrounding environment. The perceptive experience of touch, hearing and balance are all related to cellular transduction of mechanical stimuli converted into electrochemical signals, transmitted and interpreted by the brain (Orr et al., 2006). In the skin, there are different types of somatic receptors which allow us to perceive pressure, stretching, pain, temperature, muscular movement, and vibration. For a review of these different receptors, refer to Table 1 below.

Receptor Type	Anatomical Characteristics	Location	Function	Rate of adaptation	Threshold of Adaptation
Free nerve endings	Minimally specialized nerve endings	All skin	Pain, temperature, crude touch	Slow	High
Meissner's corpuscles	Encapsulated; between dermal papillae	Principally glabrous skin	Touch, pressure (dynamic)	Rapid	Low
Pacinian corpuscles	Encapsulated; onionlike covering	Subcutaneous tissue, interosseous membranes, viscera	Deep pressure, vibration (dynamic)	Rapid	Low
Merkel's disks	Encapsulated; associated with peptide-releasing cells	All skin, hair follicles	Touch, pressure (static)	Slow	Low
Ruffini's corpuscles	Encapsulated; oriented along stretch lines	All skin	Stretching of skin	Slow	Low
Muscle spindles	Highly specialized	Muscles	Muscle length	Both slow and rapid	Low
Golgi tendon organs	Highly specialized	Tendons	Muscle tension	Slow	Low
Joint receptors	Minimally specialized	Joints	Joint position	Rapid	Low

Table 1: The major classes of somatic sensory receptors, table adapted from Purves et al. (2001).

1.2.1. Mechanoreceptors

This first section will look more specifically into the processing of mechanical stimuli for the perception of tactile signals. The cells responsible for this process are called mechanoreceptors, and are present in the superficial and deep layers of the skin (see

Fig. 2). Within this class of cells there are different types and configurations throughout the body's surface. The tactile stimuli received by mechanoreceptors are used to guide motor behavior and help us interpret what we feel.

More is known about mechanoreceptive afferent neuron types in glabrous (non-hairy) skin than in hairy skin for several reasons. Glabrous skin of the hand has been much more extensively studied in humans due to its direct role in grasp and manipulation tasks. Sensitivity to tactile stimuli on hairy skin differs based on the zone - for example, responses of the receptors on the arm are different from those which innervate the face or back (Goodwin & Wheat, 2008). Merchel et al. (2015) use Stevens' power law, relating sensation magnitude to stimulus intensity, to analyse tactile intensity perception on different parts of the body, concluding that the function's exponent changes based on the site of perception (Fig. 1). For example, Stevens' exponent is observed to be higher on the arm than on the finger.

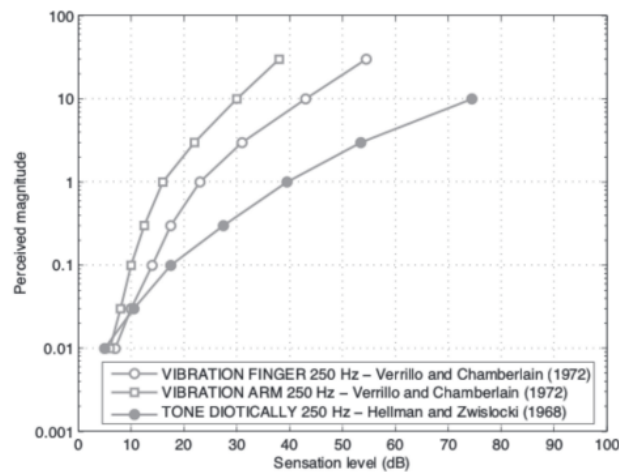


Figure 1: Figure representing the relationship between perceived sensation magnitude and the actual sensation level in dB of a vibratory stimulus, extracted from Merchel et al. (2015).

Merchel et al. (ibid.) discuss the possibility that the sensitivity of the skin at different zones is not only related to the density of each neuron type, but also related to the number of afferent neurons stimulated. This could be due to several factors: a result of the firing rate of the afferent neurons present under the stimulus zone, the firing rate of the entire population of active afferent neurons, or the number of active afferent neurons (Muniak et al. 2007). In other words, apart from differences in mechanoreceptor density, the mechanoreceptors that are stimulated could lead to a different perception based on their different responses at the site, across the neuron type, or based on the number of neurons which were activated by that stimulus. Muniak et al. (2007) conclude in their study that perceived stimulus intensity “is best accounted for by the firing rate evoked in afferents located under or near the locus of stimulation, weighted by afferent type.” Whether or not the type of afferent neuron stimulated will contribute to the perceived sensation magnitude is based on the type of stimuli studied. In the case of the previously mentioned study, vibrotactile stimuli were used to evaluate neural responses. The different types of mechanoreceptive afferent neurons respond not only to vibration but to all types of cutaneous deformation and motion.

For an in-depth description of the role and function of each type of mechanoreceptor with regards to their structures, we can refer to Johnson (2001) or Purves et al. (2001). Though each of the mechanoreceptor types has a specialized function, it is difficult to distinctly map the neural pathways of stimulation because often, due to their high sensitivity, all are activated at once by a single stimulus.

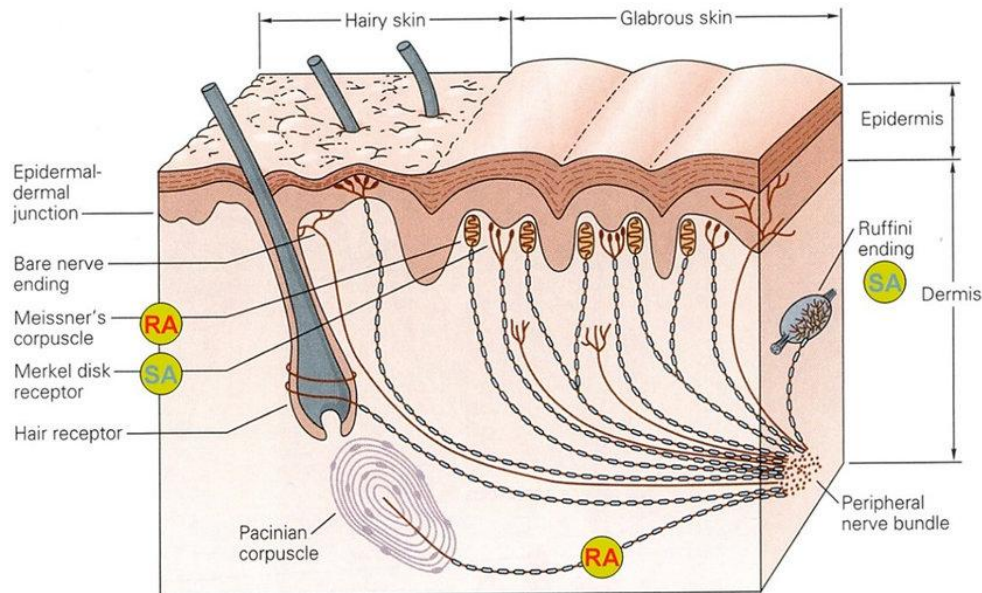


Figure 2: Illustration of the mechanoreceptors in hairy and glabrous (non-hairy) skin, (Gardner & Martin, 2000). “RA” refers to rapidly-adapting afferents, and “SA” refers to slowly-adapting afferents.

Merkel (Slowly adapting type 1) - Form and Texture Perception

Slowly adapting type 1 afferents (SA1) terminate in Merkel cells, and innervate the skin densely: on the finger, their density is 100 per cm². They are highly sensitive to points, edges and curvature, and have high spatial resolution, capable of resolving spatial detail up to 0.5 mm. Combined, these sensitivities cause SA1 afferents to be responsible for perceptions of form and texture. Merkel receptors are located on the tips of the deepest epidermal ridges.

Meissner (Rapidly adapting) - Motion Detection

Rapidly adapting afferents (RA) terminate in Meissner cells, and innervate the skin more densely than Merkel cells. Unlike the Merkel cells, Meissner cells do not respond to static skin deformation (indentations, pressure), responding only to dynamic skin deformation (movement, vibration). In contrast to Merkel cells, Meissner cells have uniform sensitivity to stimulation, giving them low spatial acuity. Meissner cells are known to detect and discriminate low-frequency vibration (20 - 200 Hz), and are located close to the surface of the epidermis.

The SA1 (Merkel) and RA (Meissner) systems complement each other. While the SA1 system has high spatial resolution and low sensitivity, the RA system has high sensitivity but poorer spatial resolution and a smaller dynamic range.

Pacinian Corpuscle - Vibration Specialization

Pacinian afferents are distributed throughout the glabrous skin of the finger (about 350 corpuscles per finger) and palm (about 800 in the palm), and are located deep in the skin. The Pacinian Corpuscle receptor is protected within a fluid-filled corpuscle, a multi-layered structure acting as a high-pass filter and protective layer to the highly sensitive receptor within. These afferents are most sensitive to vibratory stimuli around 200 Hz, but are known to be responsible to the vibrotactile perception of high-frequency stimuli, up to 1500 Hz. This high sensitivity to a wide range of frequencies makes the PC afferents responsible for the perception of distant events through transmitted vibrations to the hand. The sensitivity of these receptors is so remarkable that, when using a handheld tool, we are able to perceive the texture of the material being manipulated.

Pacinian afferents are responsible for our experiences of texture due to their high sensitivity to the widest range of frequencies. When we feel surface textures using our hands, micro vibrations are produced on the surface of the skin. The perception of different spectral characteristics of these vibrations leads to the feeling of different textures, much like how different spectral characteristics of audible oscillations lead to the experience of different timbral textures of sound (Manfredi et al., 2012).

SA2 Afferents (Ruffini Corpuscles/Endings) - Motion Direction and Stretch

SA2 afferents innervate the glabrous skin less densely than other mechanoreceptors, and are responsible for the perception of skin stretch, or horizontal tension. They are located deep within the skin. This allows these receptors to contribute to the perception of motion and of joint flexion.

1.2.2. Propagation of Vibration in the Body

Propagation of cutaneous vibratory stimuli in the body has been studied in several parts of the body, notably within the hand (Shao et al., 2016), the forearm, and the thigh (Jones & Sofia, 2012). Wave propagation on the skin surface is interesting to consider when designing haptic interfaces because it is a factor that impacts the accuracy of stimulus localization.

Exposure to vibration at one point on the skin's surface causes large populations of receptors to respond to the skin's deformation due to surface wave propagation (Manfredi et al. 2012). Using a laser Doppler vibrometer, Manfredi et al. (ibid.) studied the propagation of vibration from the tip of the finger to the end of the finger, observing that propagation decay rate and strength of afferent response are both dependent on frequency. The skin's resonant frequency, which matches the highest sensitivity of Pacinian afferents (around 200-250 Hz), was observed to cause as much as a two-fold increase in afferent response; a slow frequency decay rate at 200 Hz may be partially responsible for this peak in sensitivity. The vibration decay rate is highest at the upper and lower bounds of vibrotactile sensitivity (20 and 1000 Hz). The authors speculate that the match between skin resonance and peak Pacinian sensitivity may be due to the skin's coevolution with the Pacinian mechanoreceptor. Without the skin's frequency response of 200 Hz, the authors therefore argue that the Pacinian afferents would not have optimal sensitivity between 200-300 Hz.

Jones and Sofia (2012) studied the different rates of propagation on the palm, the forearm and the thigh, using an accelerometer array to measure the surface waves. Cholewiak and Collins (2003) observed that vibrations displayed to the tip of the finger traveled up to the arm, further than had been observed by Manfredi et al. (2012).

Whole-body (seat- or feet-transmitted) vibration propagation has been studied mainly in the context of safety (Abercromby et al., 2007), tested with high vibration magnitudes and low-range frequencies in order to reproduce the type of exposure due to high-power engines (Merchel et al., 2015; Altinsoy & Merchel, 2011).

1.2.3. Vibrotactile Perception, Body Site and Age

Vibrotactile sensation is dependent on the site of stimulation on the body. Accuracy of vibrotactile localization has been correlated to many variables: the type and characteristics of the stimulus, the duration of stimulation, the number of transducers used, the site where the transducers are placed on the body, and their spacing (Sofia & Jones, 2013). The different types of tactile afferents described in section 1.2.1 are dispersed in varying densities across the surface of the body. In an assessment of tactile pleasantness, Ackerley et al. (2014) evaluated participants' tactile sensitivity and discrimination between stimulation direction at different parts of their body: the forehead, arm, palm, thigh and shin. They found that the sites of stimulation with the highest tactile sensitivity (the palm and forehead) corresponded to those found in bodily representations like Wilder Penfield's Homunculus (Snyder & Whitaker, 2013) or Corniani and Saal's illustrations of tactile innervation densities across the body (2020) (Fig. 3). However, they did not find the same relationship between body site and tactile pleasantness, which is a more complex percept to evaluate.

Corniani and Saal (ibid.) point out that there is insufficient quantitative evidence for a direct correlation between the density of tactile innervation (amount of mechanoreceptors at a given site on the body) and cortical magnification (amount of brain area devoted to its processing). However, there is evidence of a direct connection between tactile acuity and cortical magnification (Duncan & Boynton, 2007).

Interested in belt-style devices for haptic technology applications, Cholewiak et al. (2004) studied the limits of vibrotactile localization around the circumference of the torso. The authors made three main conclusions: the place of the stimuli, the separation between the transducers, and the number of transducers affect localization performance. In a study of relative vibrotactile acuity on the torso, Johanneson et al. (2017) build on Cholewiak et al.'s findings. Gradually decreasing the distance between the transducers on the torso from 30 to 13 mm, the authors found that participants could differentiate between two stimuli in all conditions, suggesting that the spatial acuity of the torso's skin is perhaps even lower than 13 mm. However, the type of device used to transmit the stimuli affected results: a vest-like device with 40 mm separation between transducers produced worse accuracy results than a device with transducers 30 mm apart, inserted into a sponge material placed centrally on the user's back with flexible straps.

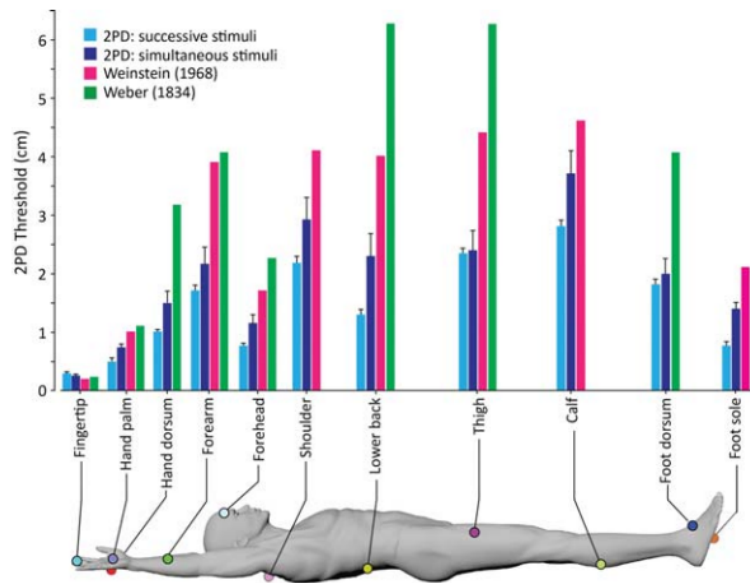


Figure 3: The two-point discrimination thresholds for different regions of the body, as reported by Mancini et al. (2014). Spatial acuity varies depending on the type of skin at the stimulated region (glabrous vs. hairy). The differences in the thresholds are related to the manner in which the stimuli were displayed to the participants (successive vs. simultaneous), or according to the different experimental method applied by Weinstein (1968) and by Weber (1834).

Due to the mechanical changes in the skin and/or neural degeneration that accompany age, increased sensory thresholds and decreased spatial acuity illustrate a general loss of tactile sensitivity with age (Thornbury & Mistretta, 1981; Verillo, 1980, as cited in Corniani & Saal, 2020).

1.2.4. Emotional Perception of Vibration

The tactile perception of vibration has also been studied with regards to its ability to communicate and elicit emotions, in the context of musical emotions (Karam et al., 2009; Schmitz et al., 2020) or emotional meaning in tactile icons (Yoo et al., 2015).

In their study conducted with 16 profoundly deaf individuals, Schmitz et al. (2020) evaluated how participants were able to identify the intended musical emotions portrayed in vibrotactile effects transmitted to their back by the Subpac M2X (a backpack-style wearable haptic device, described in State-of-the-art section 4.2.1). The authors defined “angry” music as being played in minor mode with dissonant tones and a varying tempo, “sad” music with minor mode and slow tempo, “peaceful” music in major mode with moderate tempo, and “happy” music as major mode with medium-high pitch and tempo. The vibrotactile effects were displayed via two voice-coil vibrotactile transducers located on the participants’ back, limited to a frequency range of 1-200 Hz. The participants were able to correctly identify the intended emotions of the happy and angry music displayed by the wearable device, and rated them as being more arousing than the peaceful or sad music, whose emotional significance was difficult to distinguish. As a conclusion, Schmitz et al. (ibid.) suggested some design guidelines for the vibrotactile display of musical emotions, saying that frequencies above 200 Hz, displayed to different parts of the

body than just the back, “could provide users with a more nuanced understanding of the music, which has also been suggested by Nanayakkara et al. (2009)” (p. 13).

Karam et al. (2009) studied the perception of musical emotion through the EmotiChair (described in State-of-the-art section 4.3), which employs the Model Human Cochlea, a system that maps the audio input onto the users’ back via an array of several voice-coil transducers. The authors analyzed participants’ emotional responses to the vibratory stimulation according to two types of signal distribution models: one which separates the audio input into vibratory frequency bands, and another which uses a “multitrack master recording” (p. 163). They found that the participants were better able to identify and appreciate the emotional content of several classical music recordings when the corresponding vibrations were presented to different parts of the body according to the separated tracks of the audio signal (the multitrack master recording model), in comparison to the frequency-band model and the control model.

Mazzoni and Bryan-Kinns (2015) conducted a study using a haptic device for communicating the emotional content of film, and found that the hearing-impaired audience correlated high arousal (excitement) and high valence (positive) with high vibratory frequency and tempo, and vice versa for low arousal (boredom) and low valence (negative).

1.3. Auditory Perception

As mentioned in section 1.1.1, auditory perception can be a result of several different types of wave transmission (or even none at all, in the case of tinnitus). Those waves could pass through the air, pushing and pulling particles in a series of compressions as they move through space like so many coils, finally colliding against our eardrums and setting off a chain of events that end by setting the basilar membrane, situated in the inner ear, into vibration. We can also perceive mechanical waves that propagate from within our body, reaching our inner ears through direct vibratory contact with the skull, or by traveling through musculoskeletal structures up through the cervical spine. In this section, we emphasize the diversity of sound perception, addressing not only the different anatomical phenomena that lead to auditory sensation, but also the different ways that individuals with hearing handicaps interact with sound and vibration.

1.3.1. Anatomy of the Ear

The anatomy of the peripheral auditory system can be broken down into three main sections: the external, middle and inner ear (Fig. 4). Rowe and O’Leary (2014) describe the peripheral auditory system as being “designed to collect, filter, amplify, and convert sound wave pressure into a pattern of neural impulses for transmission to the central nervous system for further processing” (p. 305).

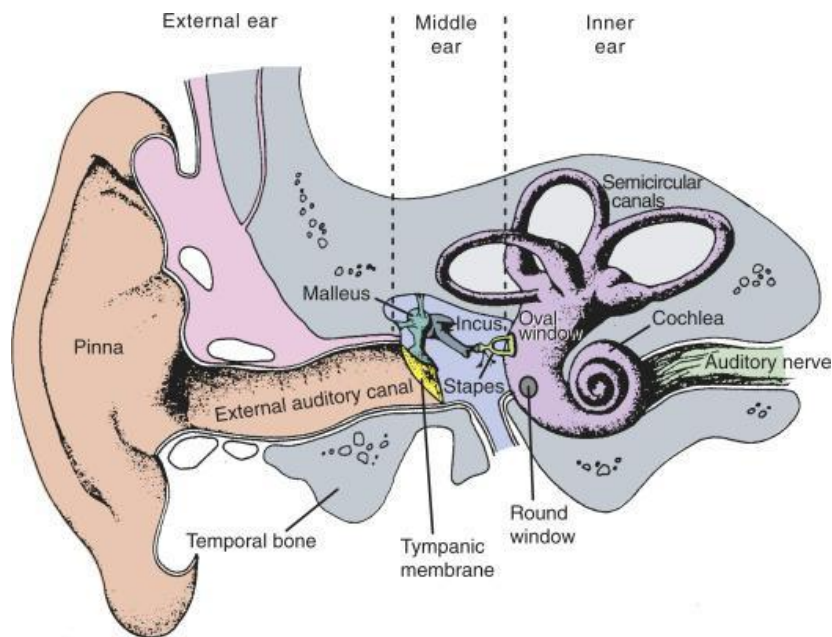


Figure 4: The peripheral auditory system, divided into the external, middle and inner ear. Image and caption adapted from Brown and Santos-Sacchi (2013):

The external ear (pinna and external auditory canal) and the middle ear (tympanic membrane or eardrum, and the three middle ear ossicles: malleus, incus, and stapes) are indicated. Also shown is the inner ear, which includes the cochlea of the auditory system and the semicircular canals of the vestibular system. There are two cochlear windows: oval and round. The oval window is the window through which the stapes conveys sound vibrations to the inner ear fluids (From Lindsay & Norman, 1972, as cited in Brown & Santos-Sacchi, 2013).

The external ear includes the pinna and the external auditory canal, up to the tympanic membrane. The shape of the pinna and its asymmetrical orientation have specific purposes: they enable us to determine spatial characteristics of sound, whether the sound is coming from in front of or behind us, and the elevation of a sound (Rowe & O’Leary, 2014).

The middle ear extends beyond the tympanic membrane (eardrum), including the three smallest bones in the human body: the malleus, the incus, and the stapes. These miniscule bones, called “ossicles”, create a continuous link between the eardrum and the oval window of the inner ear. Their purpose is to convert the energy of the eardrum’s movements, transforming sound energy and minimizing loss from the air to the fluids of the inner ear: a process called acoustic transduction.

The inner ear’s main component is the cochlea, the coiled part of the ear that is responsible for processing sound energy for transmission to the central nervous system as electrical stimuli. Filled with fluid, the cochlea is “subdivided into three compartments: (*scala vestibuli, scala media, and scala tympani*) by two membranes: the basilar membrane, which separates *scala tympani* from *scala media*; and Reissner’s membrane, which separates *scala media* from *scala vestibuli*” (Rowe & O’Leary, 2014, p. 329). The basilar membrane is responsible for processing the different frequencies of the incoming sound energy: its graded mass and stiffness create patterns of vibrations that are coded into the sound’s total component frequencies (*ibid.*). The low frequencies are coded at the extremity (apex) of the

cochlea, and the high frequencies at the base (close to the round and oval windows). The sensitivity range of the cochlea spans 20 Hz to 20 kHz in adults.

In air-conducted sound perception, the inner ear is excited by the movement of the stapes pressing against the oval window. In bone-conducted sound perception, the cochlea receives acoustic information from vibrations that have bypassed the external and middle ear, resonating from inside the skull. We will present information about bone conduction in the following section.

1.3.2. Bone Conduction

In our research, we refer to the phenomenon of conductive hearing as “extra-tympanic conduction” (ETC) instead of bone conduction, since bodily structures other than bone have also been shown to be involved: the soft matter and fluid in the skull (Freeman et al., 2000; Sohmer et al., 2000), and soft tissue sites not directly overlying the skull (Sohmer, 2017; Adelman et al., 2015). However, in this section we will refer to ETC as bone conduction, as the majority of literature refers to conduction-based hearing in this way. In later parts of the thesis, we will use the term “extra-tympanic conduction”.

Kelley (1937) presents a historical review of bone conduction, briefly resumed in this paragraph. Bone conduction of sound is a phenomenon that has been known for hundreds of years, with records of its use dating back to the 16th century, when it was first introduced as a clinical hearing tool by Hieronymus Capivacci (aka Gerolamo Cardano). Cardano’s use of a metal rod connecting a sound source to the user’s teeth was notably used by Beethoven as an attempt to overcome his progressing hearing loss, which has now been attributed to sensorineural hearing loss. Historically, the application of hearing by means of bone conduction is clinical, as an alternate means of hearing for patients with mechanical hearing impairments involving the outer or middle ear. The possibility of hearing by means of direct vibration of the skull was discovered in the same century as the apparatus of the inner and middle ear. In 1521, the first two bones of the ossicular chain were discovered, and in 1589, Cardano wrote his first text describing the use of the vibrating metal rod. Cardano asked patients to listen for a tone - if they heard it through the rod, he diagnosed the hearing loss as conductive, and if not, he diagnosed a disorder of the ‘labyrinth’, as the cochlea was only established as the primary organ of hearing in the late 16th to early 17th century. In 1757, Jorissen made the first known bone conduction communication device, known as ‘Jorissen’s stem’. Beethoven’s apparatus of choice, it was a simple wooden rod, held in the teeth of the listener and in contact with the teeth of the speaker. This same principle was used by hearing impaired individuals to listen to music, by putting their teeth in contact with instruments as they were played. See also Henry and Letowski (2007, pp. 3-6) for an in-depth review on the historical aspects of bone conduction.

Having deciphered the purpose of the basilar membrane, von Békésy went on to clarify a basic question about bone conduction: does it stimulate the cochlea in the same way as air-conducted sound? He reasoned that, if so, it should be possible to mask the perception of an air-conducted sound by the perception of a bone-conducted sound (Von Békésy 1932). Dauman (2013) recounts the experiment, explaining that Békésy “demonstrated this effect by asking a normal subject to listen to two signals of equal amplitude and frequency (0.4 kHz) but dephased by 180 degrees with respect to



each other” (p. 210). This experiment, along with that of Weaver and Bray (1936), confirmed that both air- and bone-conducted sound perception is a result of cochlear stimulation at the level of the basilar membrane. Stenfelt (2007) also repeated the results of the study, confirming the same findings.

Despite the fact that the processes of air- and bone-conduction both lead to stimulation of the basilar membrane, there are differences between the two in terms of absolute detection thresholds (Robinson & Shipton, 1982) and discrimination thresholds (Curso & Levine, 1965). Among the thresholds documented for bone-conducted sound perception, differences have been recorded in terms of the vibratory transducer used (Frank et al., 1988), the part of the skull (McBride et al., 2008; Richter & Brinkmann, 1981; Studebaker, 1962) or body (Adelman et al., 2015; Richards et al., 2021) stimulated, or depending on different masking conditions, as addressed by Walker and Stanley (2005), whose work we address in greater detail in Chapter II, section 2.3.2.

There are other physiological differences between air- and bone-conducted sound perception. Tonndorf (1976) conducted a notable study about the different mechanisms of hearing via bone conduction, illustrating a complex system with many contributing factors (Fig. 5).

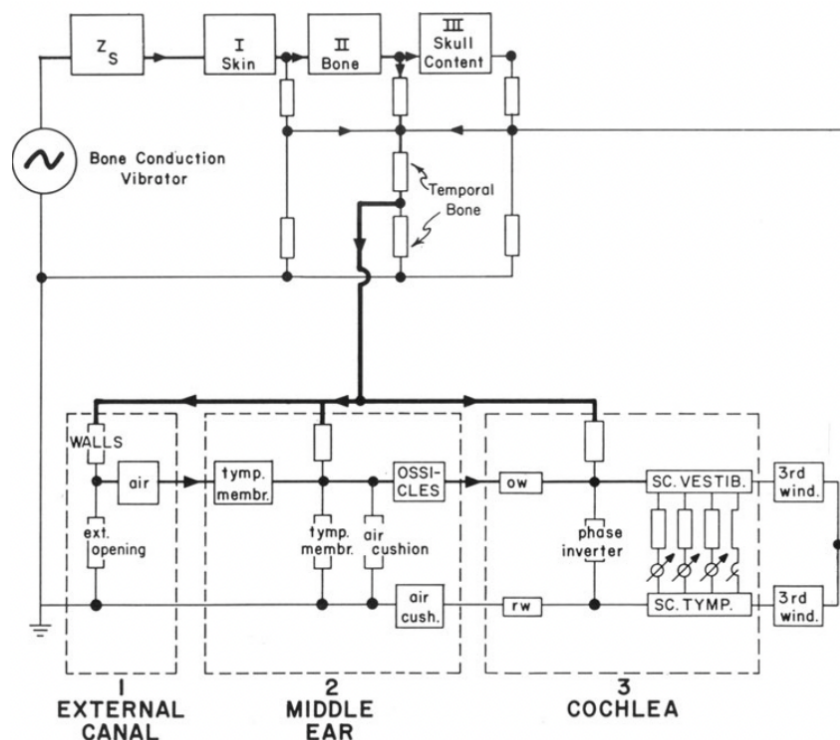


Figure 5: A block diagram of the mechanism of bone conduction, from Tonndorf (1968) as cited in Tonndorf (1976). Tonndorf (1976) describes this chain of events: “...Along what might be called the response line, i. e., the air in the external canal - the tympanic membrane - the ossicular chain - the oval window - and the cochlea, all of these various responses are collected and integrated with one another, according to their phase relations, and the integrated response, finally, leads to hair cell stimulation” (p. 80). “Hair cell stimulation” refers to the ciliated (hair-like) cells responsible for capturing fluid movements inside the cochlea.

In contrast to air conduction, which can be represented by a series of successive events (see section 1.3.1), bone conduction of sound is the result of both simultaneous and successive events, involving the skull's osseous structure, the soft matter and fluid within, and each part of the ear which ultimately all contribute to the transmission of sound pressure to the cochlear scalae (Stenfelt, 2011). However, the mechanisms of bone conduction are still not completely understood (Stieger et al., 2018; Stenfelt & Goode, 2005).

Occlusion Effect

Researchers have used various methods to mask external sounds in order to be certain that the sound perceived during bone-conducted stimulation is indeed conducted through the skull, not the air. Kelley (1937) described Wheatstone's observation in 1827 that the occlusion of the external ear has a positive influence on the perceived intensity of the bone-conducted sound. With one ear open, he perceived the sound loudest at the closed ear while the vibration was in contact with the part of the skull closest to the open ear. Wheatstone was describing the occlusion effect, which also causes one's voice (and other internal sounds) to be perceived as louder when you plug your outer ears with your fingers.

Stenfelt and Sabine (2007) defined the occlusion effect as "the perceived increase in low frequency sound subsequent to an occlusion of the ear-canal opening when the stimulation is presented through bone conduction" (p. 595). It has been reported both as a change in the perceived sound (Small & Stapells, 2003) or as a change in the ear canal pressure (Stenfelt et al., 2003). This effect of masking depends both on the positioning, depth in ear canal and type of occlusion device. Von Békésy (1941) found that if the occlusion plug is positioned deep enough in the ear canal, little to no occlusion effect is observed. If an ear muff is used to block air-conducted sound, little to no occlusion effect is observed as long as the volume within the ear muff is strong enough. Therefore, in order to avoid a potential impact on the perceived amplitude of low-frequency sounds during bone conduction perceptual testing, it is important to consider the positioning and type of masking device.

1.3.3. Hearing Handicaps and Sensory Compensation

An in-depth review about hearing loss is out of scope of this thesis, as this research does not aim to directly address the topic of hearing impairments. However, hearing loss provided fundamental inspiration for our project objectives: Claire Richards, the author, has congenital moderate sensorineural hearing loss. By briefly going over the basic categories and causes of hearing loss, we outline the diversity of sound perception and show that it is not reserved for individuals who have perfect hearing.

The different types of hearing loss can be separated into two main categories: sensorineural, where "there is a dysfunction in the inner ear" and conductive, where "vibrations cannot pass from the outer ear to the inner ear" (Alshuaib et al., 2015, p. 29). It is also possible to have mixed hearing loss, where the individual presents both conductive and sensorineural hearing impairments. An individual with conductive hearing loss will have normal bone conduction hearing thresholds and abnormal air conduction hearing thresholds. Someone with sensorineural hearing loss will respond identically to both air- and bone-conducted stimuli, because the same processing

mechanism is affected for the two pathways of hearing (the inner ear). Hearing loss can be genetic, or the result of damage to the ear(s). Both conductive and sensorineural hearing loss can result from trauma to the ears, whether that is due to excessive or repeated noise exposure that damages the fine structures of the cochlea, or blunt trauma that damages the tympanic membrane.

Within these categories, the spectrum of auditory perception is multidimensional. One ear may hear perfectly while the other could be impaired, or both ears could be affected (unilateral vs. bilateral hearing loss). Another dimension is the degree of hearing loss, which varies from mild (attenuation between 26 and 40 dB), moderate (between 41 and 55 dB), moderately severe (between 56 and 70 dB), severe (between 71 and 90 dB), to profound (> 91 dB). Hearing loss can also be characterized in terms of the affected frequencies: while some individuals will have difficulty perceiving sounds between 500 and 4000 Hz, others will only struggle to perceive frequencies higher than 6000 Hz. Finally, hearing loss can also be congenital, progressive, sudden, or age-related. For a review on the effects and onset of age-related hearing loss, please refer to Huang and Tang (2010).

2. Multimodal Processing of Sensory Stimuli

As we have explored in the previous sections of section I of the State-of-the-art, sound is essentially composed of the same type of longitudinal waves that can excite our sense of touch (vibrations). Therefore, the boundary between what defines the experience of hearing and that of feeling is arguably quite blurry. Throughout section II of the state-of-the-art, we will further highlight this “blurriness” through a brief review on multisensory processing.

2.1. Interplay and Interactions, Convergence and Integration

In the history of the sciences of perception, our sensory modalities of sight, hearing, touch, taste, smell, and proprioception (the sense of one’s body in space) were often investigated in isolation, but modern research suggests that there are constant interactions between our senses (Shimojo & Shams, 2001). In the past few decades, there has been increasing interest in the study of our senses in interaction: a domain called multisensory (or multimodal) research.

Kayser and Logothetis (2007) explain how the traditional compartmental view of sensory processing is outdated, and give direction for future research on sensory processing so that it may incorporate crossmodal and multimodal influences. They address how multisensory integration is often a term left undefined: some researchers understand it to mean “some higher level cognitive combination that merges different sensory evidence into a coherent percept, while others refer to specific response properties of neuronal activity” (p. 122). Driver and Noesselt (2008) bring clarity to the term “multisensory integration” by distinguishing between the use of multisensory “interplay” and multisensory “integration”. While interplay implies cases where one modality has been shown to directly affect another, integration implies the result of a single unified percept emerging from several modalities’ interactions. The term multisensory “convergence” can be compared to multisensory integration, though it is more commonly used with regards to the activity of multisensory neurons (Meredith, 2002). Laboratory experiments of crossmodal

audio-visual effects such as the McGurk effect (McGurk & MacDonald, 1976), the ventriloquist effect (Radeau & Bertelson, 1974), or the phi phenomenon (O’Leary & Rhodes, 1984; Staal & Donderi, 1983) have demonstrated reproducible effects of multisensory integration. Each of these sensory “illusions” shows that under certain controlled conditions, the brain is capable of merging sensory information.

In terms of audio-tactile interactions, a few studies demonstrate how the two senses are capable of influencing each other. In an experiment using vertical whole-body vibrations, Merchel et al. (2011) found that participants evaluated the loudness of auditory stimuli as being 1dB higher, on average, when they were simultaneously presented with tactile stimulation. Yau et al. (2010) also investigated the impact of tactile stimulation on perceived auditory loudness, finding that this interaction effect is crucially dependent on the synchronous timing of the two stimuli. Examples of audio-tactile interactions are particularly relevant in musical contexts. Aker et al. (2022) investigated how the alignment of parameters between audio-tactile stimuli affect vibrotactile music enhancement. They found that tactile parameters of intensity and timing caused participant ratings to fall when they were incongruent with their auditory counterparts. Discussing audio-tactile interactions in terms of human-computer interaction, Papetti (2013) calls attention to other fundamental examples: evidence that tactile stimuli facilitate detection of an auditory stimulus (Ro et al. 2009), evidence that the spectral content of an auditory cue influences tactile sensation (Guest et al. 2002), and evidence for human sensitivity to perceive separate auditory and tactile stimuli as coming from the same source despite spatial dissimilarity (Altinsoy 2005).

2.2. Crossmodality

Interest in crossmodal influences continues to grow (Stein et al., 2020). With advances in cerebral imaging technology and a better understanding of sensory processing in the brain, we have more clarity about how our senses help each other or dominate in certain mental and behavioral tasks.

The term “crossmodal” is frequently employed when discussing multimodal interactions between two sensory modalities. Crossmodal sensory interactions may be defined as the degree to which the information received from one sensory channel is influenced by our interpretation of information coming from other sensory channels (Vines et al., 2006). In the late 19th and early 20th century, early experimental psychologists were already conducting experiments involving multiple sources and types of stimuli, to attempt to see if a hierarchy of the senses could be revealed.

2.2.1. Neural Responses

In terms of neural responses, two guiding principles primarily influence how neurons respond to stimuli from different modalities: spatial arrangement and relative timing. Based on where sensory stimuli are positioned in their receptive fields, falling within or outside of a receptive field overlap can cause an enhancement or depression of multisensory neurons. Based on the timing of both stimuli, “*only stimuli that occur in close temporal proximity cause response enhancement and stimuli that are well separated in time elicit their normal unisensory response*” (Kayser & Logothetis, 2007, p. 122). Wallace et al. (1993) observed a clear topographic relationship between the different sensory cortices and their target neurons in the superior colliculus of the



cat, finding that this region of the brain represents a point of convergence for different sensory inputs. On a neural level, the authors define “crossmodal convergence” as one identical response caused by different stimuli from different modalities presented in isolation, neural activity from a stimulus in one modality which is influenced (enhanced or depressed) by a stimulus coming from another modality.

2.2.2. Plasticity

Cerebral plasticity refers to the ability of both young and old brains to reshape themselves throughout life, depending on their environment and the sensory input they receive. Crossmodal plasticity is one example of this phenomenon, where the brain reorganizes itself due to being deprived of sensory input. In a review on the evidence and effects of crossmodal plasticity, Bavelier and Neville (2002) state that “*it is generally agreed that multimodal brain areas show enhanced processing of input to the remaining modalities ... in blind and deaf humans*” (p. 443). Also, the sensory cortices that are deprived of input have been shown to become “colonized” by other remaining modalities.

For individuals with sensory loss, their brain’s plasticity enables them to adapt and optimize the processing of other sensory input: a phenomenon called crossmodal reorganization. This has been demonstrated in individuals who are deaf, for example, where areas of the brain dedicated to auditory and language-related processing were “recruited” to process instead tactile and visual information (Merabet & Pascual-Leone, 2010). A similar effect has been seen in individuals with varying degrees of hearing loss: it occurs both in those with congenitally profound deafness and in those with mild-to-moderate age-related hearing loss (Cardon & Sharma, 2018). Schürmann et al. (2006) also showed that tactile stimuli activate the auditory cortex in congenitally deaf participants, in a manner similar to how auditory stimuli activate the auditory cortex of hearing participants.

2.2.3. Crossmodal Congruences / Correspondences

The term “crossmodal” may also refer to the field of research about crossmodal correspondences. Correspondences across the senses are not, however, to be confused with synaesthetic mappings between the senses, which Spence and Deroy (2012) define as “*rare cases where certain sensory or conceptual inducers elicit idiosyncratic yet consistent, involuntary conscious sensory concurrents*” (p. 317). In *Defining Synaesthesia* (2011), Simner also addresses the common conception of synaesthesia as a “merging of the senses”, explaining that while this general understanding of the sensory phenomenon has helped disseminate the knowledge of its existence, it is also misleading. Cytowic (1995) also sharply distinguishes its phenomenology from “*metaphor, literary tropes, sound symbolism, and deliberate artistic contrivances that sometimes employ the term 'synesthesia' to describe their multisensory joinings*” (Cytowic 1995, as cited in Van Campen, 1997).

Spence (2011) draws a comparison between crossmodal and synaesthetic correspondences, in that they may both be based on associations between nonredundant sensory information - the brightness of a light and the pitch of a sound, for example. However his definition of a crossmodal correspondence implies the association of either redundant or nonredundant sensory information, as long as they produce an effect of compatibility, or congruence between stimulus dimensions.

Another consideration in studies of crossmodal congruence is semantic congruence, or whether “subjects are able to provide a congruent meaning to the stimuli in both modalities” (Turchet & Serafin, 2014, p. 59). For example, hearing the crunch of gravel while feeling the small stones beneath your feet is a semantically congruent audio-tactile experience. Turchet and Serafin (ibid.) studied the semantic congruence between audition and touch in the context of auditory and foot-haptic stimulation. Their results, which showed a higher level of semantic congruence between similar material typology (i.e. solid vs. aggregate) in the auditory and tactile modalities, demonstrated that material typologies are processed consistently between the two modalities (ibid.).

3. Design Research Methods

3.1. *What is “Research Through Design”?*

In 1993, Christopher Frayling wrote an essay that dug into the separations (or lack thereof) between the domains of art, design, and research (Frayling, 1993). He introduces his paper by clarifying the various definitions of research floating in our collective consciousness: research (with a ‘small r’) is the dictionary-defined act of carefully searching, while Research with a big ‘R’ is a professional practice associated with development, progress, novelty and improvement. He elaborates stereotypical images of the impetuous mad artist, the trend-setting workaholic designer, and the rationalist ‘Eureka’-shouting scientist. Then, he elaborates how these categorical stereotypes don’t reflect the reality of design, art, and research practices. Not all artistic works can be categorized as research, but there is a strong cognitive tradition in art. Scientific research is not just about pouring liquids into beakers and writing groundbreaking algorithms; research in the humanities, in philosophy and sociology, is much like doing design. To illustrate some of the ways that scientific and artistic processes interact in practice, Frayling makes three ‘practical suggestions’ (not to be taken as clear-cut definitions), or categories of design research: research *into* art and design, research *through* art and design, and research *for* art and design.

Research into art and design is archive-based, involving historical, aesthetic or theoretical studies on existing works and perspectives. His definition of research through art and design is less straightforward, including practices such as materials research, technological development, and action research, where the main goal is to communicate about a central research objective. Research for art and design is identified by its end product: an artefact that embodies the ideas that the researcher sought to communicate. By outlining these categories, Frayling articulates the futility of building a wall between art and science. In his essay, he demonstrated how design research (regardless of its variety) can act as a common ground for scientists and artists, providing parallels between their practices, and validating the transposition of practices between disciplines.

As reflected in Frayling’s initial definition, today’s understandings of research through design still resist a categorical, metric-based protocol - but this isn’t necessarily a bad thing. Gaver (2012) explored the use of research through design in the HCI community, organizing examples from accounts of practice. Gaver acknowledges the lack of convergence between the multiplicity of conceptual

perspectives present in research through design. However, the main argument he presents is that aiming for convergence and standardization of design research practices may actually limit the progress of the discipline, which can also benefit from discourse, criticism and disagreement.

3.2. Defining the Project Narrative

Until relatively recently, design was widely regarded as a means to an industrial product. Zurlo and Cautela (2014) describe the past 20 years of design evolution as a process of breaking away from exclusively tangible creations. Design gradually grew towards a wider, intangible (i.e. service-oriented) realm where it does not only concern objects, but also the experience of purchasing the object, the use of the object, and its connection to other parts of the user’s experience. Design also grew to become a discipline of thinking and project construction, where step-by-step processes of ergonomic and user-centered design were defined and widely accepted as tools to be employed in a vast diversity of organizational and environmental contexts.

Zurlo and Cautela (ibid.) acknowledge how design projects are inextricably connected to the organizational environment in which they are developed. That connection can be elaborated in terms of the project narrative exchanged between business and design processes. A project narrative is many things: it is a story used to construct strategy, a reason to believe in a project, a metaphor for product functionality, and an ambiguous dialogue between a narrator and a narratee that is open to interpretation. Companies elaborate particular business narratives to communicate about project ideas with designers. The authors describe these narrative frameworks as articulating the design project in terms of the company’s objectives, the innovation processes, and the relationship between the company and the designer.

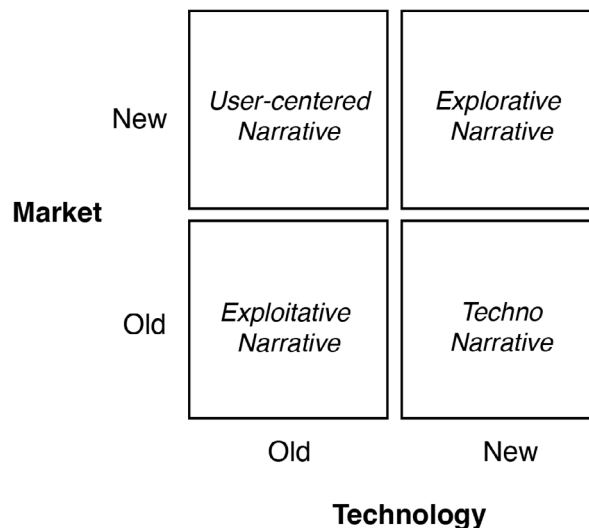


Figure 6: Figure adapted from Zurlo and Cautela (2014). The way that companies (narrators) conceptualize a project’s narrative for designers (narratees) is dependent on two main factors: the market and the technology. Working with the designer, the company must question whether they adapt to the traditional or future state of the market, at the same as they consider implementing familiar or innovative technological processes.

Zurlo and Cautela (ibid.) defined four distinct narrative fields according to the market- and technology-related factors at play in a given design project (Fig. 6). In an exploitative narrative, the company wants to direct all of their efforts towards reinterpreting an existing offering. In the techno narrative, the designer must work within the company's current innovation strategy while applying a new technology to provide a new product offering. In the user-centered narrative, the company demands that the designer adapt existing technological methods or products to create new, unconventional use contexts. Finally, in the explorative narrative, the designer is given full liberty to explore new technological opportunities in yet undeveloped market contexts; this approach requires a certain level of trust between project stakeholders and development actors.

The authors defined these narrative fields in terms of business-related contexts, giving the company the role of narrator and designer the role of narratee. However, we believe that the fields can be transposed to different contexts. For example, in a scientific context, the narrator could be the laboratory or lead researcher, who expresses their vision for a research project in terms of experimentation, publication and technological development. The narratee, in this case, would be the design-researcher: a practitioner who is familiar with the demands of a scientific environment, and who understands how the design process can be adapted to generate knowledge to the benefit of the research community and project stakeholders.

3.3. Speculative Methods for Design Research

When defining the term “speculative design”, we may directly refer to other terms in a similar vein of design research: “discursive” design, “critical” design, and “design fictions”. Each term has its specificity. Discursive design was defined by Tharp and Tharp (2013) as “the creation of utilitarian objects/services/interactions whose primary purpose is to communicate ideas—artifacts embedded with discourse” (p. 406). Bardzell et al. (2012) defined critical design as any creation that “seeks to disrupt or transgress social and cultural norms” (p. 288). Design fiction, a term coined by science-fiction writer Bruce Sterling, is a narrative process both rooted in fantasy and reality: it is “the deliberate use of diegetic prototypes to suspend disbelief about change” (Sterling, 2013, as cited in Blythe, 2014). Blythe (ibid.) argues that design fiction is a useful practice in the context of research through design, even if the fictions remain forever in imaginary form. Malpass (2013) distinguished speculative design from critical and associative design, placing it somewhere in the middle of emerging science and popular material discourse, typically focusing on the potential impact of the domestication of novel technology. He explains, “it aims to broaden the contexts and applications of work carried out in laboratories and show them in everyday contexts” (ibid., p. 338).

Though each has their specificities, one main common thread between each of these design practices is the separation from any market-related influences. In Anthony Dunne's book *Hertzian Tales*, he asserts the claim that design can also be used as a critical medium, operating outside of the commercial sphere to help us reflect on the social, cultural and ethical impacts of technology on present and future life (Dunne, 2008). Drawing from examples in fine art and architecture, Dunne

defines critical design as industrial design with the communicative purpose of applied art; a means to encourage reflection about the positive and negative potential effects of emerging technology.

Succeeding *Hertzian Tales*, in 2013 Dunne and Raby published “*Speculative Everything*”, which helped to further clarify the definition of this emerging discipline. The book’s manifesto builds on Dunne’s previous definition of critical design by developing a dichomatic list of concepts (Fig. 7). This manifesto proposes a view of design for the consumer (“A”), versus design for the citizen (“B”), with the hope and intention to spark the definition of more letters in the future (Dunne & Raby, 2013). While the other terms previously mentioned (discursive, critical, fiction) each describe non-consumerist design work, Auger (2013) preferred ‘speculative’ design over the others because it “suggests a direct correlation between the ‘here and now’ and existence of the design concept” (p. 12).

{ a }	{ b }
affirmative	critical
problem solving	problem finding
design as process	design as medium
provides answers	asks questions
in the service of industry	in the service of society
for how the world is	for how the world could be
science fiction	social fiction
futures	parallel worlds
fictional functions	functional fictions
change the world to suit us	change us to suit the world
narratives of production	narratives of consumption
anti-art	applied art
research for design	research through design
applications	implications
design for production	design for debate
fun	satire
concept design	conceptual design
consumer	citizen
user	person
training	education
makes us buy	makes us think
innovation	provocation
ergonomics	rhetoric

Figure 7: Dunne and Raby’s “A/B Design” manifesto (Dunne & Raby, 2009).

Lukens and DiSalvo (2012, p. 27) define speculative design according to the six following factors:

1. *Speculative design projects are future oriented.*
2. *Speculative design projects call attention to the possibilities and consequences of technological development and implementation.*
3. *Speculative design projects involve and encourage thinking broadly about technology—beyond a single objective or practice.*
4. *Speculative design projects are cross-disciplinary and integrative.*
5. *Speculative design projects demonstrate an understanding of the interrelationship between information resources, technological*

structures, and market forces (National Research Council, Committee on Information Technology Literacy 1999).

6. *Speculative design projects favor inquiry, experimentation, and expression over usability and marketability.*

Beyond criticizing or recontextualizing the status quo of technological design, speculative design methods can be of particular relevance when applied to design research processes. In educational, research and professional contexts where designers are learning about technology at the same time as they are being encouraged to find new applications for it, technological fluency is essential. Lukens and DiSalvo (2012) define technological fluency as the ability to be creative and spontaneous with technology. The practice of speculative design, they argue, is relevant for the process of nurturing technological fluency because of the issues and practices that they share. Relating speculative design to design research, Blythe (2014) challenged the notion that design fiction and speculative designs are most frequently associated with functioning, concrete objects. He instead focused on the development of several stories called ‘imaginary abstracts’. These imaginary abstracts propose to research design experiments and ideas without going quite so far in terms of materials: they remove the prototype from the speculative design process, and instead propose narrative-based development and analysis of a plausible fiction.

Šuran and Mitrović (2015) argued that speculative design “has potential in multidisciplinary teams... it initiates dialogue and generates a context in which the participants can simultaneously re-examine the boundaries of their disciplines and discover links with other disciplines”. They referred to designers who practice discursive, critical or speculative design as the “new” designers, who give themselves the liberty to not only create, but to question the purpose of new technologies. This is a type of designer who creates new relationships between traditionally separated disciplines: computer sciences and engineering, psychology, architecture and biotechnology. Beaver, Kerridge and Pennington (2009), editors of speculative design catalog *Material Beliefs*, suggested that the product of design isn’t just the prototype or the research process, but rather the sum of all of ‘the connections made by all those touched by the work (as cited in Lukens and DiSalvo 2012, p. 62).

In Chapter III, section 3.2, we will delve into some more examples of speculative design, relating the concept more closely to the context of our research.

3.4. The Case Study as a Model of Qualitative Data Analysis

Originally developed as a practice in the teaching of law, the case study has gradually gained presence in many disciplines. Crowe et al. (2011) define the case study as an empirical inquiry that is “particularly useful to employ when there is a need to obtain an in-depth appreciation of an issue, event or phenomenon of interest, in its natural real-life context” (p. 1). The authors describe three types of case studies: *intrinsic*, *instrumental*, and *collective* (Stake, 1995, as cited in Crowe et al., 2011). An intrinsic case study is used to describe a unique phenomenon and distinguish it from other phenomena, an instrumental case study uses a particular case to gain insight into a specific issue, and the collective case study explores several cases, at once or in sequential order, to explore one specific issue with the input of different examples.

In design research, the case study is a valuable method to analyze the space that emerges between theory and practice. Breslin and Buchanan (2008) explain the origins of the use of case studies in industrial design practice, citing a “lack of objective rigor” and a general tendency for them to end up being used as marketing pieces for companies (p. 37). To avoid this, the authors therefore propose to design researchers to adopt a more formalized, structured approach to using case studies for qualitative data collection. They suggest first to determine the topic, form clear initial hypotheses, conduct the observational research, record it, and tell the honest story about the process through those qualitative results. The convenient part of this suggestion is that designers, generally, already do all of this - elaborating the case study is just a way to gain clarity about their own process and improve its legibility and usefulness for others in the design research community. By articulating the impact of design theory through design practice, case studies’ presence and affirmation as valuable subjects in published design helps to reassert the notion that designers’ concerns can include actions and thoughts, not just products, images and symbols.

To gain insight into the application of our methods and theories to be elaborated throughout this research, we will describe an artistic collaboration as an instrumental case study on their creative implementation later on in the thesis (Chapter V, section 4).

4. Audio-Tactile Devices: A Brief Survey

What will we talk about?

As we have outlined in section 1.1, there are diverse possibilities for multisensory interaction between auditory and tactile perception. In this section, we will provide a brief survey on existing audio-tactile devices which directly relate to a mixed audio-tactile or tactile experience of sound.

The audio-tactile devices discussed in this survey pertain to musical and creative contexts of use, and will be grouped into categories according to their form: wearables, chair-based devices, or larger-scale installations. Though these vibratory devices provide an inherently accessible experience of sound for users with a diverse range of sensory abilities, they were not all created as solutions for individuals with sensory impairments. For a full review of wearable tactile devices as sensory aids for clinical needs, please refer to Shull and Damian (2015).

What won’t we talk about?

A number of tactile devices have emerged in the last decade, providing tactile illusions or tactile feedback for applications ranging from education, to virtual reality, to teleoperation (see Adilkhanov et al., 2022, for an extensive review). To filter for the purposes of our review, we will not discuss tactile devices whose context of use does not involve auditory perception, nor any clinical applications of audio-tactile perception such as the tactile improvement of speech intelligibility or any other assistive hearing applications; these are out of the scope of this research.

The main investigative axis of our research is alternative sound perception by bone conduction (which we refer to as *extra-tympanic* conduction) and vibrotactile

sensation, specifically on the torso. Therefore, existing devices which integrate bone-conduction sound transmission on the head, which are limited to the hand and/or arm, and which do not involve a tactile element of sound perception are also out of the scope of this research. For a full review of fixed or wearable tactile devices for hand-based haptic interactions, please refer to Pacchierotti et al. (2017).

4.1. Vibrotactile Motor Type

A determining factor for the design of vibrotactile devices is the type of transducer chosen to stimulate the user's skin. There are three main classes of vibrotactile transducers: eccentric rotating mass (ERM), linear resonant actuator (LRA/voice-coil) and piezoelectric encapsulated transducer (piezo). They vary mainly in terms of terms of frequency bandwidth, resonant frequency, response time, energy requirements, and ability to reproduce different types of waveforms (Azadi & Jones, 2014). Among these three categories of vibrotactile motors, it is still important for the designer to be aware of individual motor characteristics when designing vibrotactile and/or auditory sensations.

Eccentric Rotating Mass (ERM)

The basic function, ease of availability and low cost of ERM transducers makes them interesting for use cases where designers only wish to work with a limited frequency range, as their vibration amplitude is directly dependent on the driven frequency. The vibration of an ERM is generated by the rotation of a mass around the center of the motor. ERM motors therefore have direct implications for the control and range of vibrotactile feedback. As explained by Tang et al. (2014), their choice of ERM motors over LRA motors meant that “the frequency and amplitude of the vibrotactile stimulations could not be controlled independently”, causing them to limit the effects of their haptic sleeve to simple pulses on the skin, varied in terms of duration (p. 37). In the *Body:Suit:Score*, discussed in this chapter's section 5.2, the authors integrated eccentric rotating mass (ERM) transducers to display the vibrotactile effects (West et al. 2019). They chose the ERM motors for their accessibility, and strategically designed their effects in order to overcome their limitations (see section 5.2).

Linear Resonant Actuator (LRA / Voice-coil)

The linear resonant actuator (LRA) is also referred to as a voice-coil motor, a name that comes from its origins of use in loudspeakers. Azadi and Jones (2014) define LRA motors as “voice coil actuators (a moving coil actuator in a stationary magnetic field) with additional mass connected to the moving coil and a spring that connects the moving parts to the casing” (p. 352). In the LRA motor, the vibration is generated parallel to the length of the motor as a displacement along its linear axis. LRAs are interesting for designers who wish to create vibrotactile feedback in a large range of frequencies, while being able to control the amplitude. In the context of our research, we use LRA motors (Actronika Standard Actuator, datasheet in appendix pp. 193-198), as we need to reproduce a wide range of frequencies at sufficient amplitude to be perceived via extra-tympanic conduction.

Piezoelectric Transducer (Piezo)

The piezoelectric motor is often integrated in wearable vibrotactile displays for its paper-thin form factor and ability to generate a wide range of frequencies and amplitudes of the vibrotactile signal. The basic function of a piezoelectric motor is similar to a muscle: when an electric current is run across its surface, it causes a mechanical strain on the material and therefore a physical deformation (Ramadan et al., 2014).

Ramadan et al. (2014) define ‘piezoelectricity’ as describing “dielectric materials that produce electrical charges across their boundaries due to the application of a mechanical stress, which is called the direct piezoelectric effect” (p. 2). There are different types of piezoelectric materials, which produce different types of piezoelectric effects. The arrangement of ions in the crystal structure of inorganic crystalline materials like aluminum nitride causes changes in internal polarization with applied mechanical stress. Ferroelectric materials like zirconate titanate produce a piezoelectric effect due to the reorientation of internal dipoles within the material, due to the application of an electric field.

4.2. Wearable Devices for Audio-Tactile Experiences

Depending on the device and context of use, tactile stimuli provided in the context of an audio-tactile experience might serve to *enhance* the user’s appreciation of sound, to provide a sensory *substitute* for the auditory perception of sound, or to *simulate* a live experience of sound. Some industrialized wearable audio-tactile devices situate themselves at the crossroads between all three of these applications (SUBPAC, Vibeat, Woojer), while distinguishing themselves in terms of formal device features and vibratory effects. Other devices have emerged from scientific research or artistic exploration, explicitly developed as tools for musical creation and performance (Turchet et al. 2021, West et al. 2019), to provide tactile feedback where it lacks in electronic instruments or interfaces (Rovan & Hayward, 2000; Marshall & Wanderley, 2006), or to suggest the body as a canvas for musical expression (Gunther & O’Modhrain 2003; Pook, 2008). For a full review of wearable devices for audio-tactile experiences of music, see Remache-Vinueza et al. (2021) (Table 2).

In this section, we discuss audio-tactile devices that were produced in the context of academic research or design projects. In the following section, we will describe a few industrialized wearable audio-tactile products currently available on the market.

One specific category of wearable audio-tactile devices is musical haptic wearables for audiences (MHWAs) and musical haptic wearables for performers (MHWP), described by Turchet et al. (2021) as devices worn during live music performances by the audience (A) or the performer (P), aiming to “enrich musical experiences by leveraging the sense of touch as well as providing new capabilities for creative participation”. Two devices that fit into the MHWP category are the Body:Suit:Score and the MusicJacket.

HMP-WD	Year	Contact Mechanism	Type of Actuator	Stimuli	Features Explored
Cutaneous Grooves [15]	2003	Whole body suit	Voice coil, Subwoofer	Vibrotactile, Auditory	VMC
Model Human Cochlea [28]	2008	Belt	Speaker	Vibrotactile, Auditory	FM, TM, VMLE
Vibrotactile display [41]	2010	Belt	Speaker	Vibrotactile	FD ¹
Vibrotactile Music System (Design) [66]	2011	N/A	N/A	N/A	VMLE
Vibrotactile Music System [66]	2012	Not available	Not available	Not available	FD, Interval Size, Pitch Direction
Dual Band HMP [37]	2013	Mobile device mock-up	DMA	Vibrotactile, Auditory	F-EQ, Rhythm
MUVIB [59]	2014	Bracelet	Voice coil	Vibrotactile, Auditory	Intensity
Vibrotactile Chords [64]	2014	Mobile device mockup	Voice coil	Vibrotactile	MC
Vibrotactile Composition [67]	2015	Jacket, leggings	ERM	Vibrotactile	VMC
CollarBeat [46]	2015	Collar, belt	Voice coil	Vibrotactile, Auditory	VMLE
Audio-Tactile Conversion [63]	2015	Mobile device mock-up	Voice coil	Vibrotactile, Auditory	FD
Vibroacoustic Device for Music [34]	2016	Belt	Motor-String, voice coil	Vibrotactile, Auditory	Amplitude, Frequency, Rhythm, VMLE,
MuSS-Bits [18]	2016	Bracelet, magnetic, belt	ERM	Vibrotactile, Visual	Rhythm, VMLE
Mood Glove [61]	2016	Glove	Voice Coil	Vibrotactile, Auditory, Visual	Rhythm, VMLE
Feeling Music [60]	2017	Bracelet	Voice coil	Vibrotactile, Visual	Rhythm
Hedonic Haptic Player: Design [68]	2017	Belt	Voice coil	Vibrotactile	VMC
Hedonic Haptic Player [35]	2017	Belt	Voice coil	Vibrotactile	Rhythm, VMC, VMLE
Hapbeat Test [42]	2017	Belt	Motor-String, voice coil	Vibrotactile, Auditory	Amplitude, Frequency, VMLE
Haptic Melodic Interval [69]	2018	Belt, mobile device mockup	Vibrotactile	Melodic interval	
Hapbeat Re-Design [70]	2018	Belt	Motor-String	Vibrotactile	N/A
Music Sensory Substitution System [19]	2018	Bracelet	ERM	Vibrotactile, Visual	Rhythm
Musical Scale Through Haptic Actuator [62]	2018	Mobile device mock-up, VMID	Voice coil	Vibrotactile, Visual	Melody, Pitch, Timming, VME
Musical Haptic Wearables [58]	2018	Belt (armband)	N/A	Vibrotactile, Auditory, Visual	API ² , VMLE
LIVEJACKET [38]	2018	Jacket	Piezoelectric, Subwoofer	Vibrotactile, Auditory	TM, VMLE
Musical Haptic Sleeve [39]	2019	Sleeve	Speaker	Vibrotactile, Auditory	VMLE
Body:Suit:Score [65]	2019	Whole body suit	ERM	Vibrotactile, Auditory	Pitch, FM, Tempo, VME
Tactile Identification in Music [71]	2019	Glove	Voice coil	Vibrotactile, Auditory	VMLE
Tactile Musical Emotion [72]	2020	Glove	Voice coil	Vibrotactile, Auditory	Timbre, VMLE
Touching the audience [21]	2020	Bracelet, jacket	ERM	Vibrotactile, Auditory, Visual	API, VMLE
Vibrotactile Captioning [73]	2020	Glove	Voice coil	Vibrotactile, Auditory, Visual	EEG ³ , Tempo, VMLE
SENSE [74]	2020	Glove	Voice coil	Vibrotactile, Visual	VMLE

¹ Frequency Discrimination; ² Audience-Performer Interaction; ³ Vibrotactile perception supported with electroencephalogram.

Table 2: Table extracted from Remache-Vinueza et al. (2021), who conducted an extensive survey on musical haptic wearables, among which there are certain devices with a more direct connection to our research. From this list, we will discuss the Vibrotactile composition suit described in “Cutaneous Grooves” (Gunther & O’Modhrain, 2003), the Model Human Cochlea, CollarBeat, and the Body:Suit:Score in greater detail.

Body:Suit:Score

The BodySuit:Score (Fig. 8) was designed to reimagine the stationary musician's experience, enabling them to have full mobility in space as they performed to a live audience (West et al. 2019). The suit's design, a jacket-style device with integrated ERM (eccentric rotating mass) vibrotactile motors integrated on the front and back of the user's torso and arms, fits its context: its exposed control boards illuminate its technological features, while the linework, texture and lightness of the fabric lend to a more formal performance-based context.



Figure 8: The Body:Suit:Score, designed by West et al. (2019), features a “repertoire of tactons ... that can be used as symbols in a growing tactile language for conveying musical instructions” (p. 74). Composers can communicate with musicians wearing the body:suit:score in real time through the tactile sense alone, displaying information and signals on the musician's body by using these vibrotactile messages. Image extracted from West et al. (2019).

MusicJacket

The MusicJacket (Fig. 9) is destined for use by novice violin players who wish to improve their posture and bowing technique (Van der Linden et al. 2011). Seven vibrotactile motors are integrated on the musician's wrists, arms, and waist with velcro straps in order to communicate different vibratory messages depending on the movement of their body. Rotations of the different parts of the user's body are detected by several integrated inertial measurement units.

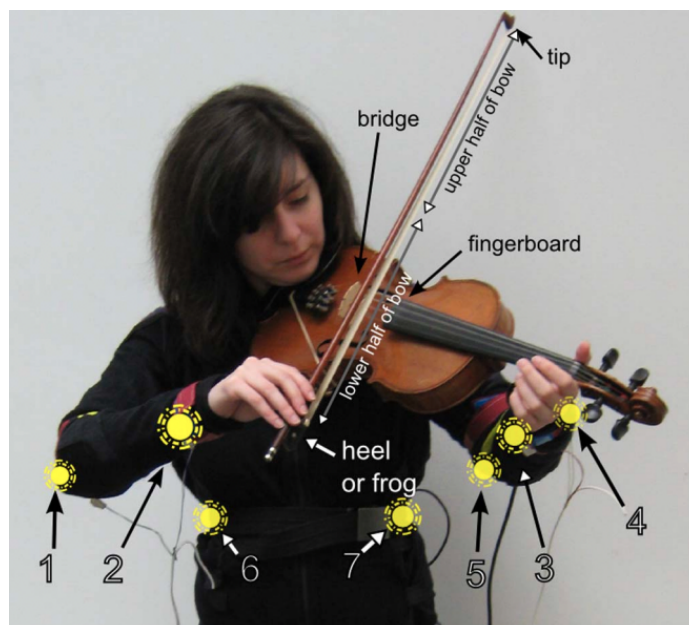


Figure 9: The MusicJacket, in use. The inertial measurement units (IMUs) contain three-axis accelerometers, gyroscopes and a magnetometer. After interpreting the information about the musician's limb movements captured by the IMUs, the different vibrotactile motors integrated in the velcro straps send signals to adjust their elbows, wrists, hands, and torso. Image extracted from Van der Linden et al. (2011).

Vibrotactile Composition Suit

Closer to the MHW category is the Vibrotactile composition suit (Fig. 10), elaborated by Gunther and O’Modhrain (2003). Applying the concept of “cutaneous choreography” developed by Eric Gunther in his Master thesis (2001), the authors composed tactile effects for a full body suit which incorporates thirteen vibrotactile transducers along the arms, torso, and legs. They designed their tactile effects with consciousness of the skin’s anatomy, basic psychophysical thresholds of the skin, its capacity to detect spatio-temporal patterns depending on site of stimulation, and the potential to elicit tactile illusions. However, the authors made the conscious choice to eliminate any chance of extra-tympanic sound perception while wearing the device, stating that “due to *skeletal leakage* of vibrations into the ear – resulting in undesirable sonic artifacts – no transducers were placed on or near the head” (p. 377). They had considered placing a transducer on the neck, but rejected it from the final design for this reason.



Figure 10: The Vibrotactile composition suit, a full-body audio-tactile wearable system designed by Gunther and O’Modhrain (2003) that integrates thirteen vibrotactile voice-coil motors. To create tactile effects perceived simultaneously with music, the authors approached the composition process from a multimodal standpoint: the tactile effects and auditory music were designed in parallel. The auditory effects were perceived via the attached headset, seen in the photo. Image extracted from Gunther and O’Modhrain (2003).

CollarBeat

Where the previous work consciously avoided the potential for hearing via extra-tympanic conduction, other authors have chosen to pursue it. Sakuragi et al. (2015) developed a neck-worn audio tactile device as part of a study on vibrotactile effects that enrich the music experience. This neck-worn device, the CollarBeat (Fig. 11) was built in order to test the clavicles as a means to present vibration to a widespread area of the body. Their objective was to reduce the number of vibrotactile motors needed to present vibration to a wide region on the body, in order to simplify the design of a tactile device for musical enhancement, in comparison to the bulky, confining nature of vests and chairs. The authors therefore chose to target the clavicles for their device design, because they judged that the conduction of the mechanical waves in the bones would allow the vibrations to travel farther in the body and create more widespread sensations with fewer integrated transducers. (The authors did not mention, however, any objective for the participants to hear the sound transmitted through their bones.)

Results collected from surveys indicated that participants judged the vibrotactile sensations that accompanied the music on the collarbone as being more comfortable, more desirable and more widespread in comparison to the head, the palm and the buttocks.



Figure 11: The CollarBeat (left: technical setup, right: in use). The authors designed and 3D-printed a neck-worn device with two voice-coil vibrotactile motors situated on the user's collarbones. The contact between the user's body and the device is ensured via 100g weights on both ends of the wearable device. Images extracted from Sakuragi et al. (2015).

Vibeat

Vibeat (Fig. 12), a wearable jewelry-like device, was designed by Liron Gino in 2016 (Tucker, 2016). She describes the device as an “alternative sensory system”, which can substitute the use of headphones for individuals who are hearing impaired or deaf. The device is composed of two Vibeat “units”, round pieces that can be clipped onto different types of jewelry, to contact either the chest or wrists. The user hooks up the system via Bluetooth to their personal device, and the vibrotactile motors within the Vibeat units translate the streamed track or film by vibrating in reaction to different frequencies and rhythms. Gino also designed the device for a mutual listening experience between a deaf and a hearing individual. There is a headphone jack integrated into the Vibeat units, so that several users can experience the same music either through touch alone, or through the ears.



Figure 12: Vibeat can be worn on several parts of the user’s body; the round units can clip onto jewelry-like cords of different lengths. Image retrieved from: <https://www.dezeen.com/2016/08/07/liron-gino-design-vibeat-listening-devices-wearable-hearing-impaired-tactile-music/>

4.2.1. Audio-Tactile Wearable Products

In the wearable category, many audio-tactile devices have been developed with the objective of industrial production. We will discuss three of these wearable devices, all of which are worn on the torso but each addressing the multimodal experience of sound in a slightly different way. They integrate different types of vibratory transducers, have different formal features, and target different types of populations and contexts of use.

SUBPAC

The SUBPAC is a wearable, vest-style device with adjustable straps (Fig. 13). It features vibrotactile transducers with a frequency response ranging from 1-200 Hz, therefore translating only the lowest frequencies from the user's connected device. Designed for use in studios, during performance, and at home, the product advertises three layers of immersion: haptics ("receptors on skin register vibrations on surface"), interoception ("receptors in muscle detect subtle change in force and pressure"), and bone conduction ("vibrations pulse through bones to the inner ear and are sensed as hearing"). The range of audible vibratory signals transmitted by the device through extra-tympanic conduction is limited, however, to the frequency response of the integrated transducers (20-200 Hz). By transmitting the deepest frequencies to the body, the device is essentially a silent replacement for the subwoofer, allowing music producers to mix music for the club without disturbing their neighbors, and allowing music enthusiasts to have an experience of deep bass without leaving their home.



Figure 13: SUBPAC, M2X version (Crofts, 2018). The wearable haptic device transmits bass vibrations to the user's back, in time with their auditory content. Along with music, it is also advertised for use in gaming, virtual reality, and home cinema experiences. SUBPAC was also imagined as an inclusive device for individuals with hearing impairments, so that they can have an immersive experience of sound via the sense of touch.

Image retrieved from: <https://www.soundonsound.com/reviews/subpac-m2x>

Soundshirt

The Soundshirt (Fig. 14), derived from the HugShirt, was designed by CuteCircuit as a wearable device for the deaf, so that they can have a tactile experience similar to the auditory experience of a philharmonic concert. Interacting with the wearable device through a mobile app or through a computer interface at concert venues, the user can experience sound in real-time through haptic sensations. The haptic sensations, transmitted by 30 haptic motors dispersed on the torso and arms (type unspecified by the designers), are spatialized “in real-time, into a tactile language that is unique to each piece of music being performed” (Cutecircuit, 2017).

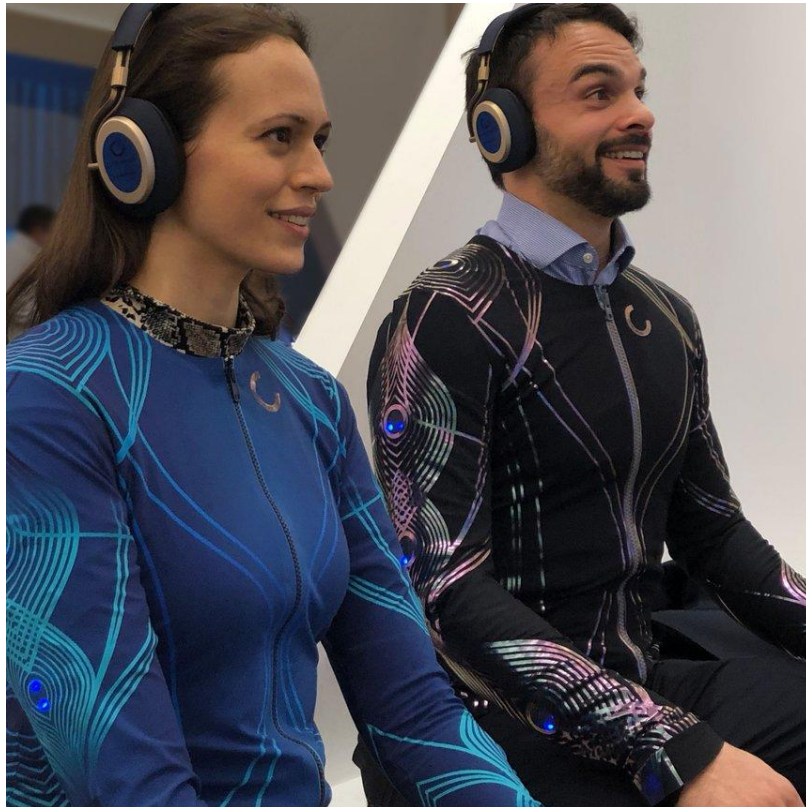


Figure 14: The Soundshirt was designed in the name of sensory accessibility, by translating the sounds of a philharmonic orchestra into locations of tactile sensations on the torso and arms.

Image retrieved from: <https://www.comptoirdessolutions.org/innovation/the-soundshirt/>

Woojer Strap

The Woojer Strap is a belt-type wearable device that can be worn around the hips or waist, or across the chest (Fig. 15) (“Strap 3 - Woojer”). It integrates one large vibrotactile transducer in the central unit (the Osci™ TRX2 patented transducer) with a frequency response of 1-250 Hz, and is available in a wide range of colors. The analog and digital inputs allow the user to connect to the device with their headphones and stream the audio from their music, games or movies in real time. The vibrotactile sensations are transformed according to the streamed audio.



Figure 15: The Woojer Strap Edge integrates one vibratory motor, encased in the central unit of the strap. Its form means it is adjustable to virtually all body sizes. It is portable and simple in design in comparison to other vest-style audio-tactile devices. Image retrieved from: <https://www.woojer.com/products/strap-3>

Though Woojer is a direct competitor to SUBPAC, the main differences between the Woojer Strap and the SUBPAC are related to their forms, the type of transducer, brand image and targeted clients. Where SUBPAC has principally targeted musicians, Woojer has principally targeted music enthusiasts and gamers.

4.3. Chairs for Audio-Tactile Experiences

The second principal category of audio-tactile devices is chair-type devices. The fixed nature of the chair has certain implications for the type of multimodal experience it can facilitate. A chair means that the user must be immobile during the audio-tactile experience, and limits the surface of vibratory stimulation to the back of their body.

EmotiChair

The Emoti-Chair, developed by Karam et al. (2010), was developed as an “interactive tactile music exhibit” in a research-based context (Fig. 16). The chair integrates a system called the model human cochlea, a “sensory substitution system” elaborated by Branje et al. (2010), which displays vibrations to the user’s back in different ranges of frequencies. Displayed on the back along two eight-row arrays of voice-coil motors, the vibrations increase in pitch from the bottom to the top of the user’s back, imitating the frequency organization found in the cochlea.



Figure 16: The EmotiChair is a vibrating chair that transmits vibrations along the user’s arms, back, and seat according to the frequencies of the auditory input. In the photo, it is in use by Ellen Hibbard, who is deaf. After using the EmotiChair, she said that she “never really thought about ‘bad’ and ‘good’ feelings with vibrations,” ... “This experience has helped [her] to understand why hearing people have strong feelings when they listen to music” (Black, 2008).

Image retrieved from:

https://www.thestar.com/life/health_wellness/2008/07/02/emotichair_delivers_good_vibrations_to_deaf.html

Haptic Chair

The Haptic Chair (Fig. 17), evaluated during a participative research study with 43 deaf and partially-deaf participants, was created in a research-based context by Nanayakkara et al. (2009). The chair's design is based on the evidence gathered from deaf musicians that suggested that "if vibrations caused by sound could be amplified and sensed through the body as they are in natural environmental conditions, this might increase the enjoyment of music over a mute visual presentation or simply increasing the volume of sound" (p. 343). Though the chair was designed primarily for a tactile experience of sound, the authors integrated voice-coil motors to the back of the chair with a wide frequency bandwidth, their argument being that the spectrum of hearing impairment is diverse, and many partially deaf individuals can still perceive some sounds via in-air conduction.

Another device similar to the Haptic Chair is the chair developed for the musical composition "Skin Music". Hayes (2015) composed a multisensory audio-tactile music piece, heard through loudspeakers adhered onto the chair, and felt on the user's body through voice-coil motors integrated on the back and bottom of the chair (Hayes, 2015). The Audiotactile chair, designed by Alessandro Perini, features eight individually-routed vibrotactile motors that transform the listening space from the room to the body of the listener (Perini, 2014).

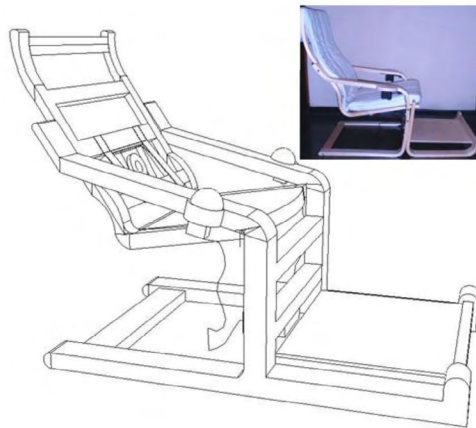


Figure 17: The Haptic Chair system has two components: the vibrating chair, and a computer display for visual effects that correspond in real-time to specific features in the music.

4.3.1. Audio-Tactile Chair Products

Aurasens

Designed by Olivier Zeller and Nicolas Leroy as a luxury well-being product, the Aurasens lounge chair (Fig. 18) integrates an array of 28 vibrotactile transducers along the user's back, arms and legs (Gervais, 2019). These transducers are connected to the Aurasens module, a patented vibrotactile design hardware and software system which spatializes the "Vibrotactile Haptic Compositions" (VHCs) to harmoniously accompany music and soundscapes. These VHC experiences were specially crafted by the designers as part of an evolving playlist of audio-tactile experiences, ranging from classical, jazz or zen styles. The user controls the listening program through an iPad, integrated onto the lounge along with a pair of headphones or speakers. The chair was produced as a limited edition series in France.



Figure 18: The Aurasens Voyager chair displays synchronized vibrotactile sensations (Vibrotactile Haptic Compositions, or VHCs) composed according to the different auditory tracks, displayed through the attached headset. The user selects their content using the integrated iPad (Halard, 2017).

Image retrieved from:

<https://www.on-mag.fr/index.php/topaudio/actualites-news/17214-aurasens-voyager-un-fauteu-il-pour-marier-massage-et-musique>

SUBPAC S2 (and X1)

The SUBPAC S2 has all of the same features as the SUBPAC M2X (see section 4.1.1), but is designed to be attached onto the back of a chair with a 3-point removable strapping system (“SUBPAC S2”). Soon to be released is the SUBPAC X1 (Fig. 19), which can be both worn on the user’s back or attached to their chair. The product is advertised for use with music, games, moves and VR, all without any external noise.



Figure 19: The SUBPAC X1 has a dual functionality: it can be worn on the user’s back (like past models M2 and M2X), or attached onto their chair (like the S2).

Image retrieved from: <https://subpac.com/subpac-s2/>.

4.4. Art Installations for Audio-Tactile Experiences

Audio-tactile art installations have been developed by scientists and artists alike to demonstrate the expressive power of vibrations. The installations detailed in this section invite the user to explore their own physical presence in the exhibit space, to question the experience of music regardless of hearing ability, or to surrender to the tactile sensations of a concert orchestrated for their body. Two of these installations were displayed as long-term exhibits at European museums. The contact-based nature of vibrotactile perception makes the connection between audience and installation (and by association, artist) that much more intimate.

Sound Forest

The Sound Forest (Fig. 20) was exhibited at the Swedish Museum of Performing Arts, as a part of a participative design-research study conducted by Frid and Lindetorp (2020). The Sound Forest, a long-term installation, is a musical room composed of light-emitting interactive strings stretching from the floor to the ceiling, vibrating platforms, and speakers. The authors created haptic compositions for the vibrating platforms, which the audience perceived by means of whole-body vibration: a process that occurs “when a human is supported by a surface that is shaking and the vibration affects body parts that are remote from the site of exposure” (Mansfield, 2004). The authors worked with the musical material while composing for the haptic sense, ensuring that there was no sensation of dissonance between the auditory and tactile modalities.



Figure 20: Photographs of the Sound Forest, extracted from Frid and Lindetorp (2020). Visitors interacted with the light-emitting interactive strings while perceiving the musical and haptic compositions through whole-body vibration, the emitting source being vibratory platforms under their feet.

Tactile Chairs

A year-long exhibit at the Museum of Art and History in Geneva, any visitor could test the Tactile Chairs developed by Jeremy Marozeau and three MSc students from Denmark Technical University (Fig. 21). The two Tactile Chairs represent the evolution of a project called Augmented Music (Sierra et al., 2021). In the first chair prototype, the device transmits low and middle vibratory frequencies to different areas of the user's body. In the second chair prototype, the vibrations are not transmitted via the base of the chair, but instead via wooden rods that are installed along the sides of the chair, inspired by the structure of the inner ear's basilar membrane (Marozeau, 2022).



Figure 21: Tactile Chairs as displayed at the Geneva Museum of Art and History. The first chair prototype is on the right, the second prototype on the left. The chairs were developed with the objective to provide hearing-impaired users with a chance to experience live music.

Image retrieved from:

<https://www.dtu.dk/english/news/all-news/music-can-be-experienced-despite-poor-hearing?id=ead0aef6-2536-4a4d-91c6-1b0fa921673a>

STiMULiNE

Lynn Pook has explored the relationship between sound and touch through her artistic works since 2003 (Pook, n.d.). One of her works, titled “Stimuline”, served as an important inspiration to this research in its earliest stages. Stimuline, developed in 2008, is an audio-tactile concert, where several audience members are equipped with wearable devices that integrate 15 voice-coil motors on the surface of the arms and torso (Fig. 22). During the live concert, the artists wore the same devices as the visitors, transmitting the vibrations via the senses of touch and hearing “*so that the vibrations travel over the skin while the sound is transmitted to the sense of hearing by bone conduction. The two musicians are also equipped with interfaces that are similar in every way to those of the audience: listeners and musicians are thus connected by a cable to the same sound matrix*” (Clauss & Pook, 2003).

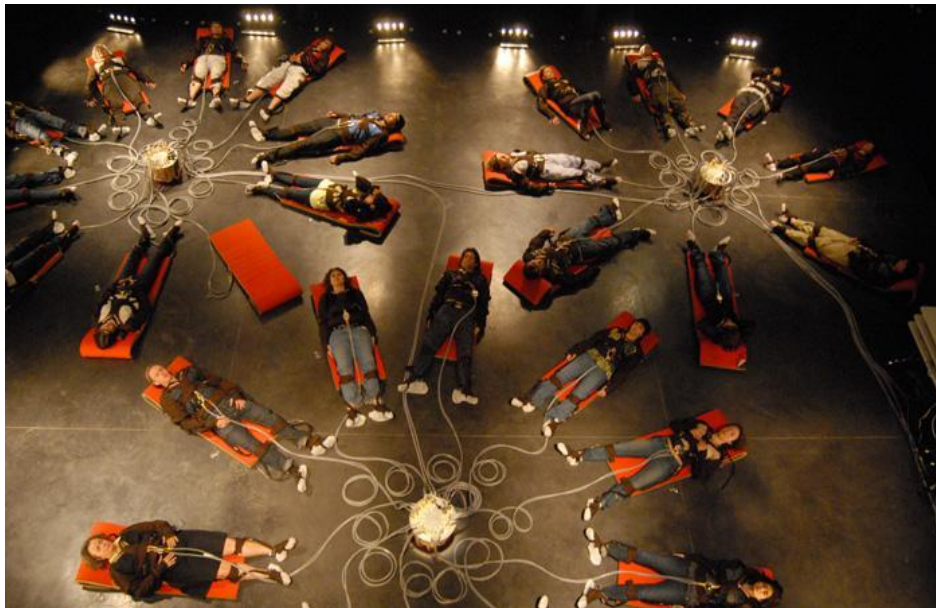


Figure 22: The Stimuline concert is both a personal and connected group experience: the audience members are isolated in their sensory suits, while all experiencing the same vibrotactile concert at the same time. The artists (Julien Clauss and Lynn Pook) used the whole body as a surface for musical perception, integrating the senses of hearing and touch through bone conduction and tactile stimulation of the skin.

Image retrieved from: <http://www.lynnpook.net/fr/projekte/stimuline/index.htm>

5. Methods for Audio-Tactile Effect Design

The skin surface is a vast canvas; its ability to sense and differentiate between vibratory stimuli presents endless possibilities for vibrotactile effect design. In section 1, we reviewed the main aspects of auditory perception and vibrotactile sensation in the skin: principal factors for audio-tactile effect design. In section 4, we reviewed aspects of hardware and device design, connecting these factors to the user's experience. Here, we explore some methods that designers and researchers have developed for creating audio-tactile sensations for integrative experiences.

Vibrotactile effects alone have been implemented via haptic feedback devices for numerous human-machine interfaces, ranging from virtual reality to navigation, rehabilitation and awareness systems (Lindeman et al., 2004; Lieberman & Breazeal, 2007; Choi & Kuchenbecker, 2012). To narrow down the focus of this section to the scope of our research, we limit this review to vibrotactile effect and interface design that incorporates auditory feedback (and vice versa), with a focus on musical applications. In some contexts, the effects may excite only the tactile modality, for example as part of an inclusive experience for individuals with hearing impairments.

5.1. Spatialisation of Effects on the Body

The vibrotactile feedback designed for the body:suit:score was based on sound to tactile translation, where the wearable device becomes a “sensory replacement” for any acoustic musical feedback (West et al., 2019). Navigating the limitations of ERM motors, the authors chose to implement a dense array of motors, and map the vibrotactile signals according to musical pitch. They mapped the pitch onto the body in terms of “pitch class”, where all notes separated by an octave were mapped to a single motor. Gunther and O’Modhrain defined this method as “frequency-to-place transformation, in which the location of stimulation on the skin corresponds to a given acoustic frequency region” (Gunther & O’Modhrain 2003, p. 260, referencing Reed et al., 1992).

The EmotiChair also features a frequency-to-place relationship, although it implements the metaphor in a slightly different way. Instead of mapping different auditory frequencies to positions of vibrotactile stimulation, the authors filtered the vibratory stimuli so that they transmit different frequencies at different positions of the user’s back (Baijal et al., 2012). Using the Model Human Cochlea system, the authors mapped frequencies in a vertical array of 16 voice-coil motors, from 25 to 1000 Hz in ascending order starting at the lower back. Haynes et al. (2021) also explored the notion of mapping vibratory sensations on the body in combination with auditory musical stimuli, in order to elicit emotional responses and enrich the musical experience.

5.2. Tactile Sensation of Auditory Timbre

Russo et al. (2012) demonstrated in a discrimination experiment that it is possible to differentiate between different musical timbres through the tactile sense alone, correctly identifying which stimuli were generated by “dull”- or “bright”-sounding instruments. Saal et al. (2016) observed similar mechanisms between touch and hearing in the processing of temporal patterns, suggesting that the auditory perception

of timbre and the tactile perception of texture may involve similar processing mechanisms.

Jack et al. (2015) incorporated timbre into their vibrotactile effect design protocol by using a noisiness measure to drive the vibratory output signal, which then interpreted that measure while interpolating between a 500 Hz sine tone and white noise. They drew inspiration from Rován and Hayward (2000) who simplified the quality of timbre in terms of “rough” and “smooth”, or the corresponding transition between complex and pure waveforms.

5.3. Filtering Techniques

Remache-Vinueza et al. (2021) described some methods for audio-tactile rendering, or the signals produced by vibrotactile music players in order to enrich the musical experience. In their extensive review, the authors discussed the use of filtering techniques for the tactile rendering of auditory rhythm, pitch, and melody.

In tactile enhancement of music, filters have proven useful for rendering rhythm because the instruments that provide rhythm are usually limited to a specific frequency bandwidth (drums, bass guitar, etc). Designers therefore have frequently used low-pass (high-shelf) filters to extract only the lowest frequencies for rhythm conversion.

Concerning pitch, the authors describe the use of frequency-band filters to route specific ranges of frequency to specific transducers on the audio-tactile device. However, the frequencies that can be detected and discriminated in the tactile range are not equivalent to those in the auditory range (see section 1.1.2). For use cases involving bone conduction, however, a wider range of frequencies can be transmitted via vibratory stimulation of the body (Richards et al., 2021) and of the skull (Robinson & Shipton, 1982). Similarly to pitch, auditory melody can also be converted to its tactile counterpart, but it is difficult to reach a satisfactory equivalence between the two modalities due to potential dissonance between auditory and filtered vibratory stimuli (Fontana et al., 2016), and the lack of awareness of pitch of hearing-impaired or deaf users.

5.4. Workflows and Interfaces for Audio-Tactile Effect Design

Gunther (2001) used the principle of frequency-to-place transformation when developing the “Skinscape” tool, the interface used to create the spatio-temporally distributed effects for the vibrotactile composition suit (Gunther & O’Modhrain, 2003). He explains that, while most people have had experiences with music throughout their lives, it is less common to have had experiences with vibrotactile effects. He expressed the belief that, in order to incorporate tactile composition as a domain of musical study, it should first be paired with auditory music in order to familiarize the naïve observer to more complex and structured tactile sensations on the skin.

There has been considerable progress concerning the development of tools dedicated to combined audio-tactile effect design, but as of today, there is no ubiquitous, “go-to” interface. Weber and Saitis (2020) highlight the current lack of standardized vibrotactile design methods and quality metrics. They suggest that sound design methods can serve as a blueprint for the introduction of vibrotactile design

frameworks. Describing the requirements for a “vibrotactile pipeline”, the authors illustrated a flowchart (Fig. 23) describing the process that a designer uses to create vibrotactile effects from existing audio assets. This approach maps an audio asset to its closest equivalent vibrotactile effect: a technique based on the approximate reproduction of an auditory signal in the vibrotactile modality. While this approach technically fits into the “audio-tactile” effect design category when applied in contexts involving both auditory and tactile sensations, it can also be used to curate tactile-only sensations.

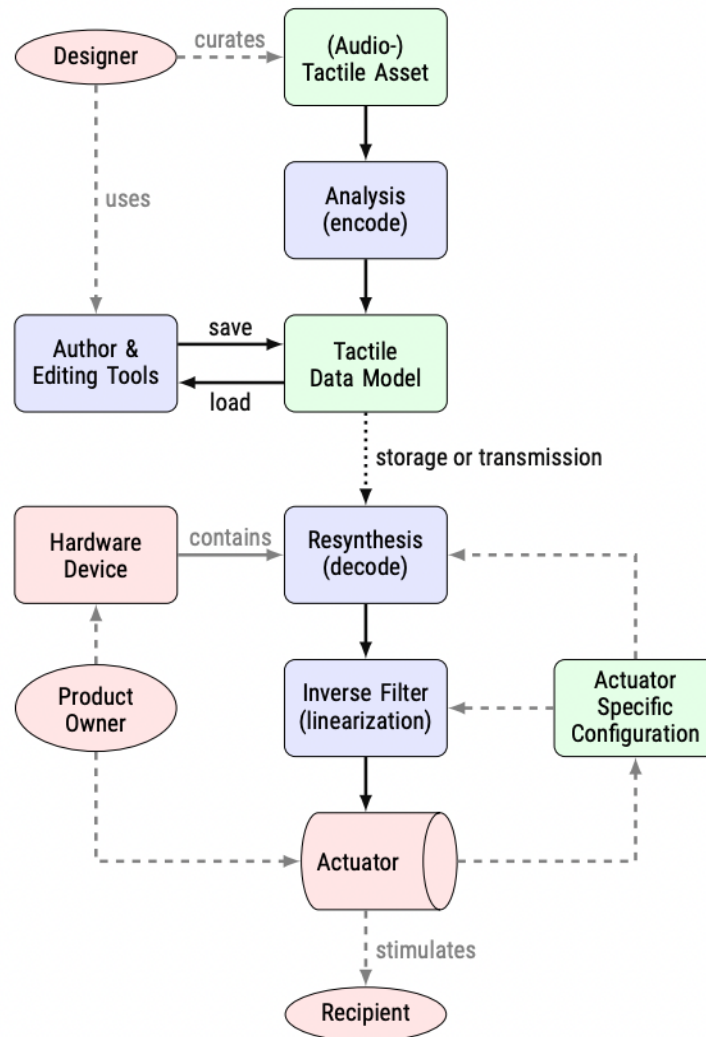


Figure 23: Weber and Saitis (2020) describe their workflow for designing vibrotactile effects based on auditory assets: “Subjects involved in the process are highlighted in the red ovals. Blue rectangles illustrate a process in the information flow. Green rectangles illustrate data files (i.e. information). The actuator hardware is illustrated as a cylinder” (p. 6).

Rovan and Hayward (2000) describe their process for creating “tactile stimulation events (TSE)”, which would be felt on the hand and foot, in relation to a user’s gestural movements. To design the TSEs, the authors created their own application in the MAX/MSP³ environment: the VR/TX Tactile Sound Generator. Researching

³ <https://cycling74.com/products/max>

different modalities of “tactile sound”, the authors used an open-air music controller to explore the different ways that audio could be used to create vibrotactile stimuli. They first defined the tactile stimulus parameters: frequency, waveform, envelope, duration, delay between repetitions, amplitude, and number of repetitions. They demonstrated a particular relevance between auditory timbre and tactile texture, finding that the transition between a pure sine tone to noise was perceived in the tactile modality as a “continuous transition from smoothness to roughness” (p. 12).

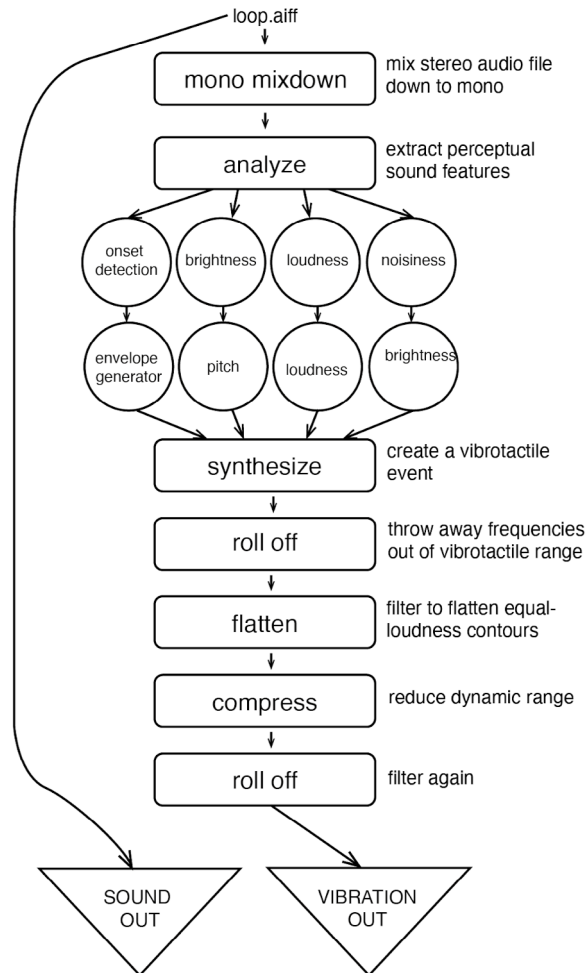


Figure 24: Birnbaum and Wanderley (2007) illustrated an abstract model of the application they designed in Max/MSP for audio-tactile effect design (here adapted for image quality).

Describing their approach to designing musical vibrotactile feedback, Birnbaum and Wanderley (2007) illustrated their MAX/MSP application which they designed to extract musical information from an audio signal and use it to map the parameters of a vibrotactile effect, similarly to the process described by Weber and Saitis (2020) and Rován and Hayward (2000). Birnbaum and Wanderley (2007), however, described slightly different vibrotactile signal parameters (Fig. 24). In the illustration of their MAX/MSP application, they also show the accompanying auditory signal at the bottom of the diagram, implying that this method is not only to extract tactile-relevant information from an auditory signal, but also to display it alongside its original

auditory counterpart. The authors also explain a filtering method used in their approach: “the spectral centroid is scaled with the lowest frequency mapped to a 40Hz vibrotactile pitch and the highest frequency mapped to 400Hz, so that the different drums in the breakbeat are represented by relative vibrotactile pitch aimed at the [Pacini] channel” (p. 6).

Karam et al. (2009) also used MAX/MSP to develop an approach for musical vibrotactile effect design while reducing the effects of masking. The authors wanted to maximize the range of vibrotactile effects for users who are hard-of-hearing or deaf, which implies more structural complexity to manage while designing those effects. The Model Human Cochlea (MHC) addresses auditory-tactile masking, which can prevent full appreciation of the diversity of audio-tactile effects due to a large range of vibrotactile stimuli occurring in parallel. They use the MHC to create “vibetracks”: sets of auditory signals which are sensed as vibrations after being routed to different vibrotactile channels on the device according to frequency range and amplitude.

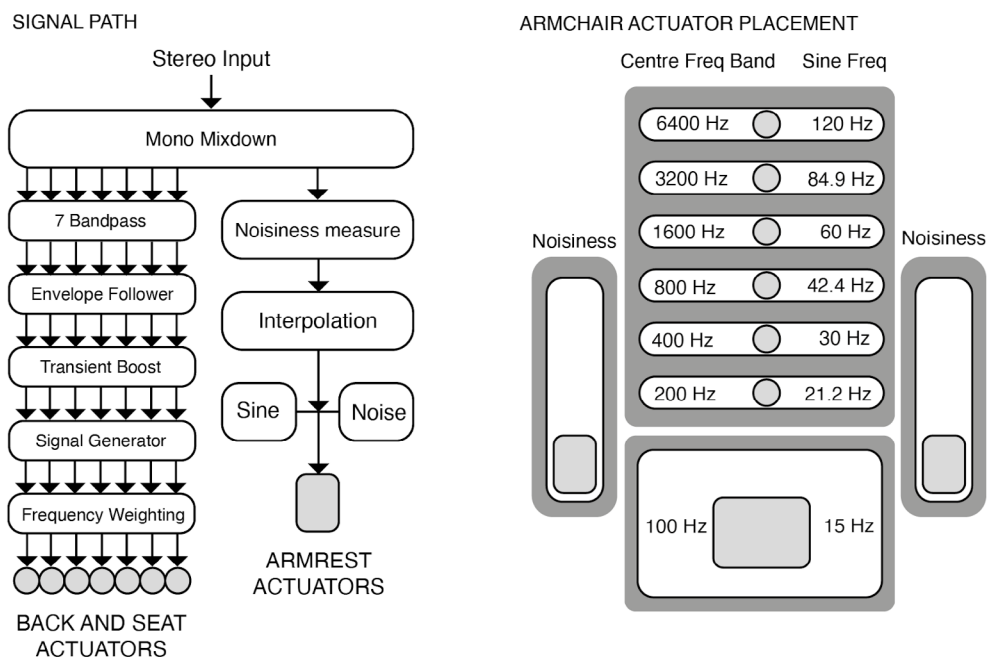


Figure 25: Illustration from Jack et al. (2015), adapted for image quality, showing a graphic representation of the signal path (audio-to-tactile mapping model) and vibrotactile effect display in the audio-tactile chair.

Explaining their audio-tactile effect design methods, Jack et al. (2015) reference the signal substitution method of Merchel et al. (2014), used for the design of whole-body vibrations displayed by a vibrotactile chair. They begin with an auditory musical signal (stereo), which they pass through a set of filters (7 bandpass filters) in order to route each band of frequencies to a specific zone on the chair (Fig. 25). They used a frequency-weighting method to tailor the auditory signal to the tactile modality, essentially converting high-frequency tones to low-frequency vibrations, at differentiable distances (half octave distances from 15 Hz to 120 Hz). Comparing their reasoning to the Fletcher-Munson equal-loudness contours, the authors also

equalized the vibrotactile signals according to the tactile modality's variation in sensitivity across frequencies, citing the FA/SA ("fast afferent, flow afferent") system developed by Birnbaum (2007).

Gunther and O'Modhain (2003) used the Protools Digi 001 interface to route audio tracks to specific transducers on their wearable device. While the interface was useful in that it allowed them to work with both auditory and vibrotactile effects at once, they said that using it to compose was "painstaking", and that "before the full potential of the tactile medium can be realized, better compositional tools must be designed" (p. 378). Choreographed along with the auditory experience of music that was perceived through headphones, the authors designed tactile compositions which were demonstrated in an hour-long concert. The authors describe two of the multimodal soundscape pieces composed for the device:

Two of the pieces in the concert were soundscapes. To build suspense, the first piece opened with a minute of just audio, including a robotic voice lecturing on the anatomy of touch. It then imitated the sound and feel of a heartbeat and the flow of blood down the limbs. On the tactile side, this was accomplished by a low-frequency sinusoidal burst on the back, shortly followed by a rapid wave of saltatory taps from the torso outward on all four limbs simultaneously. The other soundscape began with a purely tactile introduction (no music), with white noise played to mask sonic leakage from the transducers, and transitioned into a three minute simulated thunderstorm. Random taps were presented to the shoulders, forearms, wrists, and thighs, their intensity and temporal density corresponding to perspective shifts in the audio recording of the rainstorm (p. 378).

Concluding their article, Gunther and O'Modhain excitedly explained that, despite the need for tactile-specific conceptual interfaces and ergonomic device improvements, they saw strong aesthetic potential for these tactile sensations spatialized on the surface of the body. Delicately dancing across the user's skin and probing their emotions much like music, the authors believed and hoped that these types of tactile sensations could exist apart from auditory music as an inclusive artistic medium. Digital audio workstations like Ableton Live⁴, Adobe Audition⁵, or Apple Logic Pro⁶ demonstrate a clear preference for working in the auditory modality, and limits the ease of their use in mixed audio-tactile design contexts. As we can observe in the above examples of audio-tactile interfaces, researchers and designers often resort to using existing auditory effect libraries, transforming audio signals they see fit - however awkward that process may be. They also frequently use MAX/MSP, a visual programming language for musical and multimedia projects. The creative liberty afforded by MAX/MSP has proven useful in our own work (see Richards et al., 2022), but the need to program tailored applications for any given audio-tactile project is both costly and time-consuming in terms of development needs. In Chapter V, we will detail how we have addressed the persisting lack of standardized audio-tactile interfaces for combined auditory and vibrotactile effect design.

⁴ <https://www.ableton.com/en/live/>

⁵ <https://www.adobe.com/products/audition.html>

⁶ <https://www.apple.com/logic-pro/>

6. Conclusion

In this State-of-the-art, we traced the border around our research by first explaining some of the anatomical and psychophysical aspects of both auditory and tactile perception of vibrations. We related the two senses to each other, in order to highlight one principal focus of this thesis: multimodality. We then detailed each modality separately, explaining the function of the different parts of each sensory system (mechanoreceptors, the inner ear). Our research deals with the perception of vibration via extra-tympanic (aka bone) conduction and vibrotactile stimulation of the skin surface on the torso. Therefore, it was also important to address how vibratory waves propagate on the surface of the body, and how the tonotopically-organized basilar membrane of the inner ear may also be stimulated by vibratory waves conducted within the body through bones, soft tissue, and fluid matter.

We then examined the notions of multimodal perception, focusing on how our different sensory modalities interact. We distinguished multisensory interplay from multisensory integration: interplay is a broader term referring to influences across the senses, and integration refers to the perception of a unified percept. Crossmodal interactions, occurring between two senses, may either relate to the enhancement of one stimulus by another stimulus excited by another modality, to the convergence across modalities, or to the more semantic associations we make between our senses. We discussed the plasticity of the brain, and its ability to reorganize itself throughout life depending on sensory input.

Following the perceptual review, we discussed design research methods which have contributed to our reflection and structured our working processes. We addressed some of the different ways to talk about the relationship between design and research (*into, through, for*) in order to highlight the diversity of this discipline and its inherent lack of standardization. Today, the practice of design, and especially design research, goes beyond the aesthetic, and beyond a results-oriented industrial process. Design research can involve the meaningful formulation of a project's narrative according to its stakeholders and objectives. It can serve a communicative purpose, pushing the observer to re-consider the impact of technology on society.

In our review of audio-tactile devices, we provided examples of research projects and industrial products that feature a mixed audio-tactile or tactile experience of sound. Equipped with varying types of vibrotactile transducers, we surveyed some audio-tactile devices in the form of wearables (vests, neck-worn), chairs, and artistic installations. These devices served as inspiration to explore our ideas for audio-tactile perception. However, in the next chapters of the thesis, we will clearly distinguish our own device from those already developed.

Finally, we discussed some existing methods for audio-tactile effect design. Researchers have developed several methods for the conversion of auditory input into tactile effects. For example, the 'frequency-to-place transformation' method assigns auditory signals within a certain range of frequency to a specific position on the audio-tactile device. Filtering techniques are also frequently used, in order to extract only the frequencies which are relevant in the tactile domain, from the auditory signal input. In our review, MAX/MSP is the most-cited interface for audio-tactile effect design. Later in the thesis (Chapter V), we will explore how we have created our own applications for effect design, with the specific objective of simultaneous single-source audio-tactile vibratory perception.



Chapter II: Designing Audio-Tactile Devices: Purpose, Process and Outputs

1. Introduction

In this chapter, we will present two of the audio-tactile devices designed during the doctoral research: the monopoint module and the multimodal harness. We present each of the devices in terms of their purpose, their process, and their outputs: an organizational project framework defined for the content of this thesis (see Fig. 26).

We will describe first the influences, assumptions, and objectives behind the defining *purpose* of each audio-tactile device. Then, we address the *process* of building each device itself: the steps of development that integrated different collaborators, design methods and standard scientific practices. Finally, we will describe what we gained by building each device, and how these *outputs* each contributed their own, unique response to the following main research question:

What design and research methods will allow us to create and reflect on an alternative experience of sound, which involves the whole body? To do so, what tools do we need to probe the body's capacity to perceive (and appreciate) vibrations via the modalities of hearing and touch?

While traditional scientific research is more often concerned with the quality and interpretation of an investigation's results, design research is oriented towards probing the process of the research itself: the course of events and the reasoning behind the decisions that shaped the investigation (Kroes, 2002). The current thesis' approach was first structured based on clear purposes for each audio-tactile device. It evaluates both the process and products of investigation allowed by these devices, and articulates the many ways in which these two sides interact.

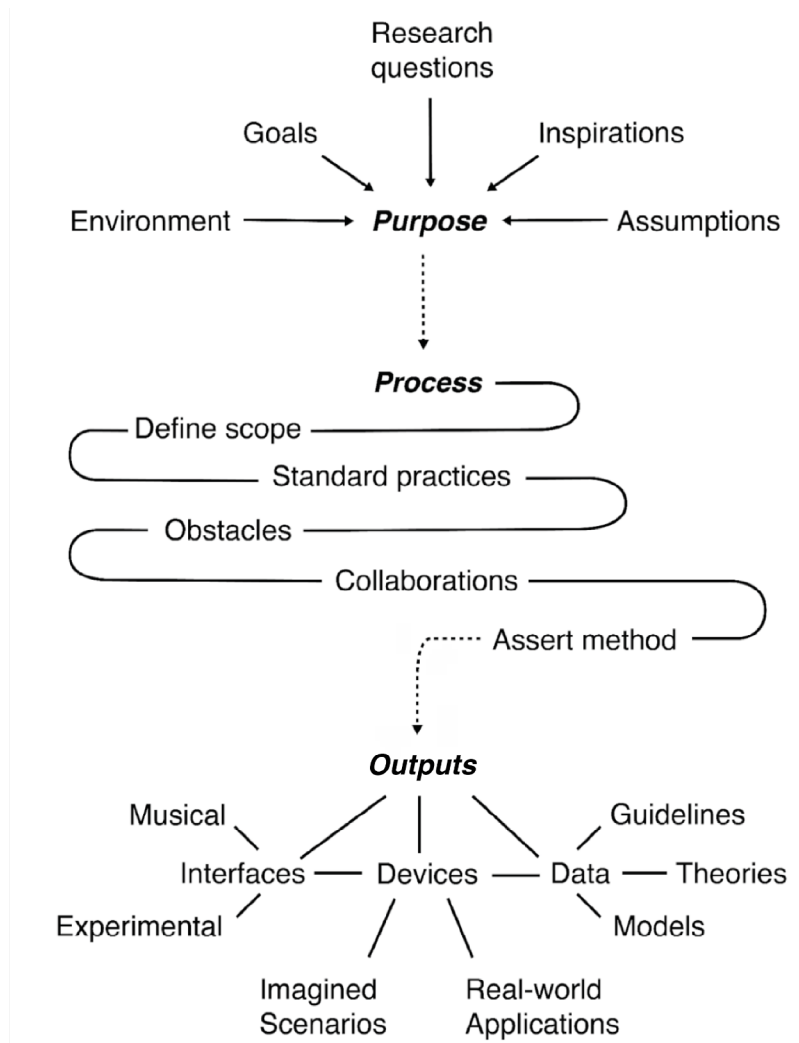


Figure 26: Illustration of the relationship between the three terms that structure this chapter: purpose, process and outputs. Together, they expose how each audio-tactile device responds to our main research question. The associated words (inspirations, assumptions...; methodology, collaborations...; interfaces, data...) describe the contributing factors that will be described in the context of each audio-tactile device.

We began the development of each audio-tactile device based on an idea about how to respond to a research question. This idea, part intuition and part informed decision, became the guiding *purpose* of the device. Describing the purpose of each device reveals the various influences behind its design criteria: the specific objectives that defined the device’s concrete features. By describing the purpose, we better understand our assumptions, inspirations, and our goals for the device, and how they were influenced by the environment in which it was conceived.

Equipped with the purpose for each device, we began taking steps to create it. In this chapter, the *process* describes the technical methods behind the device development and the obstacles that those methods helped us to overcome. While describing its process of development, we detail the device itself. Each feature of the device represents a specific choice that we made in order to respond to its design criteria. While describing the process of development, we will also describe how our

project partners contributed along the way, drawing attention to the interdisciplinary and collaborative nature of this research.

The *outputs* of the audio-tactile device design extend beyond the devices themselves. Creating each device led to tangential outcomes such as experimental methods and data, scenarios of use, sensory effects, and a concept for a commercial product. These outputs serve as tangible anchors; they provide evidence to consider potential applications of this research and help to imagine possible futures for research and development in audio-tactile device design. Regarding the outputs of the audio-tactile devices, in this chapter, we will present only those which resulted from the development of the first audio-tactile device: the monopoint module. In the following chapters, we will go into detail about the outputs that resulted from the second audio-tactile device developed during the thesis: the multimodal harness.

By elaborating the terms “purpose, process, and outputs”, we emphasize all of the steps along the way that led to the concrete results of our research, and broaden the analysis of the audio-tactile devices themselves. This thesis deals with more than the display and interpretation of end results: outcomes that can be measured in devices, interfaces, or experimental data. It also deals with why and how we created these devices. In this way, we consider all aspects surrounding the outputs of our research: the questions we pose, why we ask them and how we try to answer them.

2. Monopoint Module

2.1. Purpose

In this section, we focus on the monopoint module. The purpose of the device was to build a foundation of knowledge about audio-tactile vibratory perception on the torso, which would then help to structure the next steps of the project. Our main research question was: How do three main parameters of the vibratory stimulation signal (position on the body, frequency and amplitude) relate to the listener's thresholds of auditory perception via extra-tympanic conduction?

We aimed to establish our hypothesis that it is possible to excite the inner ear by stimulating the ventral and dorsal torso with vibrations. More precisely, we were interested in the possibility of hearing vibratory signals via extra-tympanic conduction that are presented at the spine, clavicles, and sternum: zones of the body where underlying musculoskeletal structures are relatively close to the surface of the skin. The surfaces of these parts of the body could act as entrances to pathways that mechanical waves could take to reach the upper spine, skull, and finally the inner ear. The other dimension of this hypothesis was our expectation that, based on the existing evidence of audio-tactile crossmodal enhancement and multimodal integration, the vibrotactile sensations of the vibratory signals would affect the participants' auditory perception.

To guide and inform the next phases of our research about audio-tactile device design and sensory effect design, we needed a relevant source of knowledge about the body's sensitivity to audio-tactile signals at the targeted positions of vibratory stimulation. In our hypothesis, we assumed that there would be differences in auditory sensitivity at each of the different targeted positions of stimulation. By quantifying these differences, we hoped to produce some keys about how audio-tactile effects could be calibrated for the modality-dependent variations in sensitivity at different zones of the torso. We can break our main hypothesis down into **two main questions** about vibratory signal perception on the torso:

1. To what point can one hear via extra-tympanic conduction on the torso, and how do signal parameters like frequency, amplitude, and location (distance from the inner ear) modify the auditory perception?
2. Since the actuator is in direct contact with the body in order to display the vibratory signals, does the resulting tactile sensation affect the receiver's auditory perception of the signal?

Psychophysics is the study of the relationship between a sensation (the "psychological" aspect of a sensory experience) and the stimuli that produced it (the "physical" aspect) (Jones & Tan, 2012). By obtaining quantitative data about sound perception via extra-tympanic conduction, we could relate our choices during future wearable device design processes, as well as contribute to more general knowledge about the perception of vibratory signals for the interested scientific community. The integration of psychophysical methods in this foundational phase of the project was essential in order to relate our choices in future design processes to concrete experimental data.



2.2. Process

Our first task was to design and develop the device that would display the vibratory signals on each targeted position of stimulation on the torso. A single stimulating module with one voice-coil actuator would allow us to proceed position-by-position, testing the perceptual limits at each one of the zones of the body we hypothesized to target with the future wearable device. The monopoint module was therefore the first of the audio-tactile devices designed during the doctoral research, with the goal to probe the receiver's ability to perceive vibrations via extra-tympanic conduction.

The design of the monopoint module was a collaborative effort. The first concept drawing for the monopoint module was suggested by Vincent Hayward, Chief Scientific Advisor of haptics research at Actronika. Emmanuel Flety of IRCAM's Engineering and Prototyping center⁷ helped print initial prototypes of the module, and created the electronic system used to communicate with each module component and collect the digitized experimental data. Sylvain Gaultier, embedded systems engineer at Actronika, developed the computer interface that generated the vibratory signals, processed the sensor data, recorded participants' responses and generated the data files for interpretation of the experimental results.

2.2.1. Design Criteria

We created the monopoint module with two main purposes in mind: transmit the vibratory signals at nine points along the spine, clavicles, and sternum, and maintain constant pressure against the user's body in order to allow an easily-conducted experimental protocol. These purposes translate into four main design criteria that guided its process of development.

1. Reliable pressure readings.

The module design integrates a force-sensing resistor (FSR) attached to the bottom of the device, contacting the user's body and ensuring an accurate reading of the static pressure created by this contact. A rigid surface between the module and the pressure sensor will ensure appropriate contact between the two elements.

2. Consistent contact.

Once fixed to the skin, the actuator cannot become detached during the testing process. This would cause unreliable results.

3. Minimal friction.

Any friction between internal module components will affect the quality of the signal perceived by the participant. All components must be fixed in place, with no risk of movement.

4. Protection of wires.

The wires should have not experience any friction against the plastic capsule or the participant's body.

⁷ PIP - Pôle Ingénierie et prototypage

2.2.2. Final Device Design

This section develops the choices we made for the final design of the monopoint module and its accompanying electronic interface. Table 3 describes how its features address the four design criteria. In this section, we elaborate the ergonomic aspects of the device (size, orientation), and its technical elements: the actuator, the sensors, the electronic board, and the signal transmission chain that connects each of these components to the digital experimental interface.

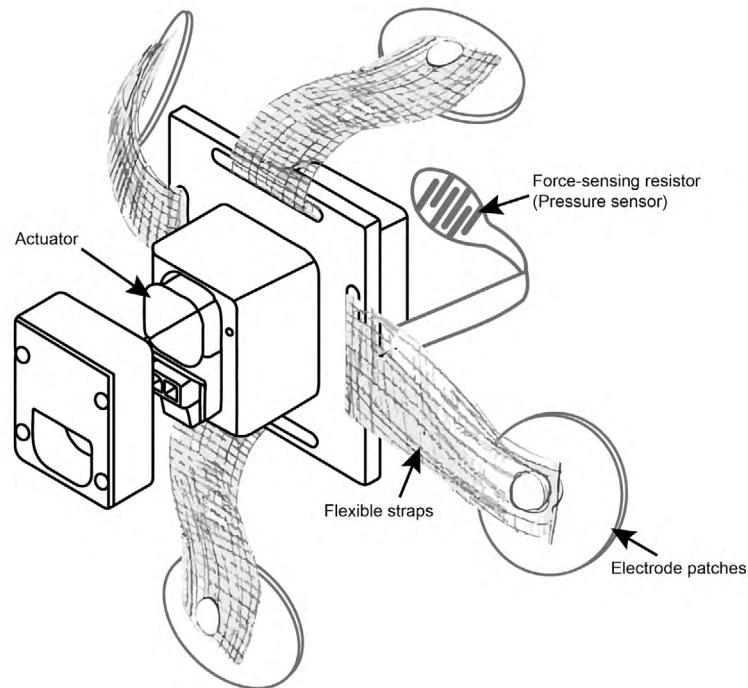


Figure 27: Illustration of the final version of the monopoint module. The actuator is inserted into a tight-fitting hole in the center of the module. The force sensor (here depicted detached from the module for visibility) is fixed on the bottom of the module. Electrode patches are attached onto four straps connected to the module.

	Design Criteria		Monopoint module feature
1	Reliable pressure measurement	✓	Force sensor allows calibrated pressure, gives static pressure reading
2	Consistent contact against skin	✓	Four adhesive electrode patches maintain device-skin contact
3	Minimized friction between elements	✓	Tight-fitting insertion slot for the actuator
4	Minimized risk for wire damage	✓	Cap secures and protects wires

Table 3: Design criteria of the monopoint module.

Responding to **design criterion 1**, the FSR ensures an accurate reading of the static pressure that the module creates against the user's skin, necessary for extra-tympanic conduction in order to reduce the attenuation of the vibratory signals caused by improper contact with the skin (Fig. 27). The stimulating module adhered to the body via four hydrogel patches, clipped onto straps that fit into each of the four side slots and allow the module to be pulled against the body in order to create consistent contact and sufficient pressure between the device and the user, responding to **design criterion 2** (Fig. 27). Responding to **design criterion 3**, the module was designed with a tight-fitting insertion slot for the actuator so that a negligible amount of energy was lost to friction. To respond to **design criterion 4**, a cap was secured on top of the actuator, protecting the ends of all wires and their soldered connection to the circuit board.

Ergonomic Aspects

Orienting the module orthogonally would theoretically improve the signals' penetration into the musculoskeletal structures and therefore the participants' auditory perception of the vibratory signals (Fig. 28). We also made this assumption based on basic principles of mechanical coupling: connections between two elements that allow one's motion to drive the other.

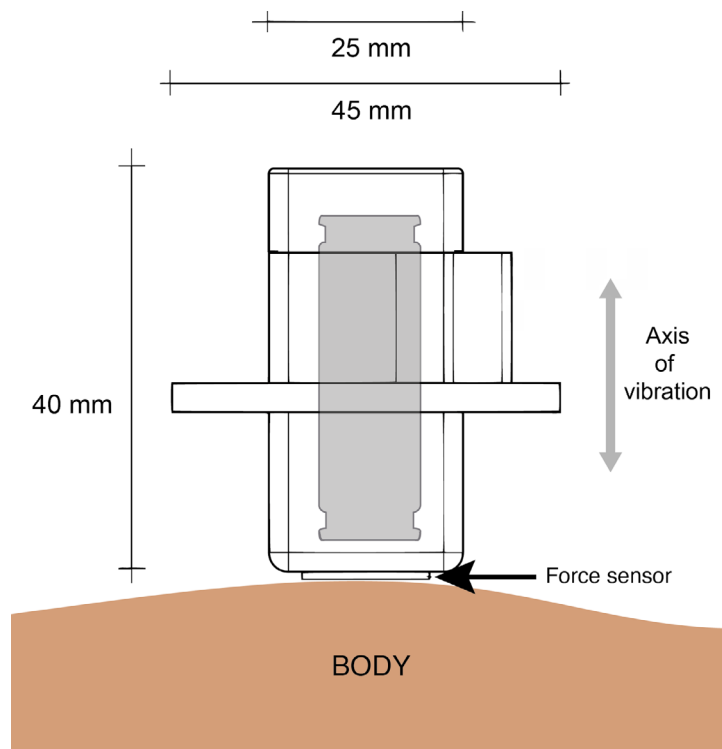


Figure 28: Technical drawing of the final version of the monopoint module. The actuator's axis of vibration runs lengthwise, as shown in the figure. We assumed that by orienting the actuator orthogonally with regards to the body's surface, the mechanical waves would propagate inwards towards the body, instead of alongside its surface as with a parallel orientation. The force sensor (FSR) is located at the bottom of the module, in contact with the skin.

Electronic Integration and Interface Development

Each functional component of the module (actuator, FSR) was wired to an electronic interface, whose signal transmission chain is described below.

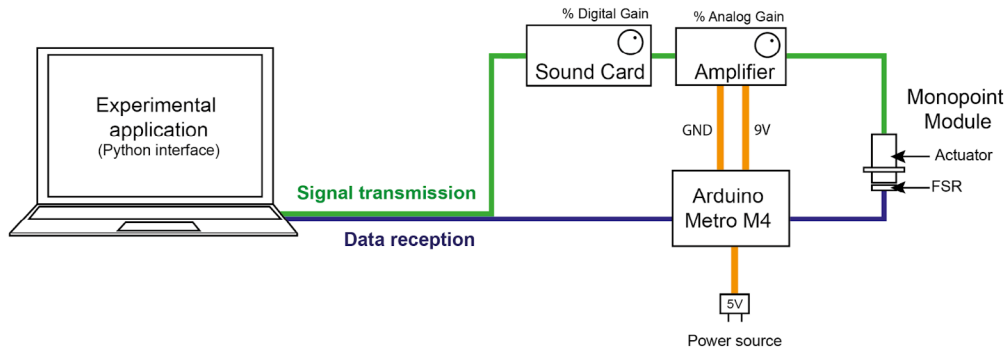


Figure 29: The signal transmission and data reception chain, developed for use during the psychophysical study on extra-tympanic hearing thresholds.

In the signal transmission chain of events (Fig. 29), the vibratory signal was first generated at the level of the digital experimental application. This signal was routed to the sound card in order to set its digital gain. After a digital to analog conversion (DAC) process, it was routed to the Class D amplifier, its analog gain modified in order to suit the electrical characteristics of the voice-coil actuator⁸. The signal then reached the actuator⁹, causing it to vibrate. As the signal was displayed, the FSR measured the amount of static pressure between the module and the body. The participant recorded their response in the experimental application. The analog sensor data was sent through to be digitized in the Arduino Metro M4 board (analog to digital conversion/ADC), and finally routed back to the computer (experimental application) for data formatting. Varying in frequency and amplitude, each vibratory signal that was displayed to the participant set this signal transmission and data reception process in motion.

⁸ To prevent signal saturation during the experiment, we first used an oscilloscope while increasing the analog gain to measure the highest value of amplitude that the actuator could tolerate without saturation (at 400 Hz). That value of gain, corresponding to 2.6 V, defined the 100% value of intensity output of the experimental interface. We then used the sound card to adjust the digital gain to an appropriate level of volume that would stimulate the ear via extra-tympanic conduction at all positions to be tested on the body.

⁹ Actronika's voice-coil actuator datasheet can be found in the appendix, pp. 193-198.



2.3. Monopoint Module : Outputs

The monopoint module was developed in order to produce experimental results that would guide the purpose and process of the subsequent wearable audio-tactile device. Its outputs therefore span the insights that it generated about experimental methods, results, and implications for future research. In this section, we will describe the outputs of the monopoint module in terms of its use as an experimental instrument for the psychophysical analysis of extra-tympanic hearing on the torso.

2.3.1. Hypothesis

With this first study, our goal was to learn more about the perception of sound via extra-tympanic conduction on the spine, clavicles, sternum and skull. Owing to the transmission properties of mechanical waves in the body, we hypothesized that the vibratory detection thresholds would increase with distance from the skull, and would depend on frequency in a manner that could reflect the integration of somatosensation and audition (Richards et al., 2021).

In more detail, our hypothesis postulated that between 50-4000 Hz, the receiver's auditory sensitivity to discrete, pure-tone signals displayed via extra-tympanic conduction would depend on their frequency, amplitude and position on the body. In other words, the limits of perception extend in three directions: by manipulating any one of these variables, the receiver's perception of the signal will change. We also hypothesized that the tactile sensation resulting from the actuator's placement on the surface of the skin would have a crossmodal impact on the receiver's evaluation of their own auditory perception. In other words, the fact that the receiver hears an auditory signal that they also feel at the same time causes them to confuse "feeling" the vibratory signal with "hearing" it, consciously or not.

2.3.2. Background

To define our experimental method, we looked to the literature. Despite a lack of existing references about hearing via extra-tympanic conduction on the torso, many prior studies have investigated the thresholds of conductive hearing on the skull. Two studies in particular, conducted by Walker and Stanley (2005) and McBride et al. (2008), both investigated the bone-conduction hearing thresholds using classic psychophysical methods. Walker and Stanley measured hearing on the mastoid (behind the ear), in three conditions: without earplugs, with earplugs, and masked. The authors chose a two-interval forced-choice method, asking participants in which of two time intervals the signal had played. The signals were displayed according to a 1-up 2-down staircase rule, with a single step size of 3 dB. McBride et al. (ibid.) measured bone-conduction hearing at 11 different positions on the skull, in quiet and white noise conditions. They applied a reversed Hughson-Westlake procedure (as defined in Newby (1979), the sound level decreased by 10dB if the signal was heard, and increased by 5dB if the signal was not heard.

2.3.3. Participants

Four participants took part in our study, two male and two female, average age 28, (standard deviation 3.8). All participants completed an audiogram prior to the

experiment in order to confirm normal hearing. Normal hearing is defined as air conduction thresholds to 500, 1000, 2000, and 4000 Hz at 15 dB HL or better bilaterally (ANSI). During the recruitment phase, participants confirmed that their body mass index was in the “normal” range (a BMI value between 18.5 to 24.9).

2.3.4. Method

In this study, we evaluated participants’ auditory detection thresholds of vibratory signals perceived via extra-tympanic conduction. Participants were briefed before the experiment that they may feel the vibratory signal as well as hear it, depending on its frequency and intensity. They were instructed to disregard this tactile sensation and focus their attention on their auditory perception of the signal in order to respond. Our experimental procedure combines different aspects of the studies conducted by Walker and Stanley (2005) and McBride et al. (2008). As in McBride et al.’s study, we tested hearing levels at several different positions in order to compare the detection thresholds in terms of location of stimulation on the body. However, instead of the skull, we investigated the torso (Fig. 30). As in Walker and Stanley’s study, we displayed the signals according to a 1-up 2-down staircase procedure: the receiver must indicate that they perceived the same signal twice in order for the signal intensity to decrease (“2-down”). When they indicate once that they did not perceive the signal, the signal intensity increases (“1-up”).

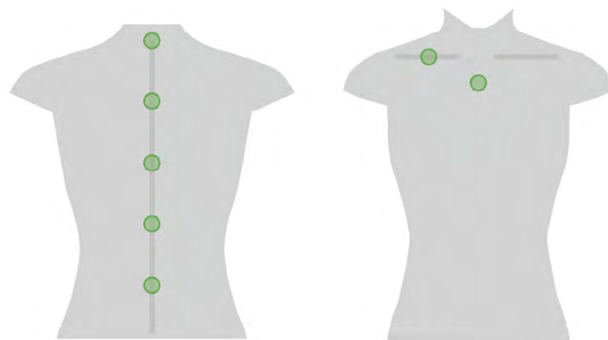


Figure 30: The positions of stimulation from the first psychophysical study. Five points were defined along the spine, each measuring 10cm apart and descending from the intersection of the neck and shoulders. The study included only the left clavicle, assuming symmetry across the sagittal plane of the body. This research focuses primarily on auditory and tactile perception via the torso, not the skull/ears.

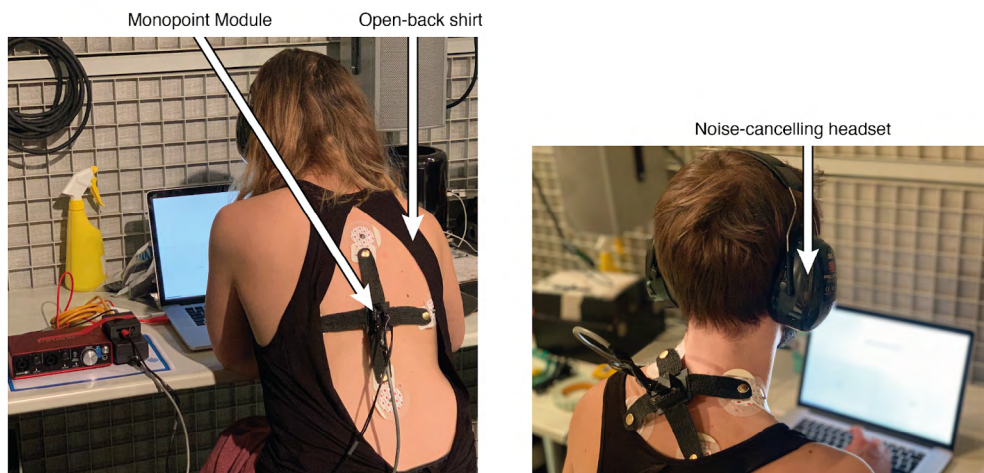


Figure 31: Photos of two participants taken during the experiment. They each wore a backless shirt in order to attach the monopoint module directly on their skin with the hypoallergenic electrode patches.

During the experiment, all participants wore ear plugs and a noise-cancelling headset (Fig. 31). We evaluated participants' detection of seven pure-tone frequencies (50, 100, 215, 440, 915, 1900, and 3950 Hz). Each frequency was repeated three times, and all of the tones were presented in a randomized order. Each tone lasted 500ms, occurring at random within a 3000ms window, to reduce the participants' anticipation of the signals. This series of presented tones was repeated for a total of seven positions of stimulation on the body: five positions along the length of the spine, one on the clavicle, and the sternum. When fixing the module to each position of stimulation, the pressure reading was verified while placing the device at every tested point on the participant's body, in order to maintain a reading of 3-5 N force, consistent with the literature (McBride et al. 2008). The participants each attended a total of three test sessions, each lasting approximately 3h, and were compensated 15€/hour.

The long duration of the test sessions is due to several factors: our adherence to standard methods in psychophysical testing (signal repetition, 1-up-2-down process), the range of seven frequencies we wished to evaluate, and the high number of points on the body to test per session, in between each of which we needed to reposition the monopoint module. To reduce the length of the sessions in similar future experiments about auditory detection thresholds via ETC, one could further restrict the evaluated frequencies and positions of stimulation. This could help reduce potential fatigue participants, and enable the recruitment of more subjects.

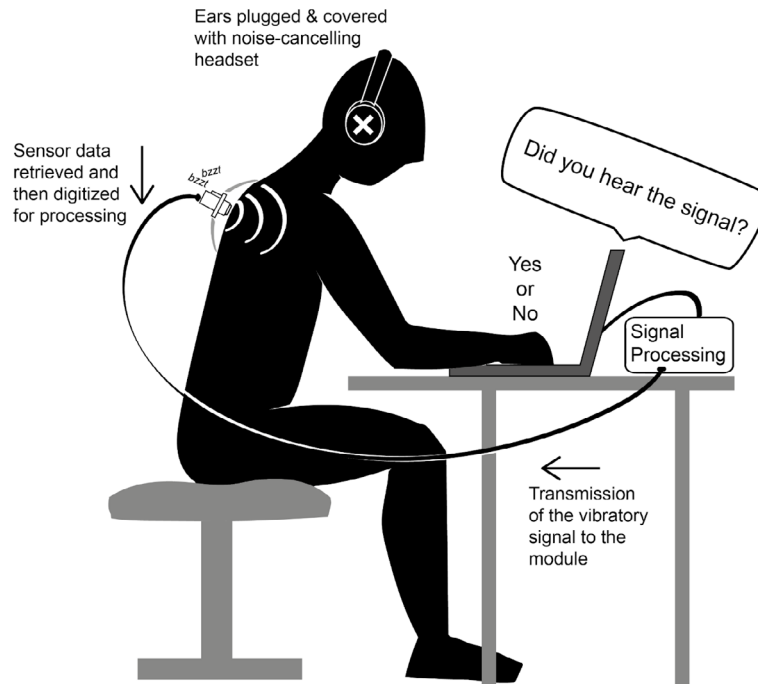


Figure 32: The experiment setup. Participants recorded their responses to the vibratory signals, answering the question “Did you hear the signal?” with either “Yes” or “No”.

Psychophysical Method Details

We applied a 2AFC 1-up 2-down adaptive staircase psychophysical method. Participants responded to one question: “Did you hear the signal?”. After each signal, participants responded by indicating either “Yes” (signal heard) or “No” (signal not heard) in the test interface (Fig. 32). Although it was possible for the participants to also feel the vibratory signals at some tested frequencies (50, 100, 215, 440, 915 Hz) (Merchel & Altinsoy, 2020), they were instructed to respond only according to their auditory perception.

To record their response on the test interface, participants could either click the corresponding button on the screen, or press the “Y” key or “N” key on the keyboard. A reversal refers to each time the participant changes their response from “Yes” to “No”. The participant must go through seven reversals in order to complete the descending staircase. The descending staircase procedure is the process of decreasing a signal’s intensity in discrete steps, gradually lowering its intensity to a point that hovers between perceptible and imperceptible. This point describes the participant’s detection threshold, or the lowest level at which they are certain to perceive the signal. The step size describes the degree to which the signal changes after each recorded response. In our study, the step size started off at 3dB. After the first reversal, the step size decreased to 1dB.

2.3.5. Results

Between 50 and 915 Hz, the auditory and tactile systems have overlapping sensitivity: participants could have both heard and felt the vibratory signals (Merchel & Altinsoy, 2020). The results from this study confirm one aspect of our hypothesis: in this zone of sensory overlap, the tactile sensation may affect auditory perception of the

vibratory signal. The low thresholds in the range of tested frequencies between 100 and 440 Hz could indicate this type of crossmodal effect. The skin's sensitivity to vibrations depends on frequency, peak sensitivity occurring at approximately 250 Hz (Verillo, 1966). Figures 33 and 34 both demonstrate this effect, showing details of all participants' thresholds and a detailed view of a single participants' thresholds, respectively. However, it is difficult to determine whether this crossmodal effect impacts the participants' judgments at a perceptual or cognitive level. In other words, we cannot say for sure whether the participants' auditory and somatosensory systems crossed paths without their conscious awareness, or if the participants were simply more likely to say "Yes" (I heard) if their tactile sense was telling them that the signal was there. In both of these potential interpretations, the tactile sensation is influencing the auditory perception of the signal.

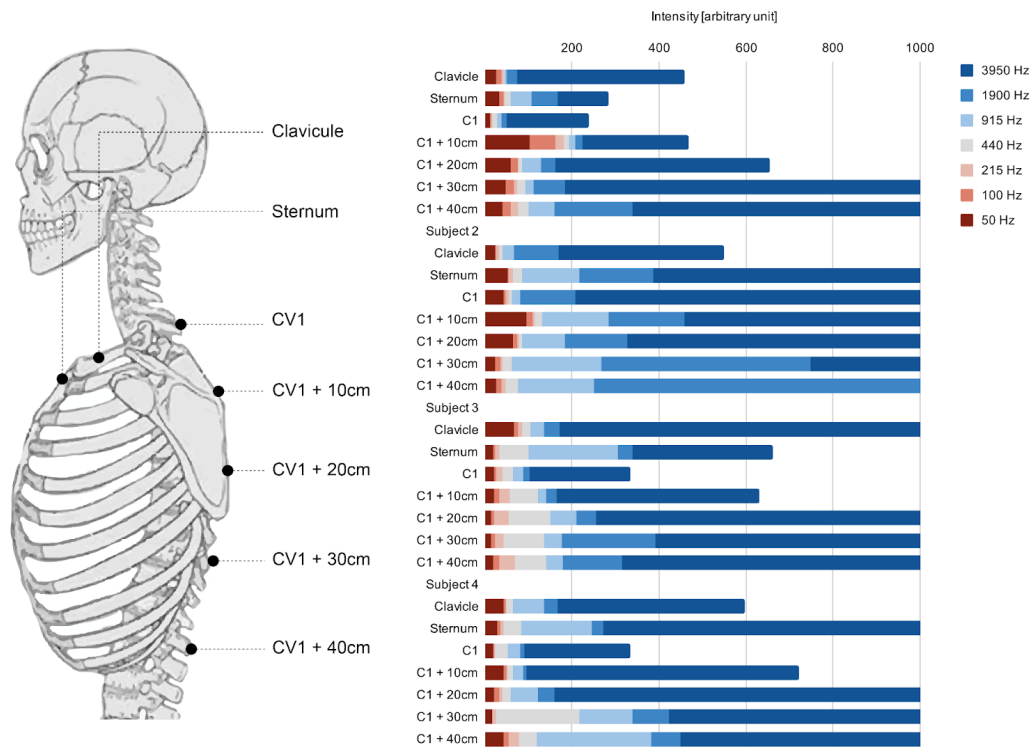


Figure 33: This figure displays the values of the detection thresholds in arbitrary units, across all frequencies, for all four participants. The thinner the bar, the lower the threshold, and vice versa.

In Figures 33-34, we see that participants had higher detection thresholds for frequencies above 440 Hz, in comparison to frequencies between 100 and 440 Hz. At 50 Hz, there is more variability in threshold values across participants. Between 915 and 3950 Hz, the thresholds generally increase as the position of stimulation grows more distant from the top of the spine. Across all participants and positions, the lowest thresholds are in between 100 and 440 Hz. At 3950 Hz, across the majority of positions, we observed that most participants could not detect the vibratory signal, even at the highest level of intensity.

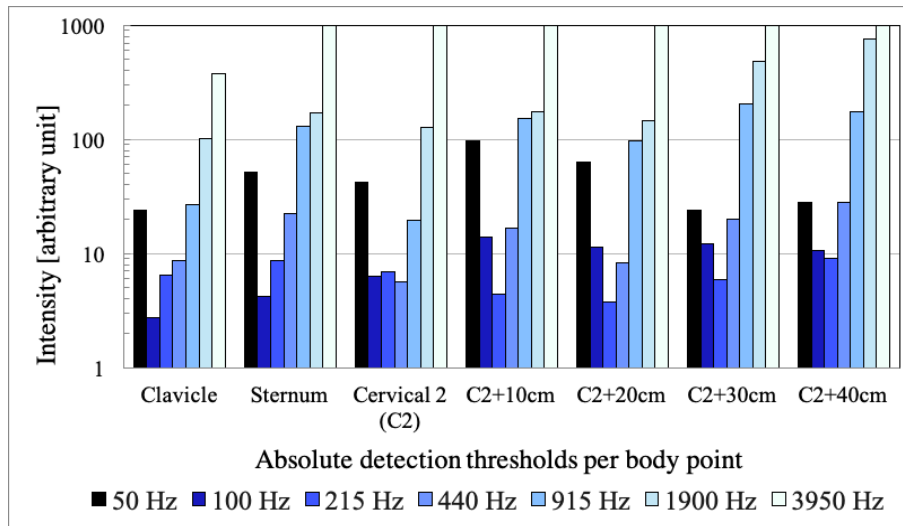


Figure 34: Vibratory detection thresholds of a single, typical participant in arbitrary units of intensity. For this participant, the low sensitivity at 3950 Hz suggests an effective frequency cutoff for signal detection at most of the tested body regions. This participant showed a marked decrease in sensitivity at 915 and 1900 Hz with increasing distance from the skull/inner ear. They had consistently high sensitivity between 100 and 440 Hz frequencies that center around the peak vibrotactile sensitivity of the Pacinian corpuscles (250 Hz), but not at 50 Hz. (Richards et al. 2021).

The physical properties of the mechanical waves propagating within the musculoskeletal structures of the body could have had an effect on vibratory signal perception. 100-440 Hz corresponds to 330-75 cm wavelength, while 4000 Hz corresponds to about 8 cm wavelength. Extrapolating from our results, there is a possibility that a shorter wavelength corresponds to a higher threshold (and vice versa), because frequencies with shorter wavelengths do not travel as far in the body as frequencies with longer wavelengths (Manfredi et al., 2012). However, this theory remains speculative; further psychophysical research is needed in order to confirm or deny it.

2.3.6. Limitations

Morphological Differences

Another limitation of this study and a potential reason for the differences across participants' results is the variation in participants' body mass at the different positions of stimulation, and the variations in participants' overall body morphologies. Though we verified prior to the experiment that each participant was in the normal range of BMI, there is still the possibility that other localized physical characteristics may play a role in the perception of sound via extra-tympanic conduction. Since this study was not conducted in a clinical context, we could not gather more precise information about participants' body mass at each site of stimulation (skin thickness, muscle mass, etc). We therefore have no comparative physiological data about each of the participants' morphological differences. Due to the nature of mechanical wave transmission in solid materials, it is possible that

attenuation of the vibratory signal may vary due to different densities of skin tissue beneath the stimulating device across participants and across testing sites. Since we applied equivalent pressure (approximately 3 N) to each point of vibratory stimulation on the body, the variations in threshold results may reflect these differences in corporal mass.

This study does not include a diverse range of body types. We chose participants with similar body types (normal BMI range) in order to simplify the comparison of their results as much as possible. However, it would be useful to extend the scope of this study in order to include a larger set of participants, and a wider spectrum of BMI-types, with the objective to explore the potential effect of body mass on the propagation of vibratory signals within the body via extra-tympanic hearing thresholds.

2.3.7. Discussion

Our results confirm the possibility of perceiving sound via extra-tympanic conduction (ETC) on sites of the body distant from the skull. They also suggest a possible influence of tactile sensation, and thus multimodal interaction: the highest thresholds of auditory detection were situated around 250 Hz, the peak of vibrotactile sensitivity. Stenfelt (2011) noted the likelihood of tactile sensation impacting perceived loudness at the lower frequencies of auditory stimuli perceived via ETC versus air-conduction.

Whether they refer to ETC sound perception as soft-tissue conduction (STC) (Adelman et al., 2015, Sohmer 2017) or body conduction (Ravicz, 2001), other researchers have also come to the conclusion that it is possible to hear vibrations displayed at points on the body that are distant from the skull. However, the researchers' reasons for exploring the perception of sound via ETC change the type of information gained from these studies. Our reason to explore perception of sound via ETC and the accompanying influence of tactile perception was directly connected to our objectives for audio-tactile device design. We chose to examine specific points of stimulation, only on the torso, since they would be targeted by our future wearable device. In our experimental method, we displayed pure-tone signals in a wide range of frequencies (50-4000 Hz) which would enable users' perception of the signals via both their senses of hearing and of touch.

Adelman et al. (2015) conducted a similar sensitivity mapping study of the upper body, examining the variations in soft-tissue conducted sound perception along the length of the spine. They analyzed the auditory signal perception according to two physiological factors: one factor evaluating the correlation with the distance of the actuator from the skull, and the other evaluating the effect of the distribution of soft (adipose, muscle) tissue. The researchers were not investigating the potential effect of tactile sensation on auditory perception. They explicitly chose to use a 2000 Hz warble tone because this would prevent the vibrotactile sensation of the signal. Their study's goal was to examine the effect of the participant's morphology on their ability to hear the signal - not to measure the variations in thresholds of several different frequencies, as in our study.

The results of their study present a clear case of interest for our wearable audio-tactile device development, and partially correlate with our own. Up until the bottom of the thoracic spine (T12), most participants perceived the 2000 Hz signals, with a positive relationship between the threshold value and distance from the skull. The authors included the mastoid as a point of comparison to the hearing levels at the

other positions of stimulation, since the mastoid is a standard testing site for bone conduction. Adelman et al. (ibid.) sought to compare hearing thresholds on the body to those on the skull, the standard selection for ETC stimulation. Besides the fact that these authors already studied the mastoid vs. torso hearing comparison, we limited our study to the torso because of our project's focus on alternative, body-based methods for sound perception.

3. The Multimodal Harness

3.1. Purpose

The multimodal harness, developed in two iterations, is the wearable audio-tactile device created during the doctoral research. We designed it in order for its user to perceive vibrations on the surface of their skin, and within their inner ear via ETC. The multimodal harness is the core of this project: the doctoral research has been organized around preparation for its development, followed by experimental, creative and theoretical analysis of its functionality. It embodies the integration between creative exploration and classic scientific procedure that is omnipresent in this project, providing a concrete example of the encounter of diverse research processes from the disciplines of design research and the science of perception.

The functional, concrete nature of the multimodal harness does not imply that we aimed to solve an existing practical problem by developing the device. The device was not designed in a necessarily inclusive way of thinking, with targeted users and based on diverse hearing abilities. Rather, the fundamental purpose of the multimodal harness is to encourage one to reconsider the human body's ability to perceive and appreciate sound as vibration, beyond the head and ears, and regardless of their hearing ability. The multimodal harness was primarily designed in order to explore the perceptual possibilities afforded by ETC on the torso. Between 20 to 1000 Hz (as discussed in section 1.1.2), the tactile sensation of the vibratory signals brings another perceptual dimension to the experience of the multimodal harness. The nature of the device renders it inclusive in terms of sensory accessibility, even to individuals who are deaf or hard of hearing (either via ETC or vibrotactile sensation). We designed this device with the help of apparel design and electronic experts, in order to enable this specific audio-tactile experience.

David Christoffel conducted an interview with one of our first study participants for his radio program *Métaclassique*, featured in his episode called "Toucher" ("To touch") (Christoffel, 2021). He asked her if she had known about bone conduction before participating in the perceptual experiment. Translated from French, her response went beyond the scope of this question, and expressed the type of thought process that we hoped to encourage by developing the multimodal harness:

I think I was never interested [about bone conduction] before now, and it's true that I've now caught myself asking questions. Last night, for example, I was doing it to myself: plugging my ears, and trying to see what I could hear - things like that. I think it makes me wonder, really, I'd never thought about it before. Hearing, we tell ourselves it's so obvious, we just think of hearing with our ears. It's rare that we try to put ourselves in the place of a

person who has a handicap, or to imagine ourselves without a sense that for us is totally normal, taken for granted. Unless I were to be confronted with someone who has a handicap, who has this limitation, or somehow became interested in the subject, I would never have thought about this.

Though we did not initially design our research around this approach, our aim to provoke thought and challenge assumptions through the creation of this novel technology could theoretically classify our research as an example of speculative design. Previously examined in the State-of-the-art, section 3.3, speculative design presents an alternative vision of design, one whose core focus is the debate about the concept it puts forward, not the consumer it serves. We will go into further detail about how we have integrated the speculative design approach in our research in Chapter III, section 4.

3.1.1. Universal Design

Before beginning to develop the multimodal harness, we asked a specific research question: How can we design a wearable device that simultaneously stimulates both the senses of hearing (via extra-tympanic conduction) and of touch (via vibrotactile stimulation) with vibrations, thus enabling experimental research and creative applications related to the multi-/cross-modal perception of the two senses?

Our goal was to find a way to use vibrations to uncover a multisensory experience of sound available to anybody, no matter their sensory capacities: hearing, hearing impaired, or deaf. This type of disability-inspired thought process is closely related to the principles of universal design.

A term coined by the architect Ronald Mace, universal design is the design of spaces, products and services that are accessible to the greatest number of individuals, regardless of ability (Mace, 1985). It is a design thinking process that acknowledges the full scope of human diversity, and the widespread presence of people with disabilities: it is design inspired by the needs of the few, serving the needs of many. The United Nations defines universal design as “the design of products, environments, programs and services to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design” (Herwig, 2008). Many examples of universal design are related to physical mobility, such as rounded curb cuts, dropped curbs, and textured walkways. These seemingly subtle changes made to existing everyday objects improve everyone’s safety, not just that of the individuals whose physical disabilities inspired their creation. In this way, universal design concepts seek to include the individuals at the farther edges of the spectrum of human diversity into the fabric of our generic societal structure.

Universal design can also extend beyond the more practical contexts of use that concern basic physical mobility and well-being. In the context of this research, the project goal is to design a wearable listening device for everyone to use, aiming to show that *the experience of sound is really about the experience of vibrations - something that everybody can perceive, and appreciate in their own way*. Since its purpose was to challenge the necessity of using one’s ears to experience sound, the multimodal harness naturally became accessible to a greater diversity of sensory capacities.

3.2. Process

The process of designing the multimodal harness occurred in several phases. Based on our objectives for the device's functionality, we first defined the initial design criteria that would inform its key structural aspects. We then presented these criteria, along with some initial concept drawings, to our project collaborators at Les Vertugadins. Their expertise in apparel design, the proportions of the body, and morphological diversity guided us through the relation of each of our design criteria to the ergonomic aspects of the wearable device design.

The development process was organized so that the design of the two principal elements could occur in parallel: the design of the vibratory module and the design of the wearable structure. The wearable device structure involves everything related to how the device fits on the user's body: the length of the straps, the type of attachments, the precise placement of each vibratory module on the body, etc. The vibratory module is the unit that contains the voice-coil actuator, nine of which contact the body at the targeted positions of stimulation. Our collaborators at Les Vertugadins guided both elements of device development. Actronika also participated throughout the developmental process of the multimodal harness, providing the electronic system, the vibrotactile motors and the 3D skills and equipment needed to create certain structural elements of the device.

In this section, we will first present the design criteria that we defined in order to guide the development of the wearable device. Then, to better illustrate the steps in our reflective process, we will describe some alternative concept propositions that preceded the final choice for the wearable device. Finally, we will present the final design: the multimodal harness.

We developed two iterations of the multimodal harness; each maintains the same purpose as described in the previous section. After testing the first iteration of the multimodal harness (MH.1), our own observations and user feedback informed new goals for optimizing the experience of the wearable device. To present the second iteration of the multimodal harness (MH.2), we will discuss how we implemented those objectives in its updated design criteria, and demonstrate how those new criteria translated into changes to both the formal and functional aspects of the wearable device.



3.2.1. Design definition: MH.1

Design Criteria

We defined the design criteria of the first iteration of the multimodal harness (MH.1) in collaboration with Les Vertugadins¹⁰, costume and clothing design experts, after presenting the purpose and objectives for the wearable device. Following each design criterion, we briefly summarize the strategies employed during the development of the multimodal harness according to two broad categories: user comfort, and vibratory signal perception. In the following section, we will relate these criteria to each device feature. For more photos of the MH.1, please refer to the appendix (pp. 237-239).

Signal Perception

1. Consistency of vibratory transmission.

The device should adjust to each individual's body in a similar fashion, no matter their size, in order to display the signals consistently across participants, and across positions of stimulation on the body. In order to reduce the potential of variability between different individuals' sensory experience of the device, we aimed to maximize the device adjustability. Since we were only developing one wearable device, and not several devices of different sizes (S, M, L, etc.), we prioritized device adjustability in order to allow it to adapt to different body types and sizes.

2. Isolated vibratory sensation.

In order to transmit the vibratory signals to the user in such a way as to create illusions of movement across the surface of the body, the user must be able to differentiate between the different positions of stimulation. The distance between the positions of stimulation on the device should not be lower than the two-point discrimination threshold of the back (approximately 5cm) (Stronks et al. 2016).

3. Ergonomics and efficiency.

In the psychophysical study detailed in section 2.3, we tested the thresholds of perception via extra-tympanic conduction on the spine, clavicle and sternum. Though the sternum was an efficient position in terms of vibratory signal perception, we decided to remove this position of stimulation from the wearable device because it introduced a certain level of complexity regarding the adjustment of the front of the device. Instead, we added two positions of stimulation on either side of the ribs which are easier to integrate into the wearable device.

User Comfort

4. Tight fit, without discomfort.

The device fit encompasses many contributing factors: comfort, flexibility of movement, adjustability, and the precision of vibratory stimulation. For optimal signal

¹⁰ <http://www.vertugadins.com/>

transmission via extra-tympanic conduction, the wearable device should fit tightly against the user's body in order to ensure contact between the skin's surface and the vibratory modules. A tight fit would also limit the effects of the users' body movements on signal transmission. The material at the point of contact between the vibratory modules and the skin should be hard, since soft materials would attenuate the vibratory signal before it could penetrate the body.

5. Durable, yet lightweight.

Since the multimodal harness was not conceived with any goals for industrialization, we prioritized the durability of the one copy we would create. We chose strong device materials that would support the potential stress caused due to being in constant tension against the body. To maximize users' comfort and minimize any strain that the device may cause to the body, we aimed to make the device as light-weight as possible.

MH.1: Final Design

The final design of the multimodal harness involved the definition of two principal elements: the wearable device structure, and the vibratory module structure. They are both informed by all five design criteria, as demonstrated in Table 4. These two elements will be further elaborated according to the design criteria in the following two subsections.

	Design Criteria		Wearable structure feature	Vibratory module feature
1	Consistent transmission	✓	Adjustment of the velcro straps creates evenly distributed pressure	Frame-based structure allows adjusted pressure to different body shapes
2	Isolated vibrations	✓	The vibratory modules do not touch - the straps provide distance	The module's vibrating central unit is disconnected from all other device parts, attached on stretched fabric within a frame
3	Tight fit, hard body-contact surface	✓	The straps tighten all corners of each vibratory module against body	Modules are printed with hard plastic
4	Sturdy, lightweight	✓	The structure tightens the modules against all targeted positions of stimulation, and can adjust to any body size of waist between 64-90 cm	Module components 3D-printed with lightweight plastic. All electronic components are replaceable.
5	Ergonomic design	✓	The structure is made of lightweight resistant nylon material	Skin-to-module contact pieces are rounded, and shaped according to the targeted body position

Table 4: Design criteria of the first iteration of the multimodal harness.

MH.1 Device Element 1: Wearable Structure

The wearable structure describes the system that integrates all of the vibratory modules into one cohesive wearable device.

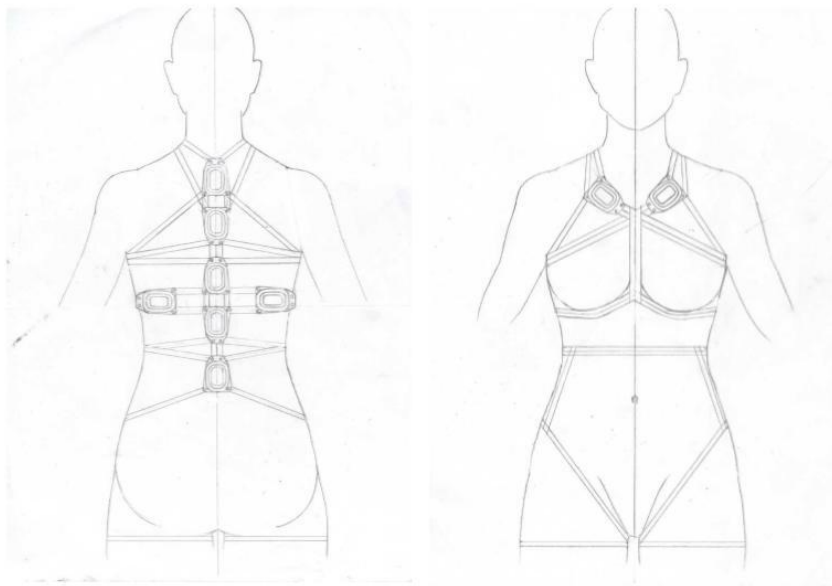


Figure 35: Technical drawing of the MH.1, from Les Vertugadins. The drawing indicates each of the nine positions of stimulation, on top of which the wearable device structure integrates each of the vibratory modules. Each of these modules are integrated to the wearable device structure with nylon straps, tightened against the body with velcro.

Figure 36 shows a mock-up version of the MH.1 designed by Les Vertugadins, which allowed us to study the body's form and determine how we could create the necessary tension between each of the nine vibratory modules and the positions of stimulation along the spine, ribs and clavicles (see also Fig. 35, 37). To create that tension, each vibratory module (simulated with foam cut-outs) is attached to four different straps, pulling in opposite directions at the four corners of each module.



Figure 36: Mock-up version of the MH.1, produced by Les Vertugadins.



Figure 37: Photos of the MH.1 audio-tactile wearable device. Users wear the device on top of their clothing, ideally with no more than one layer to reduce vibratory signal attenuation. To maximize the device adjustability to different body types while maintaining consistent pressure of the vibratory modules against the body, there are seven points of adjustment on either side of the body (14 total velcro adjustments). (Photo credit: Véronique Huyghe).

MH.1 Device Element 2: Vibratory Module Structure

The MH.1's vibratory module was designed in order to respond to all five design criteria. It contains two main elements: the structural frame, and the central vibrating unit (Fig. 38). The structural frame serves two purposes: attachments to straps on each of its four corners connects each vibratory module to the wearable structure, and the semi-rigid fabric stretched between its edges serves the same function as a diaphragm on a speaker. The frame isolates the propagation of the vibrations created by the central unit clipped onto the fabric. This constrains each module's vibrations to its specific position of stimulation and reduces the amount of vibrations perceived between each module. The frame therefore allows the user to perceive localized vibrotactile sensations, while providing the structure that creates the necessary pressure to elicit extra-tympanic sound perception. Since the components were 3D-printed with durable lightweight plastic, each vibratory module is lightweight (the entire structure of the MH.1 weighs .84 kg).

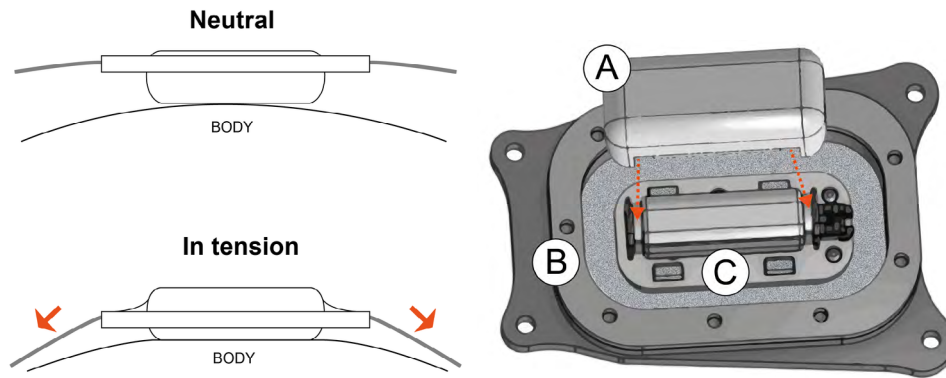


Figure 38: *Left*: A semi-rigid fabric allows the actuator to “breathe” within its structural frame, naturally adjusting its pressure on each part of the body. *Right*: The module snaps onto the extended fabric, between the edges of the frame (B), via the clip attachment on the PCB (C). The 3D-printed clip-on piece (A) attaches onto the indented edges of the actuator, and comes into direct contact with the body, transmitting the vibrations to the user. We designed several versions of these clip-on pieces, ergonomically shaped according to each position of stimulation (wide and flat on the ribs, extruded on the lower spine, rounded on the clavicles).

3.2.2. Design definition: MH.2

After building the first iteration of the multimodal harness, we had the opportunity to test it, form our own observations and collect user feedback during a participatory workshop for audio-tactile effect design. This workshop will be further elaborated as one of the creative outputs of the multimodal harness in Chapter V, section 2. The insight we gained through our own and users’ feedback motivated us to take the design of the multimodal harness one step farther and develop a second iteration. To clarify the aspects we wanted to improve in this new version (MH.2), we added some new design criteria. In this section, we will first describe these new design criteria, and then discuss how specific aspects of the MH.2’s features take them into account. For more photos of the MH.2, please refer to the appendix (pp. 238-239).

Design Criteria

6. Optimize sound perception.

For the MH.1, we integrated the actuators parallel to the surface of the body. The main motivator to develop a second iteration of the multimodal harness was to improve the user's auditory perception while wearing the device, since the most common complaint related to use of the device was weak volume. For the MH.2 (Fig. 39), we therefore chose to orient the actuators orthogonally against the body based on an empirical test about our perception of identical signals between parallel (tangential) and orthogonal (normal) orientations of the actuator, during which we noticed a clear improvement in extra-tympanic sound perception with orthogonal orientation.

7. Minimal adjustments, maximum comfort.

For the MH.2, we wanted to maintain device adaptability, but minimize the overall number of adjustments. We therefore removed the leg straps and decreased the number of straps in order to improve user comfort. By removing the leg straps, we removed the support that pressed the lowest vibratory module against the back. We therefore needed to adjust the positioning of the modules along the spine so that the lowest module could be tightened against the body with a waist strap.

8. Minimal external sound.

The stimulating modules integrated on the MH.1 left the actuators exposed to the outside air, causing considerable air-conducted acoustic transmission of the vibratory signals. It was noisy for anyone near the device, apart from the user who wears noise-cancelling headphones and earplugs. For the MH.2, our main goal was to increase the transmission of the vibratory signals into the body in order to improve auditory perception. By re-orienting the actuators and improving the vibratory transmission into the body, we would also improve the device efficiency: less signal amplitude would be required to elicit the same perceptual experience. This would also decrease the amount of air-conducted sound caused by the vibratory modules. We also reduced the external noise by surrounding each actuator with soft sound-absorbing material, and by encasing them in solid capsules.



Final Design

Table 5 displays how the MH.2 adapted to three new design criteria. The five criteria defined for the MH.1 are addressed in the same way for the MH.2.

	Design Criteria		Wearable structure feature	Vibratory module feature
6	Optimize penetration of vibrations into body	✓	Spine modules integrated higher up on the wearable structure	Orthogonal module orientation
7	Minimize device adjustment time	✓	Large surface of velcro fabric, reduced number of straps	Smaller vibratory module size
8	Minimize external sound leakage	✓		Orthogonal module orientation, noise-attenuating insulated cap

Table 5: Updated design criteria for the MH.2. All of the design criteria defined for the MH.1 carry over for the second iteration of the audio-tactile device.

MH.2: Wearable Structure

To better adhere to the design criteria defined for the MH.1 and the MH.2's new design criteria, we adapted the structure of the wearable device in a few key ways. Fewer, wider straps reduced the number of adjustments and distributed the pressure more evenly across the torso. The entire front of the MH.2 is made of a soft velcro fabric, so the straps can be attached anywhere. The MH.2 was also designed so that the positions of stimulation on the spinal column are situated higher. The uppermost vibratory module is therefore closer to the skull. Based on results obtained in the psychophysical study, this positioning could improve the user's perception of the higher frequencies.



Figure 39: The second iteration of the multimodal harness (MH.2). The main design changes for this version of the wearable audio-tactile device are resumed in section 3.2.2. (Photo credit: Véronique Huyghe).

MH.2: Vibratory Module

For the second iteration of the vibratory module, the actuators were integrated in an orthogonal position relative to the surface of the body, instead of in a parallel position (Fig. 40). This allows the voice-coil actuator's lengthwise-directed vibrations to penetrate the surface of the body instead of rubbing horizontally across the skin, the objective being to increase the perception of sound without impacting the quality of vibrotactile stimulation. We aimed to increase sound perception in the mid-to-high frequency range (800-2000 Hz) in order to bring more clarity to certain instrumentals and vocal sounds transmitted by the multimodal harness.

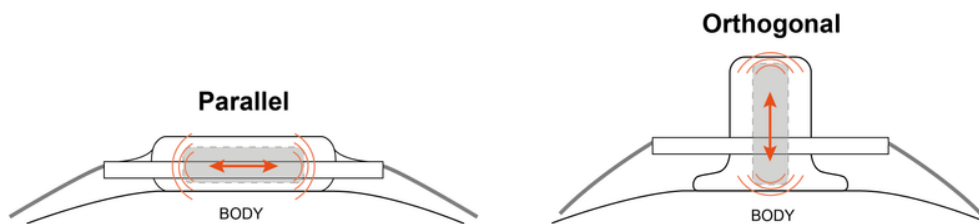


Figure 40: Illustration of the orientation change of the actuator, from parallel to orthogonal with respect to the body. The actuator's axis of vibration is lengthwise.

We hypothesized that the new configuration of the actuator within the vibratory module (Figs. 41-42) would increase the penetration of the mechanical waves towards the musculoskeletal structures, improving the conduction of sound from the external positions of stimulation towards the inner ear, without impacting the quality of tactile stimulation. This reorientation increases the device's efficiency in terms of auditory stimulation, therefore decreasing the amplitude required to elicit auditory perception and the external noise generated by the module.

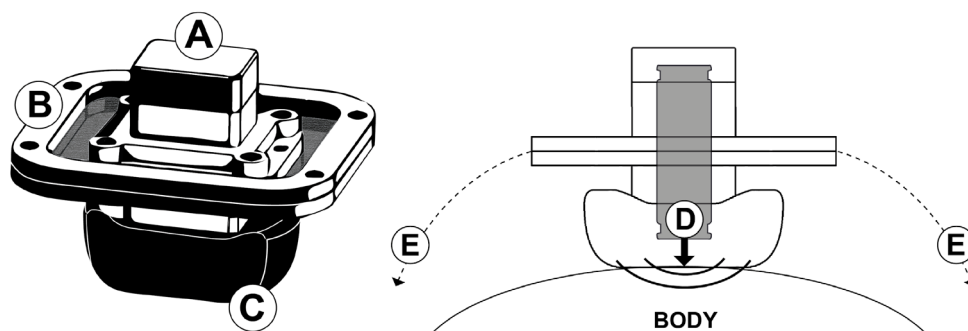


Figure 41: The final design of the second iteration of the vibratory module. Integrated in the structure of the harness, each vibratory module (A) clips onto a piece of semi-rigid fabric stretched between the edges of its supporting frame (B). Its hard, rounded bottom (C) touches the surface of the body, transmitting the vibrations from the actuator to the user. The actuator's axis of vibration (D) is oriented towards the

user's body, orthogonally situated with respect to the skin's surface. The straps attached to the four corners of the module (E) pull it against the user's body.

The vibratory module's fabric-suspended frame serves the same purpose as the MH.1's module: it allows the central unit of the module to naturally adjust its pressure at each position of stimulation, isolates the vibrations, and provides four points of attachment for the straps. The MH.2's vibratory module has a square frame, which reduces the overall size of the module. This therefore decreases the overall length required for the five modules to be spaced apart on the back. By reducing the length of the spinal column section of the device from 51 cm to 45 cm, we were able to use a belt-strap around the waist, instead of leg straps, to tighten the lowest module against the back.

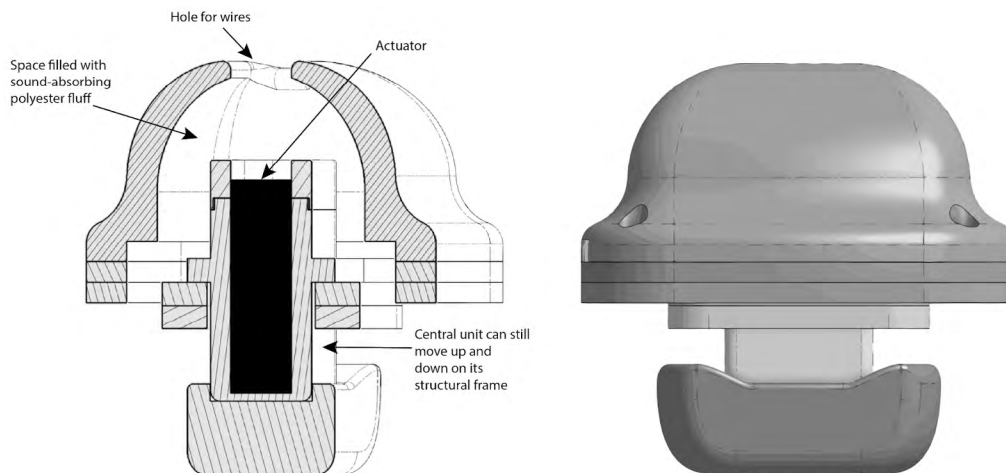


Figure 42: Section drawing and 3D illustration of the MH.2's vibratory module. Each of the nine modules integrated in the device have insulated caps attached on the outside of the device (not shown in Fig. 41), in order to limit the air-conducted transmission of noise as much as possible. This final modification to the MH.2 responds to design criterion 8.

3.3. Multimodal Harness: Limitations of Use

Though we tried to optimize every aspect of the multimodal harness in order to best facilitate any individual's auditory and tactile perception of the vibratory effects, our choices also had certain consequences for the user experience. We needed to take each of the following limitations into account for any future experimental applications of the device: size, perception, and comfort affect all aspects of experimental design: the duration of the tasks, the participant selection criteria, and the experimental methodology.

Size

The harness straps can be adjusted to fit individuals with a waistline measuring between 64 and 90cm. We wanted to be able to include any individual in the sensory experience of the device, and collect diverse feedback about the perception of the audio-tactile effects. However, we would need to create several different sizes of the

wearable device to make the experience accessible to a wider range of body types: a task that was out of scope of the doctoral research. The size-related limitation meant that we were not able to collect qualitative feedback nor experimental results from individuals outside of the size range supported by the device. This introduces some discriminatory bias regarding users' body size, and the overall accessibility of the experience facilitated by the device.

Perception

The multimodal harness is meant to demonstrate an alternative approach towards sound perception. The auditory experience provided by both iterations of the device should not be compared to the auditory experience provided by a set of headphones, or that of other existing vibratory listening devices (as detailed in the State-of-the-art, Chapter I, section 4). On the torso, the upper limit of the audible range of frequencies is between 2000 and 4000 Hz, using the maximum possible amplitude of the voice-coil actuators integrated in the device (Richards et al., 2021). The device cannot provide the full auditory spectrum (20 Hz-20 kHz) to the user, and all audible frequencies are attenuated by the transmission of the mechanical waves inside of the body. In order to avoid users' misunderstanding of its functionality, we have learned that it is important to mentally prepare them for the perceptual experience of the multimodal harness by explaining that the device was not designed as a substitute for existing acoustic technology.

Comfort

For both iterations of the multimodal harness, we aimed to find a middle ground between user comfort and vibratory perception. The device was therefore designed to create pressure against the body, with strong emphasis on adjustability: it will only be as tight as the user adjusts it to their body. However, if the user wants to optimize their auditory perception, they need to tighten the device to the limit of their comfort. While helping users put on the multimodal harness, we ask them to fill their lungs with air before we tighten the straps around their waist and ribs. This adjustment defines the maximum comfortable level of tightness.



4. Conclusion

In this chapter, we presented two audio-tactile devices developed during the doctoral research: the monopoint module and the multimodal harness. We explained how their guiding purposes were influenced by our assumptions, our objectives, and the environment in which they were conceived. In describing the process of their development, we revealed the relationship between our precise objectives (design criteria), and the formal and functional aspects of the devices.

We presented the monopoint module's outputs in terms of the experimental results it generated: results from the psychophysical study confirmed our hypothesis that specific positions of stimulation on the torso offer viable pathways for vibrations to excite the inner ear via extra-tympanic conduction. Finally, we focused on the definition and development of the multimodal harness.

In the following chapters, we will present the outputs of the multimodal harness, organizing them based on commercial, theoretical, experimental and creative themes of application. We have used the multimodal harness as a tool for theoretical reflection, for experimentation, and for artistic creation. It has helped us to analyze the design processes that coexist in our research. In terms of experimental analysis, it has served as an instrument in two audio-tactile perceptual studies. Finally, it has also provoked the development of new digital interfaces for audio-tactile effect design, allowing us to create multisensory compositions for the body.

Using the multimodal harness as a tool in each of these branches of the doctoral project demonstrates the many ways that the design research process can integrate different disciplines. Aspects of sound design, multisensory perception, haptics, music composition, and design theory find commonality in the fact that they are all connected to the multimodal harness. In Chapter III, we discuss the theoretical and concrete outputs of the multimodal harness that most closely relate to the project's industrial context. In Chapter IV, we will detail the outputs of scientific experimentation generated by the multimodal harness. Finally, in Chapter V we will show how it acted as a vessel for new audio-tactile sensory experiences by describing its most creative outputs.

Chapter III: Integrating Design Approaches

1. Introduction

Throughout the course of the doctoral project, the industrial environment¹¹ has oriented a part of our research towards the consumer. This doctoral research is qualified as a design research thesis, and has therefore grown to be fundamentally articulated with an industrial design project, advanced design questions and achievements. This practical context encouraged us to consider applications of our research that align with an industrial product design approach, and consequently inspired us to evaluate the other design methods at work.

In this chapter, we first present the outputs of the multimodal harness that most closely relate to the industrial environment in which it was conceived. In the first section, we address this influence by describing the commercial offshoot of the multimodal harness: an audio-tactile product concept called Ryzm™. Though it was informed by the same experimental results and inspired by the same sensory experience that the multimodal harness elicits, we co-conceived the future product concept with a different purpose: to suit consumers' desires and needs. This user-centered purpose sets it apart from the more investigational, eccentric character of the multimodal harness, and brings new design questions to develop during this chapter. In the second section of this chapter, we dissect the relationship between the multimodal harness and Ryzm™ by explaining how the combined approaches of speculative and product design propelled both devices' development.

Speculative and product design are not the only two disciplines that were brought together by the multimodal harness. Aspects of sound design, haptic design, experimental, experiential and interface design, apparel design and mechanical design all share the multimodal harness as their common focus. Beyond associating broad categorical disciplines, the will to create the experience facilitated by the multimodal harness has brought together the unique perspectives of our different collaborators, and introduced a new way of integrating sensory modalities. In the last section of this chapter, we will introduce the term “integrative design” to describe the approach of this project as a whole.

¹¹ The industrial environment refers to the collaborative industrial framework of the research, funded by industrial partner Actronika SAS and the Association Nationale de la Recherche et de la Technologie (ANRT), in collaboration with the Design Research Laboratory le Centre de Recherche en Design ENSCI - ENS Paris-Saclay (CRD) and IRCAM Science and Technology of Music and Sound laboratory.

2. Product Design-Research: RYZM™

In this section, we introduce the output of the multimodal harness that is the most directly related to its industrial context: a consumer product concept called Ryzm™. We initiated the development of Ryzm™ in order to demonstrate the relevance of our research to the goals of our industrial project partner, Actronika. Ryzm™ is an output of our research whose implications reach beyond the experimental, and whose development allowed us to integrate our industrial partner in a co-creation process. Reorienting our research towards product design pushed us to consider its implications from a different point of view: one that puts user acceptability at the heart of device development, instead of the perceptual experience itself.

Due to its early stage of development, we qualify Ryzm™ as an audio-tactile device concept, not in terms of its functional evaluation. We will therefore present Ryzm™ not in the same terms as for the monopoint module and the multimodal harness (purpose, process, outputs). Instead, we present it in terms of how it enabled us to integrate two seemingly oppositional, yet essential, aspects of our project: scientific investigation and product design strategy. The design recommendations for the product concept show how we approached our research in terms of its potential to inspire and inform a commercial application. They show how we mediated the concept development while incorporating Actronika's contributions, and finally, how the product concept cultivates and synthesizes our main research objective.

2.1. Product Design Recommendations

Through these design recommendations, we defined our objectives for Ryzm™: a wearable audio-tactile device currently in development at Actronika as a future consumer product. Defined in collaboration with Actronika, these criteria serve as a common language, forming a concrete connection between the experimental objectives and potential commercial applications of our research. These recommendations differ from the design criteria previously described for the monopoint module and the multimodal harness in that they are limited to the scope of the conceptual phase of the audio-tactile device development: they serve more as design recommendations than descriptors of the final device functionality or use. Frequently, we will elaborate Ryzm™'s design recommendations in comparison to the experience of the multimodal harness. During the design process, aspects of the multimodal harness that are the least appropriate for a consumer product served as guiding constraints for Ryzm™'s design space.

1. Targeted applications.

Ryzm™ will be marketed by Actronika as a haptic listening accessory, with a double functionality as an acoustic/haptic listening device. The device's targeted use cases are all related to entertainment: haptic-augmented auditory experiences of music, home cinema, and video games. The device will support augmented listening experiences for a diverse range of hearing profiles (normal/partially impaired/deaf), but it will not serve as an assistive listening device. Though it will enable a user with a hearing handicap to experience sound through vibrations and/or extra-tympanic

conduction, it is not meant to be used as an aid for speech comprehension, nor does it presume to replace any existing hearing aids.

The entertainment use cases targeted by Ryzm™ (music, movies, games) correspond to Actronika's existing knowledge in haptic product development, and are intrinsically diverse in terms of the user profiles that they each attract. As such, the future vibratory effects designed by Actronika for the device will be tailored to each use case, and evaluated by representative groups of users (see also design recommendation 4).

2. Distinguishable, yet familiar design.

Existing devices can be compared to the product concept based on the way they are worn by the user (neck speakers) or their basic premise of functionality (haptic listening accessories like Subpac, Basslet, Woojer, etc.). Ryzm™'s inclusive approach to sound perception will enable users of any hearing capacity to perceive sound, whether by the sense of touch, hearing, or a mix of the two. Ryzm™ will distinguish itself from other existing acoustic and haptic listening devices on the market through three main aspects: its inclusive approach towards hearing, proprietary AI methods for tactile effect design, and the positions of vibratory stimulation, selected for their efficiency to elicit both extra-tympanic sound perception and tactile perception of the vibratory effects.

3. Relation to experimental results.

We defined Ryzm™'s main features based on the experimental results of the psychophysical study with the monopoint module: all participants' lowest thresholds of hearing via extra-tympanic conduction came from the vibratory stimuli that were transmitted at the highest spinal position and clavicle. The vibrotactile actuators will therefore be integrated in Ryzm™ so that they touch these positions on the body, and maximize the potential for extra-tympanic sound conduction. These three positions (left and right clavicle, upper spine) are also strategic for two other reasons: they provide possibilities for spatialized or stereo-type vibrotactile effects, and are arguably more convenient than other positions like the ribs or lower spine for a one-size-fits-all device design.

In Figure 43, three photos taken during the rough prototyping phase of a brainstorm session show colleagues at Actronika working through some preliminary wearable design ideas. During this collaborative brainstorm session, we first presented our experimental results, encouraging the participants to consider the heightened sensitivity of the upper spine and clavicles in their designs while specifying that the future product must fit the ergonomic expectations of a real consumer. This brainstorm helped our industrial partner to appropriate the doctoral research results on their terms. The design concept illustrated in Fig. 42 distills several aspects of the rough prototypes that were developed during the brainstorm session.

4. Inclusivity and accessibility.

Ryzm™'s concept should communicate a message of inclusivity: its main function is to make the experience of sound accessible to any individual, with any type of

hearing profile. The accessibility of the device may be measured both in terms of physical and sensory fit. In terms of physical fit, Ryzm™ should be adaptable to any user's body type, no matter their body type.

In terms of sensory fit, the experience of using Ryzm™ should enable any user to perceive sound through tactile, auditory, or mixed perception. However, the way that the device stimulates the user's auditory perception is not necessarily limited to extra-tympanic conduction. The way that Ryzm™ excites the user's hearing will depend on future prototype tests, and evaluations of users' auditory perception via extra-tympanic conduction and air conduction. Extra-tympanic sound conduction is most easily accessible to users who have conductive or mechanical hearing impairments. For other users (with normal hearing or sensorineural impairments), extra-tympanic conducted sound is not necessarily preferable to air-conducted sound.

To achieve the best sensory fit for most users, Ryzm™ should therefore offer two possibilities for sound perception, via extra-tympanic conduction and air conduction. The device could enable air-conducted sound perception either via integrated headphones, or could offer Bluetooth connectivity to stream the user's sound through a separate audio device (speakers or headphones). When testing the future prototypes, evaluations of the device's accessibility should involve tests with representative users, corresponding to the different physical and sensory abilities targeted for inclusion (Sears & Hanson, 2011).

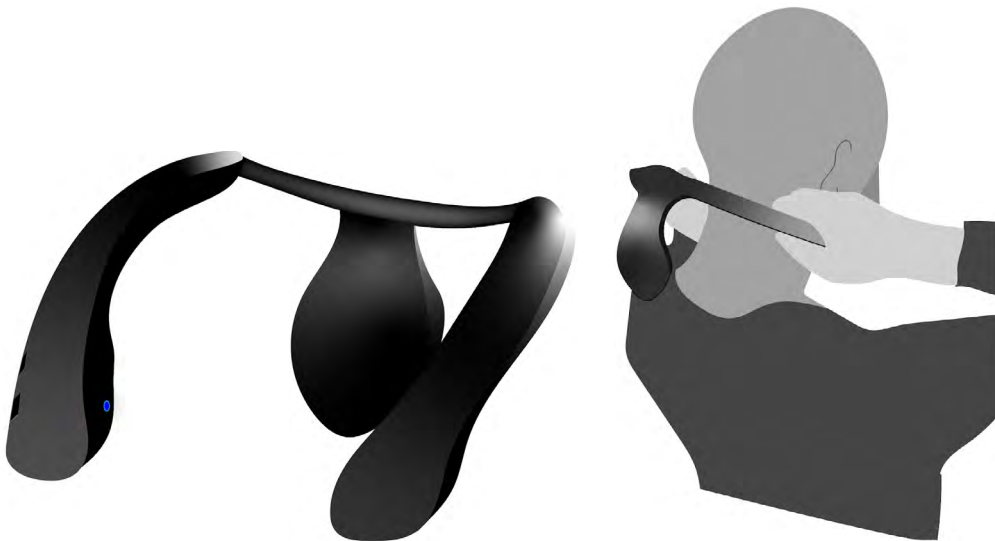


Figure 43: The first illustration of the Ryzm™ product concept. This illustration was based off of several rough prototype ideas developed during the collaborative brainstorm session (Fig. 44), and its formal features were designed to recall neck-worn speakers in order to improve the familiarity of the design in terms of an acoustic product concept.

5. Innovative, yet acceptable.

Our idea behind Ryzm™ is directly related to the sensory experience of the multimodal harness; it reinterprets the same concept of inclusive audio-tactile listening. However, while designing Ryzm™, we are more concerned about users' perception of the device functionality. Its form needs to take the user's perspective into account, and allow them to intuitively appreciate its function as an augmented listening device. Beyond targeting the three most sensitive positions for

extra-tympanic sound perception, the form of the device concept was imagined to resemble formal features of neck-worn smart speakers, acoustic devices that are gradually gaining in presence and popularity: acoustic companies including Sony, Bose, JBL, Sonos, Doss, Marshall, Samsung and others have all developed their own version of a neck-worn speaker (Corrigan, 2022). In Fig. 43, an illustration of the first Ryzm™ concept, there is a clear resemblance to the neck-worn speakers on the market today. The additional element on the back of the neck provides a third position for vibratory stimulation, and visually distinguishes Ryzm™'s function from other similar devices. With these features, we try to incorporate a balance of the technology's perceived typicality and novelty: aspects that, when combined, may give the best chances to create a successful innovative product (Hekkert et al., 2003).

Disruptive, novel technologies such as Ryzm™ are adopted by users in several phases: first by tech enthusiasts or *innovators*, then by bold *early adopters*, followed by the patient *early majority* and finally skeptical *late majority* groups (Kim, 2015). By properly identifying the niche market where there is already pre-established success of adoption of similar technology, it will be easier to convince the hesitant majority of customers of the device's value.

Users will also judge the acceptability of a device based on its *ease of use*, a measure of usability developed by Shackel (1986). Ease of use can be evaluated based on how the user adapts to the novel device: the length of their learning process, the number of errors, and the frustration associated with first uses. Bengts (2004) also points out the importance of cognitive and affective judgments in device usability: is it memorable, comfortable, and enjoyable? In contrast to the multimodal harness, with Ryzm™ we want to let users have an augmented audio-tactile experience of sound *comfortably* and without forcing their body into a tight, repressive device. However, by moving comfort up on Ryzm™'s list of priorities, we will likely need to bump down the efficiency of auditory perception via extra-tympanic conduction. Ryzm™'s final design will consider the device's usability in terms of the device's total weight and weight distribution, its adjustability, overall user comfort, and the perceived quality of the vibrotactile signals both in terms of auditory and tactile perception.

6. Distinct from other products.

In terms of functionality, devices comparable to Ryzm™ integrate vibrotactile stimulation to enhance the user's auditory experience of music. Products like Woojer, BassMe, and SUBPAC use deep bass vibrations (generally no higher than 200 Hz) to stimulate the user's body as if they were feeling the deep vibrations of a concert. The first main distinguishing factor of Ryzm™ can be defined in terms of the quality of vibratory sensation. Instead of limiting the tactile bandwidth to low-range frequencies to produce the sensation of thumping bass, Ryzm™ will transmit more precise tactile sensations that exploit the entire bandwidth of the skin's sensitivity. While the previously cited products are worn around the waist (Woojer Strap), clipped onto the torso (BassMe) or as a vest (SUBPAC and Woojer Vest), Ryzm™ will be worn around the neck, stimulating the back of the neck and clavicles with vibrations. This placement on the body is its second main distinguishing factor. In terms of ease of use and overall comfort, a neck-worn device is compact, and with some basic adjustability features, will be able to fit essentially any user's morphology.



7. Disseminate the fundamental research narrative.

Ryzm™ will reach users who have no connection to the academic side of the doctoral research. In this way, the continued development of Ryzm™ will broaden the scope of our research objective: to encourage an understanding that hearing extends beyond the ears.

The recurring narrative of this research is the notion that *vibrations are perceived and appreciated aesthetically whether the skin's mechanoreceptors or the cochlea's ciliated cells are responsible for processing them*. The fact that Ryzm™ mixes users' perception of hearing and touch could spread this view. The device has applications in a variety of use cases that are, today, addressed by haptic and acoustic accessories that are restricted to either one or the other modality. Ryzm™ communicates the integration between these two modalities by demonstrating potential for multimodal listening experiences in a variety of use cases.



Figure 44: A collaborative brainstorm session, during which we presented the doctoral research to colleagues at Actronika, along with an overview of related wearable devices on the market. We then asked the participants to come up with their own ideas for a new wearable audio-tactile device that could become a commercial product.

3. Design Approaches

In this section, we begin by defining two design approaches that contributed to the creation of the multimodal harness and Ryzm™: speculative and product design. Our project has simultaneously positioned itself in both of these approaches. We will first present an overview of product and speculative design, also providing a few examples of projects that embody these approaches.

In the context of our industrial research, speculative and product design have developed a mutually beneficial relationship, each feeding into the advancement of the other. In the second part of this section, an article presented at the 2022 Haptics and Audio Interaction Design (HAID) conference details the interaction between the two approaches in terms of the two audio-tactile devices that embody them.

3.1. Product Design

To develop Ryzm™, a commercial product concept, we looked at our research through the perspective of a product designer. Product design is a consumer-centered industrial design discipline, focused on the analysis of real users' existing and future needs in service of the market (Hsiao & Chou, 2004). It is a research-based problem-solving process: the designer is searching for answers to users' expectations or needs in a pattern that cycles from exploration, to generation, to evaluation.

Wash, Rinse, Repeat

Product designers observe, imagine, create, iterate, test, interview, and repeat this process until they find a satisfactory solution, or time runs out on the development agenda. On a macro level, product design can be framed in terms of the product's measured profitability, and its positive impact on the company's program (Cooper & Kleinschmidt, 1995). In terms of methodology, product design can be described in terms of the different strategies used by the designer. Nigel Cross (2000) acknowledges the intrinsically unpredictable nature of the product design process. Although the designer generally begins their process by outlining many potential solutions and honing in on the best probable concept, "sometimes... the analysis and evaluation show fundamental flaws in the initial conjecture and it has to be abandoned, a new concept generated and started again" (Cross, 2000, p. 28).



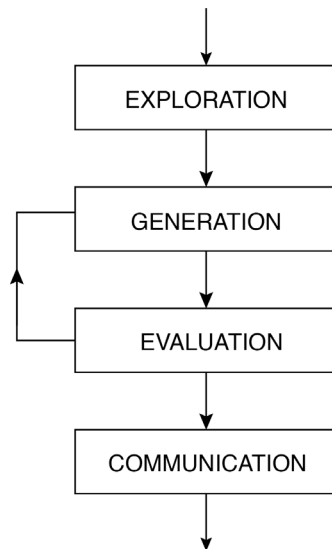


Figure 45: Cross's simple four-stage model of the design process. He explained, "Assuming that the evaluation stage does not always lead directly onto the communication of a final design, but that sometimes a new and more satisfactory concept has to be chosen, an iterative feedback loop is shown from the evaluation stage to the generation stage" (Cross, 2000, p.30).

Cross describes product design as the means to an end: the design which allows the making process to begin. He portrays this detailed description as the "end-point" of the product design process, explaining, "in a sense, perhaps, it does not matter how the designer works, so long as he or she produces that final description of the proposed artefact" (ibid., p. 4). There are, however, learned techniques that the professional product designer is taught to employ, as illustrated in Figs. 45-46.

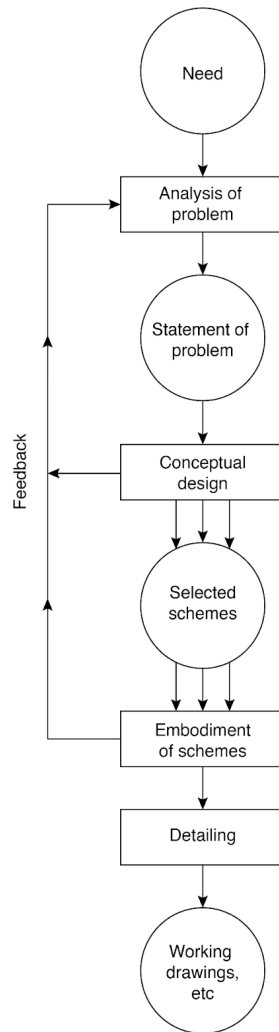


Figure 46: French’s model of the design process (French, 1985). The first design activity is analysis of the problem, or the “need”. The conceptual design phase “takes the statement of the problem and generates broad solutions to it in the form of schemes” (Cross, 2000, p.31). For French, the end product of this process is usually a set of finessed drawings, after a final detail-oriented phase which reduces the chance of errors.

Ergonomics and Human Factors

To create a good product, one needs to understand how it relates to its user. To understand the user, one needs to understand their body and their psychology, their limitations, needs, and their organizational context. Closely related to the discipline of product design is Ergonomics and Human Factors of design, a field of studies concerned with the effect of our built environment on our health and productivity. Research in Ergonomics and Human Factors takes into account the diversity of user populations, analyzing bodily characteristics (anthropometrics), cognitive and perceptual processes, and considering how built things may enable interactions that “optimize human well-being and overall system performance” (Karkowski, 2005, p. 438). Karwowski (2005) defines Ergonomics and Human Factors as a discipline “that focuses on the nature of human-artefact interactions, viewed from the unified

perspective of the science, engineering, design, technology and management of human-compatible systems" (ibid., p. 436). Kanis (1998) points out that human factors studies tend to emphasize the most measurable human characteristics as they apply to product design, rather than the human activities that shape the diversity of interactions naturally formed between users and their everyday products. He evaluates product design from a functional point of view, arguing that "human characteristics are not, or only loosely, associated with user activities, and cannot, in consequence, serve for the prediction of user activities" (Kanis, 1998, p. 81).

A Case Study in Product Design: The Walkman

The Walkman (Fig. 47) is a prime example of influential product design - it has revolutionized the way we experience music. It enables its user to carry around and listen to whichever sounds they like, creating a personal auditory bubble. Prior to the Walkman, sound was a democratic experience, shared by all in its vicinity. Paired with portable headphones, this product changed the experience and purpose of sound. Music could now be used not only as a means to create cohesion between listeners, but also to create isolation, and a sense of separation from others. Arguably the first widespread wearable technology after glasses and watches, the Walkman's permanent influence on the user's sensory world exemplifies how one product can mark cultural history, and completely change our relationship to our sense of hearing.



Figure 47: Left: the original 1979 Sony Walkman, right: A 1981 print ad for the device. The text in the advertisement reads: "Until Sony introduced the Walkman..., there was no way to hear quality sound reproduction this good unless you bought a ticket to Carnegie Hall, or sat home with an expensive stereo...it was impossible to ski, work, roller-skate or take a walk in a concert hall or your living room..." Left image retrieved from: <https://commons.wikimedia.org/w/index.php?curid=40687158>. Right image retrieved from: <https://www.ebay.com/itm/164023469775>

Some philosophical thinkers have studied the Walkman's profound effect on the human sensory experience of sound, notably in terms of its phenomenological implications. A phenomenological analysis of a product transcends the object itself, and studies the ways it manifests itself in the user's world. This could refer to how the product "may be a phenomenon in the external world of the senses, a visual quality in the sphere of experience, or the symbolic manifestation of intellectual structures or processes" (Bürdek, 2005, p. 240).

In his phenomenological study on the Walkman, Schönhammer (1989) addresses the aspect of auditory isolation, of shutting oneself apart from one's environment and others in it when he or she so chooses. He says, "The possibility of using the device to secure a kind of musical shelter in exposed situations creates a corresponding valence of the object: the Walkman becomes a symbol of a life beyond the separation between subject and world, a symbol for the permanent possibility of experiencing fusion". Schönhammer himself admitted to being irritated by the first users of the Walkman. Though it's taken for granted today, public acceptance of this individualist listening experience took time - tiny-earphone listeners were seen as "immature, withdrawn, narcissistic..., and so forth" (Schönhammer, 1989, p. 129). His frustration with Walkman-users sparked a deeper curiosity, leading him to understand that "people with earphones seem to violate an unwritten law of interpersonal reciprocity: the certainty of common sensual presence in shared situations" (ibid., p. 130). Since the 1980s, this common sensual presence has considerably been worn away: personal listening devices and noise-cancelling earphones are nearly omnipresent.

The example of the Walkman shows that product design is not just about the iterative process of development, or different strategies that designers may employ to create a profitable, user-friendly, ergonomically-shaped and aesthetically pleasing device. It is also about how an object can change its user's life: a product can alter their emotions, their relation to others and to the sensory world that surrounds them.

We believe that Ryzm™ represents a stepping stone on the path towards a more inclusive world of audio technology, where the tactile sensation of vibrations for our skin is produced, mastered and remixed much like music for our ears today. As Schönhammer (1988) addressed during the early days of the Walkman, the acceptability of new technology is not just about comfort of fit and seamless user-experience design. The perception of that device in society is also a driving force when any new, groundbreaking product is launched - especially if that product has an effect on something as intimate as the sense of touch. Understanding and predicting that societal perception can be made easier by integrating a user-centered design approach, which is a design process where the end-user has a direct involvement in the development process, "influencing how a design takes shape" (Abrás et al., 2004, p. 1). Ryzm™ is a direct product of research; the concept was elaborated based on the perceived aesthetic and perceptual potential of vibrotactile sensations observed during our research. Further along in its developmental process, the critical device evaluation will directly involve targeted end-users.

Extensive user testing of the future product should be structured around the analysis of not only device comfort and the quality of audio-tactile sensations, but also some more psychological implications of use, addressing questions like: do users perceive a risk of being judged when wearing the device in public? What would they think of someone else, if they saw them wearing the device? What would make them

seem attractive when using the product? Since it is a wearable device, visible to others, keeping in mind the public eye will be crucial when designing for public use. The definition of Ryzm™'s exact user testing protocol is out of scope of this research, but the design recommendations elaborated in the current chapter's section 2.1, along with these considerations, provide takeoff points for the future of its development.

3.2. Speculative Design

We provided an in-depth overview of speculative design in the State-of-the-art, section 3.3. Here, we will provide some examples of speculative design projects to further contextualize the diversity of approaches inherent in its definition.

Auger (2013) gives several diverse examples of speculative design, ranging from a battery fueled by a loved-one's ashes (*Afterlife*), to a floppy disk that stands up on its little legs when it detects there is water nearby (*Floppy Legs*). The unique nature of each speculative design, “and the diversity of possible subjects, contexts, technologies, perspectives and audiences make a definitive ‘how to’ guide impossible” (Auger, 2013, p. 31). To demonstrate speculative design through a single case study would paint an incomplete picture of the approach, so we will instead provide several examples with brief project explanations. These examples were found in the book *Critical, Speculative and Alternative Things* by Bruce and Stephanie Tharp (2018).

Asimov's First Law bathroom scales (Fig. 48) question Isaac Asimov's first law for robots: a robot may not harm a human being. However, existing domestic technology already harms us: they are already damaging us psychologically. In the first of the series, the White Lies scale (left image) “allows one to lie to him/herself. The further back you stand, the lighter you become. The user can gradually move closer and closer to reality.” The Half Truth scale makes your partner responsible to tell you the truth or lie to you about your actual weight.



Figure 48: Asimov's First Law bathroom scales, Alison Wang. Isaac Asimov's first law for robots is “A robot may not harm a human being.”

Image retrieved from:

<https://www.dezeen.com/2008/03/02/asimovs-first-law-scales-by-alice-wang/>

The Urban Canaries project (Fig. 49) features a small toy-like device, designed to be carried by a child. It lights up in different colors (shades of green, yellow and red) to alert levels of toxic air pollution, sending signals to the child's parents when needed.

Frank Kolkman developed the provocative OpenSurgery project (Fig. 50), which “aims to provoke alternative thinking about medical innovation by challenging the socioeconomic frameworks healthcare currently operates within” (Kolkman, 2015). These DIY surgery robots suggest a more accessible, alternative way to bring surgical procedures to communities in need, outside of existing healthcare frameworks.

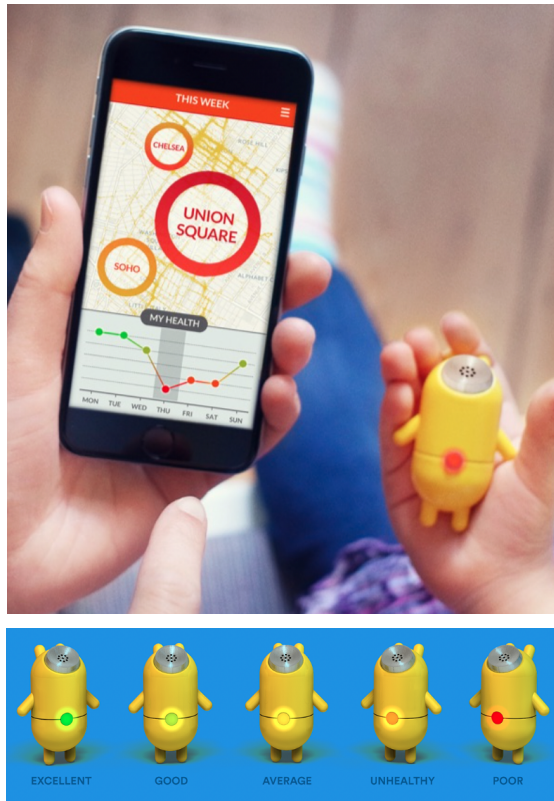


Figure 49: Urban Canaries, Daniel Goddemeyer. This project features a small, portable device that is destined for use by children, whose parents can follow the amount of pollution exposure throughout the day.
 Images retrieved from: <http://urbancanaries.com/>



Figure 50: OpenSurgery, Frank Kolkman. This imaginary surgery technology provides a DIY solution to people without adequate access to health care in their region.
 Image retrieved from: <http://www.opensurgery.net/>

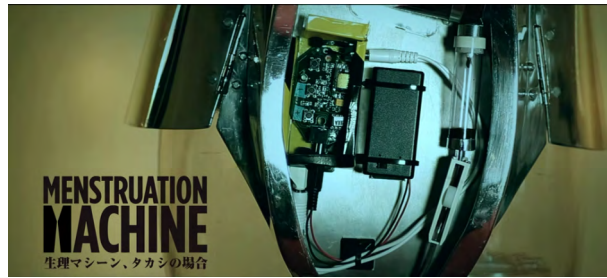


Figure 51: Menstruation Machine by Sputniko!, as shown in video stills. The menstruation machine simulates the pain of menstruation, making it possible for any individual to experience.

Images retrieved from: <https://sputniko.com/Menstruation-Machine>

Finally, the Menstruation Machine by Sputniko! tells the story of a blood-dispensing device with integrated electrodes that cause the same kind of pain experienced by women during their periods (Fig. 51). Men, children or postmenopausal women can wear the machine to understand what it's like to experience menstruation. The above video stills show Sputniko!'s film where a character, Takashi, builds and wears the machine in public: “thus, an internal, private process is transformed into a wearable and manipulatable design, a public display of pain and identity” (Tharp & Tharp, p. 412).

The multimodal harness is an example of speculative design in many senses of the term; it could theoretically fit in with the other examples listed above. However, we designed the multimodal harness not as a critique about today's existing personal listening devices, nor as speculation about the future of wearable technology for perceptual enhancement. A simple message drove its design: the experience of sound is about the experience of vibrations, whether we perceive them with our ears, with our skin, through the air or through our body. The multimodal harness embodies this message in that its functionality enables all of these modalities and parts of the body to participate in the experience of sound. The multisensory experience that the device facilitates is thought-provoking, but not provocative in an extreme sense: we do not use it to revulse or shock the user. Categorizing the multimodal harness by using a recognized term like ‘speculative design’ (though many people have their own terms for a similar approach towards design), is useful in order to improve visibility of the project, to simplify the understanding that it is not meant to be a consumer product, and to encourage debate about its implications for human auditory perception. It is useful to note, perhaps, that we did not specifically develop the device with the principles of speculative design in mind. Auger (2013) mentions that many people inadvertently conduct critical and speculative design.

4. “The Reciprocity of Speculative and Product Design Research in an Industrial Framework”

In this section, we present section excerpts of an article presented at the 2022 Haptics and Audio Interaction Design conference (HAID), titled “The Reciprocity of Speculative and Product Design Research in an Industrial Framework” (Richards et al., 2022, pp. 81-91). Based on what we have already elaborated in the previous chapters and sections of the thesis manuscript, we removed all redundant sections of the article. The article’s content has not been modified for this section, apart from the heading style, figure numbers, and citation style. For reference, the full article can be found in the appendix, pp. 213-222.

Introduction (Richards et al., 2022, p. 81)

Our research centers on the creation and study of wearable audio-tactile devices, built to transmit vibrations that stimulate both the senses of touch and hearing. To better understand the potential for body-based listening and the compositional possibilities it affords, we focus on three main axes: the exploration of sensory capacities (Richards et al., 2021), wearable device design processes, and audio-tactile sensory effect composition (Richards et al., 2022). Here, we focus on the second axis: understanding how design processes have shaped the purpose and form of two wearable audio-tactile devices, defined as design artifacts. Both of the artifacts manifest the main objective behind our research: push the possibilities for including more of the body in the listening experience. However, at the start of their development, the devices had contrasting purposes: one aimed for novel experimental possibilities, while the other centered on commercial applications.

In this case study, we position these artifacts of our research in terms of speculative and product design. Our goal in categorizing our work and retrospectively evaluating these design processes is to demonstrate the value of coordinated scientific and commercial work, which has ultimately advanced our research objective and better integrated our project within its industrial environment.

Speculative Design Artifact

Speculative Artifact Purpose (Article p. 84)

The multimodal harness was born from the motivation to challenge the status quo of listening experiences, one that assumes we need properly functioning ears to appreciate sound. This motive naturally led us to create an object that looks strange, even absurd. The notion of hearing through our skin and bones may also seem bizarre, but the multimodal harness makes this a real experience, while keeping it at arm’s length from practical everyday use due to its inherent ergonomic constraints and cyborg aesthetic. Beyond its look, the experience of the multimodal harness is also an argument for its classification as speculative design. The act of putting on the harness requires the user to question their assumptions about sound perception. In order to hear, users must first become deaf: when using the harness, they cover their ears from all external, airborne sounds in order to ensure they are only hearing via extra-tympanic conduction. Instead of perceiving the sounds via one central point (the head), the user’s torso is covered with vibrating modules that stimulate their skin,

muscles, ligaments and bones. The harness is therefore a vessel for speculative debate, blurring the boundaries of auditory experiences.

By using initial interfaces for multimodal effect design, we can create sensory effects that support our hypothesized mode of listening: sounds reach the ears from within the body, paired with accompanying spatialized tactile sensations that expand, slide and dart across the outer skin's surface (Richards et al., 2022). During demo sessions of these interfaces, users have commented that after an initial period of adjustment, they feel a rapid connection to their bodies, concentrating only on the sounds and sensations. In this direction of thought, the multimodal harness fits in an alternate timeline of our physical connection to sound... could we design interfaces to envelop our bodies in sound in the way that headphones envelop our heads.

Product Design Artifact

Product Artifact Purpose (Richards et al., 2022, p. 86)

With Ryzm™, we bridge the gap between our ongoing scientific investigation and the tangible value of our work to our research partner, Actronika, a growing deep-tech business specialized in vibrotactile integration and product development. By adapting to this industrial context, we find ourselves in what is probably a common situation, as “the majority of design research is paid for by the development industry” (Zimmerman et al., 2007). To adapt, we identified a use case that fit our initial results and the company's haptic expertise: tactile-augmented listening experiences. Ryzm™ was imagined as a tactile listening device that will build on things consumers have already experienced about audio technology and haptic accessories, but in a slightly different way. To make new technology more easily acceptable, that degree of difference should sway users' perception of the product towards an improved existing experience rather than one that is totally new and unusual (Desmet and Hekkert, 2007). If successful, Ryzm™ may allow us to inject an aspect of our research into society at large, communicating that sensory experiences of sound are diverse and arguably under-served by today's dominant audio technology.

Positive Project Impacts (Richards et al., 2022, pp. 87-88)

Through a retrospective view on the artifacts' development, we can give a few insights about the complementarity of the speculative and product design processes. Their reciprocal nature can be demonstrated in terms of three main positive project impacts: it advanced a common objective, defined the product concept, and built mutual understanding between our commercial and scientific partners.

Positive impact 1: Advancing a common objective

Though their purposes and forms are different, the process of creating the two design artifacts has taken our research objective in a common direction. The act of wearing the multimodal harness forces the user to challenge their assumptions about sound perception and helps to imagine another evolutionary path of personal listening devices. However, its speculative purpose constrains its use to experimentation: it is heavy, wired, requires the use of earplugs, and users can realistically wear it only for short periods of time due to the tight fit. Finding its roots in the same research

objective, Ryzm™ offers a compromise between idealism and practicality. The product concept suggests a more easily acceptable, ergonomic and less time-consuming solution to the industrial development of novel audio-tactile wearable technology. Such a product could already introduce ETC and tactile sensations of sound to the upper neck and clavicles, and potentially pave the way for more of the body in future listening devices.

Positive impact 2: Defining a product concept

In Fig. 52, we illustrate how the “problematic” nature of the speculative artifact helped define the product concept in terms of industrial considerations: the user, the scale of development, the market, and project timelines. We first identified the most impractical aspects of the multimodal harness to define Ryzm™’s future characteristics: uni-size, lightweight, simplified development and use, and familiar appearance. Without the multimodal harness at hand, we would not have had these points of comparison that helped guide the definition of a user-centered product.

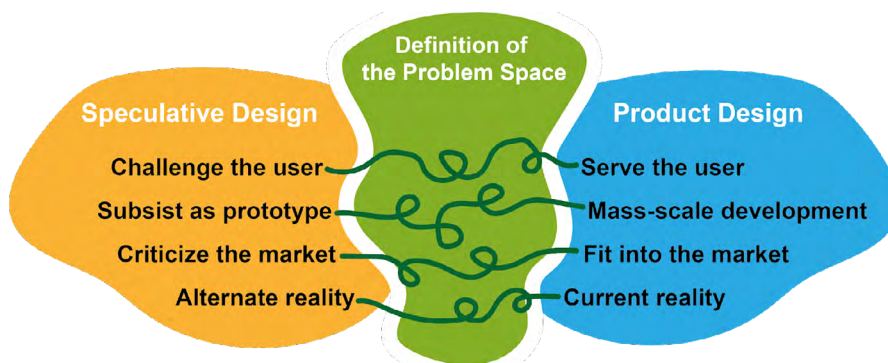


Figure 52. In our project, the speculative design process influenced the product design process due to the problem space which naturally emerged between them. This problem space was built on contrasting purposes, as shown in the figure. The most “problematic” aspects of the multimodal harness revealed how Ryzm™ must be different in order to be commercially practical.

Positive impact 3: Fostering mutual understanding

Certain key moments in each artifacts’ development demonstrate the interactions between the two design processes (see Fig. 53). To be able to respond to our industrial partner’s commercial requirements for our project, we needed to understand their expectations and facilitate their understanding of our research: something best done through a collaborative activity. We therefore started the Ryzm™ project during a workshop with colleagues. This resulted in an initial design concept, sketched while we finalized the first multimodal harness prototype. As we developed initial prototypes of the Ryzm™ product, we also developed the second prototype of the harness. By developing the prototypes at the same time, we were able to maintain close contact with Actronika’s mechanical and electronic design teams. Through our research, we also created another connection with Actronika’s co-development partner, Les Vertugadins. The consistent internal communication and integration of our project in our partner’s external network helped to assimilate the speculative

research in the industrial context, building mutual understanding and accelerating both artifacts' development.

Conclusion (Richards et al., 2022, pp. 88-89)

Through all of these aspects of our case study, we demonstrate that the two parallel design processes had a reciprocal relationship: the interactions between them propelled both speculative and product development, and advanced our research in body-based listening experiences. The industrial environment that gave life to our work has helped to ground our speculative design approach and emphasize the importance of a practical output: an objective of commercial product design. The two design artifacts are interdependent despite their contrasting purposes: the scientific context for developing the multimodal harness could not have existed without the commercial context for developing Ryzm™, and vice versa. While speculative artifacts like the multimodal harness don't target commercial use, they give the design researcher the freedom of imagination. This creative liberty may seem to be at odds with the controlled nature of the scientific method and time-sensitive commercial development, but without it, neither design artifact would exist. Through this case study, we hope to have illustrated the value of a peaceful coexistence between uninhibited creativity (speculation) and practical constraint (commercialization) in an industrial environment. In future work, we will extend this analysis to other audio-tactile device development, with the hopes to expose commonalities and explore the diversity of speculative methods in multidisciplinary product design projects.

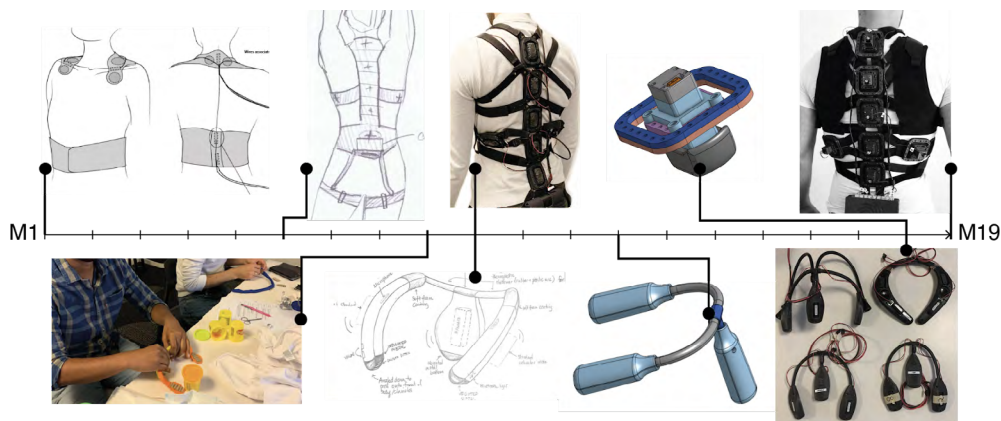


Figure 53. Overlaid 19-month timeline of speculative (top) and product (bottom) artifact development. Images are taken from project records. The two processes overlap: phases of brainstorming, sketching and prototyping occurred in parallel and provided momentum for both artifacts' development.

Acknowledgements

This research is part of a CIFRE industrial PhD contract, funded by Actronika SAS and the ANRT. We thank James Auger, Frédérique Pain and Pablo Arias for their contributions through insightful discussion. We also thank all of our colleagues and our co-development partner Les Vertugadins for their continued partnership.

5. Integrative Design

By using speculative design to describe the multimodal harness, and product design to describe Ryzm™, our ultimate goal was to relate each approach to the other, and show that in the scope of this project, they have a cohesive, reciprocal relationship. If we were to analyze the rest of the project according to the interactions between other contributing disciplines, pair-by-pair, we would find ourselves within an infinite array of intricately connected design processes. To avoid this confusion, this chapter's final section elaborates an integrative approach to design research. In this way, we demonstrate that the project is a cohesive whole, rather than a haphazard collection of contributions from diverse methodologies, collaborators and disciplines.

The Design-Science Dynamic

In this section, we present a partial view of the history of design and the many ways one may interpret the evolving dynamic that exists between design and science. Archer (1981) wrote, "Design, like science, is a way of looking at the world and imposing structure on it." Over time, the popular understanding of design has transformed from a field of arts and crafts to describe a wide-ranging domain of multiple industrial and academic disciplines, spanning processes and theories, apparel and interiors, interfaces and electronics, experimentation and events. This multiplicity of design categories is a reflection of the infinite number of ways mankind has manipulated nature. Design therefore has no singular, generic definition, as is reflected by the ongoing debates about the many categories of design practice, research and theory.

The etymology of the word "design" comes from the prefix "*de*" and the Latin verb "*signare*": *designare*, to mark, mark out or sign. It describes the designer's conceptual process, concerned with imagination and interpretation. In Western culture, design is often associated with the search for new processes and products; it is highly correlated with the words "innovation" and "novelty" (Terzidis, 2007). The association to novelty and problem solving that reflect design methods of today can be traced back to the emergence of early design methods in the 1950s and 60s, which were drafted as procedural responses to urgent problems resulting from the second World War, and as a way to gain a competitive, creative edge in an increasingly globalized society (Cross, 1993). The earliest authors of design methodology promoted a stark distinction between design and science, arguing that "science is analytic, design is constructive" (Gregory, 1966), and differentiating the two realms based on the existing and the novel: "The natural sciences are concerned with how things are... design on the other hand is concerned with how things ought to be" (Simon, 1988). However, as Cross points out, this dichomatic perspective becomes too simplistic when we observe the similarities between the hypotheses and theories that guide the working processes of both scientists and designers.

One key argument used to distinguish design and science is reproducibility: repeated results of a scientific process must show consistency, while results of a design process can speak for themselves. This does not imply that concrete results of a design process cannot be scientific (i.e. reproducible), but rather that they do not need to be in order to be viewed as designerly. Industrial product design, for example, adheres to the scientific process in that each result of the industrial design process is rigorously evaluated in terms of consistency of quality. We estimate that Cross would

deem this to be *scientific design*: modern, industrialized design that is distinct from craft-oriented design. He differentiates *scientific design* from *design science*, which approaches design as a systematic, organized, and rational scientific activity (Cross, 1993).

As previously discussed in the state of the art section 3.1, Frayling (1993) built on the relationship between design and science by approaching science through the lens of the word “research”. He described three main research-based approaches to design: research *into* art and design, *through* art and design, and *for* art and design. Research *into* design is historical, and is focused on the exploration of existing theories and perspectives. Research *through* design is centered on development and action; it could involve, for example “customizing a piece of technology to do something no-one had considered before” (Frayling, 1993, p. 5). In research *through* design, the designer-researcher aims to contextualize the results of their actions by reporting them, communicating their findings to others. Research *for* design considers the end results as an artefact: an iconic, concrete result that embodies aspects of the research that cannot be communicated verbally. These three possible types of design research proposed by Frayling, though admittedly vague, have served as a guideline for categorizing possible academic approaches to design. Most importantly, they establish the designer as not only a creator, or a productive participant in society, but also as a thinker and a researcher. The designer does more than come up with new ideas for products, draft a plan for a building, and design user interfaces. They also report about and analyze their own and others’ creations, theorize about the broader implications of their work, and debate about design’s place in the scientific realm.

Friedman (2008) addresses Frayling’s proposal, arguing that his three different categories of design research were not meant to be understood literally, as established fact, but rather as intellectual probes to open possibilities for different categories of design research. He points out that there have been few successfully clear examples of research by design, for design or through design (Cross (1999) had also noticed this). In his perspective, since these categories of research were meant to be suggestions, open to interpretation, not much design work can be made to fit into any of them. Frayling succeeded in offering new, relevant thoughts about potential types of practice-based connections between design and research, but Friedman argues that many have misread the categories of design research he proposed as being proof that design practice can be equated to design research. He states: “While we learn the art and craft of research by practising research, we do not undertake research simply by practising the art or craft to which the research field is linked” (Friedman, 2008, p.156).

Positioning our design research approach in the science-design dynamic is a question of perspective. In its entirety, our project does not fit inside any distinct category of design research. Aspects of scientific design, design science, research-by-, -for-, and -through-design each appear according to the selected practical, theoretical or experimental aspect of our project that we may choose to analyze. If we analyze our project in terms of its artefacts, the audio-tactile devices that embody our research objective, we align with the “for” design approach. Reporting the choices in the process of creating those devices and evaluating their functionality according to our hypotheses plants our research in a “through” design perspective. As an industrializable product concept, Ryzm™ reflects “scientific design”, while the “design science” process could describe the way we recount the experimental

applications of the monopoint module and the multimodal harness. The fact that our project resonates with each one of these existing types of design research demonstrates their relevance, but they also introduce unnecessarily complicated levels of categorization, and don't encourage a cohesive view of our research objective.

Gestalt Theory

Gestalt theory is commonly used to refer to the organization of visual elements (in French it has been referred to as *la psychologie de la forme*¹²). It describes visual effects of "holism" due to proximity grouping, continuation, similarity and structural economy (Behrens, 1998). Principles of Gestalt thought can also help us to communicate an integrative perspective towards our design research. In 1890, Christian von Ehrenfels wrote a paper "On Gestalt Properties", arguing that, "clearly, if a melody and the notes that comprise it are so independent, then a whole is not simply the sum of its parts, but a synergistic 'whole effect', or *gestalt*" (Heider, 1973).

One of the founders of Gestalt philosophy, Kurt Koffka, recognizes the potential for generalization about what defines a Gestalt. In *Principles of Gestalt Psychology* (1935), he asks,

Do we then claim that all facts are contained in such interconnected groups or units that each quantification is a description of true quality, each complex and sequence of events orderly and meaningful? In short, do we claim that the universe and all events in it form one big Gestalt?

His answer is, of course, no. He explains,

The Gestalt category does not mean that any two states or events belong together in one Gestalt. "To apply the category of cause and effect means to find out which parts of nature stand in this relation. Similarly, to apply the Gestalt category means to find out which parts of nature belong as parts to functional wholes, to discover their position in these wholes, their degree of relative independence, and the articulation of larger wholes into sub-wholes." (Koffka, 1931, cited in Koffka, 1935.)

What Koffka has illustrated at the end of this paragraph describes the analytic approach that we seek to put forward for our multidisciplinary, yet integrative, design research project. Rather than to analyze each of the different parts of our research in terms of their individual disciplinary approach, it is more relevant to view them in terms of the whole project; in terms of how each output of the audio-tactile devices is more or less independent, how each relates to the others, and how each participates in forming a cohesive response to our main research question: *What design and research methods will allow us to create and reflect on an alternative experience of sound, which involves the whole body?*

¹² 'the psychology of form'

Integrative Design

Inspired by the principles of Gestalt theory, we propose “integrative design” as a new term to describe design research projects whose outputs don’t fit into any one single existing category. We define this term out of functional necessity for our project: it brings structural clarity and emphasizes the connections between seemingly discrete thematic contexts. The integrative design approach allows such a project to be identified as a whole, rather than as a collection of distinct parts. Here, we could ask the same question Koffka posed regarding the formation of a Gestalt: Do we claim that all multidimensional design research is integrative design research? Similarly, our response is no. Integrative design follows the same essential rule as Gestalt theory: not any combination of elements can form a cohesive, integrated “whole”. The inclusion of each contributing part needs to be justified in terms of its relation to the central project narrative.

Our integrative design approach is not the same as “integrated” design, a term used to describe the “coordinated development effort in timing and substance of the various disciplines and organizational functions that span the life-cycle of new products and services” (Ettlie, 1996, p.33). Ettlie (1996) defines the integrated design approach according to refined, accelerated methods used to sustain a company’s competitive advantage in the market. The integrated process is an industrial methodology, used to speed up a product’s time to market and optimize its market success. It applies three key methods: speed up existing task completion, simplify jobs and remove unnecessary tasks, and eliminate redundancy. Vajna (2020) describes Integrated Design Engineering (IDE) as the evolution of Integrated Product Development (IPD), a similar concept to what was described previously by Ettlie (1996). Vajna (ibid.) describes the integrations that define IDE as being related to the connections between individual departments of a company, teamwork methods, and computer-aided applications used across different activities in the industrial structure.

The key difference between integrative and integrated design is, therefore, the fact that integrative design is not a strategic industrial approach towards product development. Both approaches describe methods to bring cohesion to projects involving diverse actors and disciplines. However, integrative design describes a cohesive position towards a multidisciplinary design research process, and is not limited to product design. Therefore, it can include various design processes and methods. It is more of a property of, or perspective towards a design research process than a separate type of design research, in that it integrates various research methods and developments in the project.

Integrative Design: Project Criteria

A broad understanding of integrative design may reflect aspects that are standard to design research. To bring precision to our specific approach in terms of how it has functioned in this particular project, we will describe its defining features in a consistent and useful way for future design research. We propose the following six criteria to define integrative design according to our project approach:

1. Integrative design is inherently **multidisciplinary**. The design research project involves contributions from multiple disciplines, design and otherwise.
2. The project's defining purpose is the designer's **aim to integrate**: systems, people, modalities, etc.
3. The project integrates the **design-science dynamic**, establishing connections between design and scientific methods.
4. Each output of the research has a **unique** position as a part of the whole project.
5. The message behind the different elements of the research is cohesive: each output of the research disseminates a variation of the same project **narrative**.
6. The **design process** supporting those research outputs articulates the connections between their corresponding disciplines.

Integrative Design: Project Narratives

One particular aspect of integrative design that may be of practical use is the definition of a project's narratives (criterion 5 of the list above). Each element of the project tells the story of our research objective in the terms of its corresponding domain. These narratives address the diversity of the project and adapt it according to the perspectives and objectives of the project partners who have shaped the products of our research. In an effort to understand how design changes according to different organizational contexts, Zurlo and Cautela (2014) describe how different narrative frameworks relate the design project to the different companies, innovation processes, and coordinate relationships with different designers, making the unfamiliar more familiar to the different project actors. Citing Bartel and Garud (2009), they identify that narratives serve a primary function of *translation*: they translate ideas across different parts of an organization, they translate ambiguous situations to promote problem solving, and they translate ideas that embody accumulated past innovations.

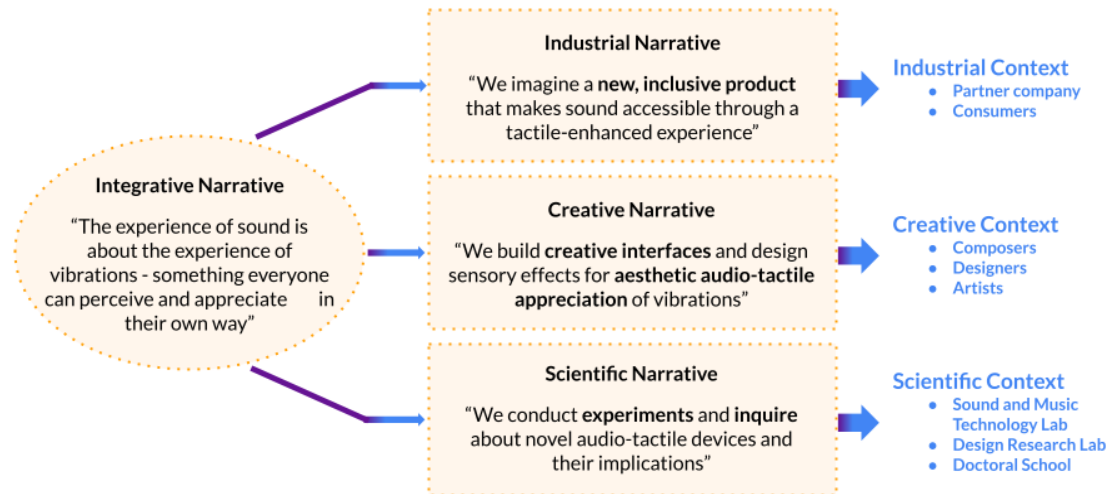


Figure 54: Articulating different narrative contexts of the doctoral research project contributed to its overall cohesion. Throughout the research, we used context-specific narratives to reach common ground with respective project partners. Actors in the haptics-specialized partner company, the doctoral institution, the design research lab, and the sound and music research lab find familiarity in different variations on the integrative narrative. These narratives also served as guides for ourselves, as we navigated how to orient our approach according to the diversity of research objectives.

If narratives serve a purpose of translation across the project organization, integrative design is multilingual, translating the core narrative message so that it becomes familiar to each individual actor. The spectrum of our project’s narrative framework encompasses a range of vocabularies (ergonomic, user-centered, experimental, psychophysical, creative, haptic, acoustic, multimodal, musical, mechanical electronic...) to speak in three main narrative languages: experimental/scientific, industrial, and creative. The experimental narrative validates the purpose of our work in the eyes of scientific experts in the field of multisensory research, the industrial narrative speaks to the objectives of our industrial partner, and the creative narrative contextualizes the outputs of research for creative use. At the center of these is the integrative narrative, whose core message is reinterpreted for each context (see Fig. 54 for an interpretation in terms of our project’s narratives).

Integrative narrative:

“The experience of sound is really about the experience of vibrations - something that everybody can perceive, and appreciate in their own way.”

→ *Experimental narrative:*

“We design **experiments** to study the **audio-tactile perception** and appreciation of vibrations.”

→ *Industrial narrative:*

“We imagine a **new product** that makes **sound accessible** to users through haptics and bone conduction.”

→ *Creative narrative:*

“We **design creative interfaces** and **compose multisensory effects** for the body.”

Regardless of the precise vocabulary employed in each domain-specific narrative, this aspect of the integrative design approach can allow the design-researcher to reorient themselves according to their different project goals, and acknowledge the needs of the diverse project actors in their own terms, facilitating communication and improving cohesion within the project’s organizational framework.

6. Conclusion

In this chapter, we have focused on the beneficial influence of the industrial context on the advancement of our main research objective, and how this has enabled us to articulate the connection between speculative and product design approaches. Categories help to reveal commonalities between different works, stimulate debate and inspire new contributions. However, evaluating multidisciplinary design work according to existing categorical definitions can also needlessly limit the scope of its analysis. If we were to separate each of the outputs of this research in terms of *either* product design *or* speculative design *or* sound design *or* universal design, etc., this would neglect the fact that they are interconnected, *integrated*. They find cohesion through the different ways that they respond to our main research question: an investigation of diverse methods for the creation of an alternative, body-based experience of sound, along with their accompanying theoretical implications.

Whether they appear before or after this section, each output of our research symbolizes the common thread of integration. By defining integrative design at this point in the thesis, we represent the timeline of thought as it occurred during the course of the doctoral research, and we emphasize its particular relevance to the final experimental and creative outputs of the multimodal harness, which will be described in the following Chapters IV and V.

In our project, we can identify one key integrative artefact: the multimodal harness. It fully embodies the integrative nature of our project, both in terms of its functionality as a device for multimodal perception, and in terms of how it has connected contributions from all of the diverse disciplines involved in our research. In Chapters IV and V of the thesis, we will describe the outputs of this device according to the ways in which it has introduced different experimental and creative methods as responses to our research objective.

Chapter IV: Audio-Tactile Perception and Judgment of Vibratory Stimuli

1. Introduction

In this chapter, we present an overview of the experimental outputs generated by the multimodal harness. These experiments generated contextual relevance of our research for the scientific community, guidance about how we may better design audio-tactile effects for the body, and clear opportunities for future investigation about audio-tactile perception. Prior to designing the two experiments of this chapter, we confronted ourselves with practical questions about the multimodal harness, essentially related to its use in creative contexts. To design audio-tactile effects for the body, we first wondered how to elucidate some of the finer details about the multimodal perception of the vibratory signals. The user's ability to hear, feel, or simultaneously hear and feel the audio-tactile effects depends on the parameters we may manipulate in a creative interface: the signal's intensity, its frequency, and its position on the device. We also wondered how the multimodal harness might be used as a complement to a more traditional mode of listening: with headphones. If, in a certain creative context, we wish to focus only on the tactile aspect of the vibrations transmitted by the multimodal harness, we should know what aspects of those vibrations allow the user to appreciate and feel most connected to their musical experience.

In this chapter, we address these queries through two experimental procedures, both developed in collaboration with our research partners at Actronika: Vincent Hayward and Damien Faux. The experiment developed in section 2 was developed with Scott Aker and his thesis director Jeremy Marozeau, in the framework of an international collaboration with the Technical University of Denmark and the industrial project sponsor Demant. It deals with the associations, or congruences, between auditory and tactile stimuli, in particular in terms of auditory pitch and placement of tactile stimuli on the body. In section 3, we describe an experiment whose aim was to help us better estimate the user's perception of a given vibratory signal while wearing the multimodal harness, according to how much they heard it, versus felt it.

2. “Evaluation of Audio-Tactile Congruences for a Wearable Musical Interface”

The following passage contains an article in preparation for submission, written with the co-authors: Claire Richards, Scott Aker, Jeremy Marozeau, Damien Faux, and Nicolas Misdariis. This manuscript contains the content as it was originally submitted to the Multisensory Research Journal. At the time of the final version of this manuscript (May 2023), the authors are reworking the content and preparing to resubmit to the Journal of New Music Research.

All sections of the submitted article are identical to those in this passage, save for the removal of the description of the multimodal harness to avoid redundancy. Figures are numbered according to their position in this manuscript. All references in this article have been gathered in the thesis’ bibliography.

Abstract

The development of wearable technology for tactile-augmented musical experiences is growing, and with it the need to consider how we may best design tactile effects for the body. Since associations between auditory pitch and spatial elevation are strong across hearing and sight, we evaluated whether the same type of crossmodal correspondence might benefit music experiences across hearing and touch. In a MUSHRA-style experiment, 21 participants (musicians and non-musicians) wore a wearable tactile device and rated a series of musical audio-tactile stimuli based on their preference. The musical stimuli were three simple melodies, composed to facilitate detection of comparatively high and low tones. Note by note, we varied the association of the tactile stimuli’s intensity, timing, and placement along the vertical axis of the back with the auditory stimuli’s intensity, timing, and pitch, respectively. Though we hypothesized that the pitch-height mapping would have a positive effect on perceived audio-tactile congruence, the results showed that only intensity and timing served as strong predictors for tactile musical enhancement.

Keywords: Crossmodal correspondence, audio-tactile congruence, wearable technology, music enhancement

Article Content

Introduction, Background and Study Structure

I. Introduction

We are inclined to associate high-pitched sounds with objects high in spatial elevation (Melara and O’Brien, 1987; Dolschied et al., 2014; Parkinson et al., 2012). Therefore, it seems intuitive to code auditory pitch to elevation in audio-haptic technology, which are often used to enhance music using tactile vibrations. Data supporting these crossmodal associations tells us that they are innate, and come from our earliest, neonatal neural mechanisms (Dolschied et al. 2014). However, it is not known if these associations translate into an appreciable benefit of coding auditory pitch to a vertical display of tactile signals (tactile signal “height”). The current study addresses this question by evaluating vibrotactile stimulation as a means for multimodal musical

enhancement. In a previous study, Aker et al. (2022) demonstrated that vibrotactile music enhancement can be derived from intensity-congruent and timing-aligned features in paired vibratory and musical stimuli. In the current study, we build on the authors' previous findings by testing the torso instead of the finger, in order to investigate which parameters of audio-tactile effects are most relevant for musical haptic wearables. We stimulate five different loci along the length of the back, evaluating whether the alignment of auditory pitch and spatial elevation of the tactile stimulation on the body contributes to musical enhancement.

A. Background

Spence (2011) describes crossmodal correspondences as “the many non-arbitrary associations that appear to exist between different basic physical stimulus attributes, or features, in different sensory modalities.” For example, it might feel natural to say that a small light-colored ball makes a high-pitched noise, while a large dark-colored ball makes a deeper noise (Mondloch and Maurer, 2004).

Research points towards a universal perceptual correspondence between spatial location and auditory pitch, in particular along the vertical axis: high-pitched sounds are often associated with objects located high up. Certain studies have documented crossmodal associations between auditory pitch and spatial elevation occurring regardless of the listener's stage of linguistic development: Dolschied et al. (2014) found that prelinguistic infants spent a significantly longer amount of time looking at stimuli that were cross-modally congruent in terms of spatial-pitch mappings. Parkinson et al. (2012) also demonstrated this association during experiments with a remote Cambodian tribe whose language does not use similar words to describe “high” pitch and “high” elevation. In a series of experiments, Chiou and Rich (2012) found that, by changing auditory pitch to lower or higher tones, they can shift participants' attention to correspondingly lower or higher spatial locations. Orchard-Mills et al. (2014) investigated the crossmodal correspondence between pitch and elevation by manipulating an illusion called the temporal ventriloquist effect. The participants' task was to report which of two visual stimuli were presented first, while high and low pitched tones were presented before and after the visual stimuli. Their experiment showed that, in contrast to height-congruent auditory tones, a tone that is incongruent in comparison to the height of the visual stimulus (i.e., a lower pitch for a visual stimulus placed above the fixation point) eliminates the improvement in performance on the temporal order judgment task. These results suggest that crossmodal congruency could influence the binding of information across the senses. Crossmodal associations between vibrotactile and auditory stimuli have also been observed in Occelli et al. (2009), in which discrimination responses between high and low frequency sounds, and high and low elevation vibrations, were improved when both the high frequency sounds and high elevation vibrations were associated to the same key.

Pitch-height correspondence has previously been used to justify pitch-height associations in musical haptic technology. The Emoti-Chair, an audio-tactile sensory substitution device designed by Bajjal et al. (2012), routes vibrations to the user's back according to an ascending frequency spectrum from the bottom to the top of the body. The authors explain their choice for this arrangement as informed by the literature that suggests a strong association between high spatial location and high

pitch (see Rusconi et al., 2006). Fletcher et al. (2020) also utilized a pitch-spatial map in their audio-tactile neuroprosthetic to show that vibrotactile stimulation can be used to enhance pitch discrimination for cochlear implant users. Regardless of mapping on the body, vibrations alone have also been shown to enhance a music listening experience (Merchel and Altinsoy, 2014). Several existing gilet-based haptic devices (SUBPAC, Skinetic, bHaptics TactSuit) transmit vibrations to the user's back in order to augment their musical or virtual reality experience, but do not utilize a pitch-height map. In a review of musical haptic devices for audiences, Turchet et al. (2021) explain that the main reasons for a lack of appreciation of the haptic experience are the choice of placement for the vibratory sensations on the body, and a lack of understanding about the relation between what is heard and what is felt.

Furthermore, it is important to consider the role of musicianship in both cross-modal correspondence and vibrotactile music enhancement. Musical training is a multimodal exercise; it primes the brain for inter-modal plasticity and creates connections between sensorimotor, somatosensory and auditory processing (Lappe et al., 2008; Zatorre et al., 2007). Kuchenbuch et al. (2014) demonstrate the impact of musicianship on audio-tactile associations. The authors created an audio-tactile correspondence paradigm where participants' fingers were stimulated with vibrations according to one of four auditory pitches, the spatial-pitch map organized in ascending order from the index to the little finger: similar to that of a stringed instrument. Listening to eight five-tone melodies, they had to evaluate whether the audio-tactile stimuli were congruent or incongruent. While cross-modal incongruencies are difficult to evaluate for both groups, the musicians were more adept at identifying which of the audio-tactile melodies were incongruent across modalities, showing that they have a higher multisensory incongruency response than non-musicians. However, this effect is also intrinsically related to the experimental context: Kuchenbuch et al. (ibid.) chose to route the tactile stimuli to participants' fingers in a way conforming to the natural arrangement on a stringed instrument.

Investigating the role of pitch-height correspondence on vibrotactile music enhancement could help inform how the tactile effects designed for music haptic devices might better correspond to the natural associations between sound and touch. Previous work by co-authors S.C. Aker and J. Marozeau has investigated how different audio-tactile congruencies affect vibrotactile music enhancement (Aker et al., in press). Participants were asked to rate audio-tactile melodies based on preference which were congruent or incongruent in intensity, frequency and timing which were presented through headphones and a haptic actuator held in the fingertips. The tactile parameters of intensity and timing caused participant ratings to drop when made incongruent with their auditory counterparts.

In the current study, we explored the effects of audio-tactile congruencies in a musical context, exploring the alignments between intensity, timing, and pitch-height mapping. We used a specific haptic device to present the tactile stimuli to the participant's torso: the Multimodal Harness. We investigated the pitch-height relationship with regards to the location of tactile stimulation on the back: when presented with high-pitched sounds, will participants indeed prefer to feel the accompanying tactile stimuli at a high position on the back, and vice versa for low-pitched sounds? Our main hypothesis lies in the congruency parameter of pitch-height mapping. We designed the pitch-height congruency parameter according to the assumption that participants, especially musicians, will demonstrate greater

appreciation for the stimuli whose high-pitched auditory component occurs at the same time as a high-positioned tactile stimulus on their back. By investigating which audio-tactile congruences improve participant ratings, future musical haptic devices can have their audio-tactile effect parameters made more perceptually relevant to users.

B. Structure of the Current Study

We structured our experiment based on the paradigm used in Aker et al. (2022). Participants were asked to rate audio-tactile stimuli which were congruent or incongruent based on three parameters of audio-tactile congruence that may affect the appreciation of music: pitch-height mapping, along with intensity and timing alignment (see section II.B for parameter details). The current experiment is different from Aker et al. in that stimuli were rated compared to a reference stimulus, which was only time-aligned between the tactile and auditory components. Amongst the rated stimuli was one stimulus identical to the reference (a hidden reference), and one made timing-incongruent (a hidden anchor), similar to a MUSHRA (Multiple Stimuli with Hidden Reference and Anchor, BS Series 2019). We evaluated the multisensory incongruency response through tactile stimulation along the vertical axis of the back. Through the current study, we aim to test the hypothesis that high pitches which correspond to vibrations placed high up on the body, and vice versa for low pitches, benefit vibrotactile music enhancement.

Our main hypothesis can be broken down according to several secondary assumptions, based on the parameters of the tactile musical stimuli which we manipulated to have different levels of congruence to the auditory musical stimuli: timing, intensity, and pitch-height mapping. In all conditions, the participants would rate the stimuli in terms of their preference, incorporating both auditory and tactile components. First, we assumed that they would rate the hidden reference stimulus at 0, as being identical to the reference stimulus. Second, we assumed that the tactile stimulus with mismatched rhythm, or timing unaligned, would be rated as worse than the reference in all conditions. Regarding the parameter of intensity, we assumed that stimuli that were aligned across audio-tactile intensity cues would be rated more positively than the reference, which had incongruent auditory and tactile intensities. We also expected participants to rate stimuli which were congruent in terms of intensity and pitch-height mapping higher than 0, and even more so than the stimuli which were congruent only in terms of pitch-height mapping. Finally, according to our principal assumptions about the effect of pitch-height mapping, we assumed that participants would evaluate stimuli whose channel mapping was upright (where high pitch corresponds to a high position of tactile stimulation, and low pitch to a low position) positively, and more so when the tactile stimulus was aligned with auditory intensity. On the other hand, we assumed that the stimuli whose channel mapping was upside down (where high pitch corresponds to a low position of tactile stimulation, and low pitch to a high position) would be rated negatively.

Methods

II. Methods

A. Participants

Twenty-one participants were recruited for the study, (11 males, 10 females, mean age 25.4 years, StD 2.5 years). To test for a potential effect of musical experience on the judgment of audio-tactile congruence, half of the participants were musicians (N = 11), and half non-musicians (N = 10). Participants must have been regularly practicing an instrument for at least 6 years in order to meet the musicianship criteria. All participants reported to have normal hearing. In accordance with the Declaration of Helsinki, all participants provided informed, written consent prior to the study. The INSEAD IRB provided ethical approval of this study (Protocol ID 2022-35).

B. Stimuli

1. Auditory Stimuli

Auditory stimuli were generated in MATLAB 2021b and routed to Beyerdynamic DT 770 PRO 80 ohm headphones through one channel on the Multimodal Harness' integrated sound card and amplifier (Actronika Mk.1). For all tasks, background masking noise (70 dB SPL pink noise) was presented in addition to the target stimulus in order to prevent any distractions due to ambient noise.

Music stimuli was adapted from three melodies, or “songs,” which incorporated high and low tones in different ways (see Fig. 55). All songs were in the key of D Major. Song 1 is a simple melody similar to the one used in Aker et al. (2022), which was adapted from the bassline of a song “szárad a száj” by the band “Chalga”. Song 2 is a drum-like rhythm based on the drum break, “Amen Break”, and was chosen as a melody with a large and constant difference between the two pitches. Song 3 is a pentatonic scale (see notations in Figure 55) and was chosen to have a clear rising and falling direction of pitch. Songs were manually written as MIDI (Musical Instrument Digital Interface protocol) files based on their respective origins. The pitches for the MIDI files were transposed to have a lowest pitch of D2 (73.42 Hz). The velocity of each note was manually rounded to either 127 (high intensity) or 64 (low intensity). The MIDI files were then converted to audio for use as stimulus. Each note was represented as a sine wave with the respective frequency of the original pitch, and a linear window of 31 ms. “Strong” velocity notes were scaled to have a dB SPL of 86, and “weak” velocity notes were scaled to have a dB SPL of 67.

Song 1

♩ = 100



Song 2

♩ = 100



Song 3

♩ = 80



Figure 55: The three melodies used for the audio-tactile stimuli define the congruences between the auditory and tactile intensity, timing, and pitch-height mapping. Song 1 is the melody used in Aker et al. (2022), which was adapted from the bassline of a song “szárad a száj” by the band “Chalga”. Song 2 is adapted from the “Amen break,” a drum break commonly sampled in popular music. Song 3 is a pentatonic scale.

2. Tactile Stimuli

The tactile stimuli were generated through MATLAB 2021b and routed through five different channels on the connected electronic board and amplifier (Actronika Mk.1) to the five transducers (Actronika HapCoil One) along the back of the Multimodal Harness. Tactile tones were 100 Hz sine waves with a duration of 1 second and a 31 ms linear window. Tones presented in succession had a one second gap between them. Tones presented to the bottom module had two intensity levels of “strong” and “weak,” which had an input voltage of 1.41 V and 0.50 V respectively. Tactile musical stimuli presented through the Multimodal Harness were generated from the same MIDI files as used for the auditory stimuli. The other four vibratory modules were calibrated on the device by the participants during the intensity matching task (see section II.C.1) to the “strong” and “weak” reference intensity levels of the bottom module. The tactile signals corresponding to the two notes of Song 2 were displayed to the top and bottom modules of the Multimodal Harness.

3. Congruence

a) Timing Congruence

Timing-aligned tactile stimuli used a rhythm with the exact same onset times and duration as its auditory counterpart, while timing unaligned tactile stimuli used a randomly generated rhythm (Fig. 56). The random rhythm was created by manually dividing the original melody into phrases, then generating a new permutation of each phrase which controlled for number of notes and total note duration.

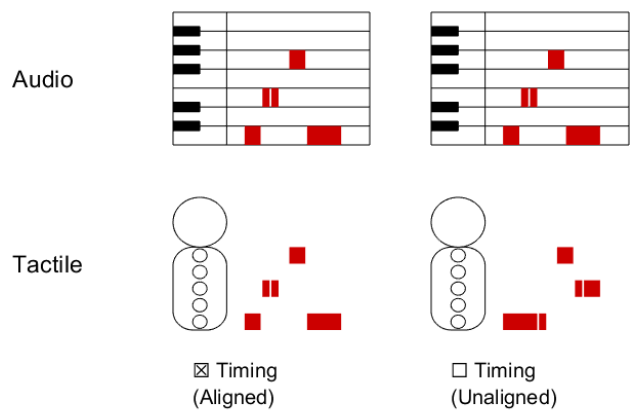


Figure 56: Graphic representation of timing incongruence. The x-axis for each subplot shows time, and the y-axis for each subplot shows either pitch for the audio stimulus, or height for the tactile stimulus. The timing of the tactile stimulus subplot on the left is timing aligned (or congruent) with the audio stimulus subplot on the left, represented by the checked timing box. On the right, the tactile stimulus subplot is timing unaligned with the audio stimulus subplot, represented by the unchecked box. Note that when the timing of the two stimuli are unaligned, the number and total duration of notes of the tactile stimulus is still equal to the number and total duration of notes of the audio stimulus.

b) Intensity Congruence

Intensity congruent tactile stimuli corresponded in terms of the calibrated levels of “strong” and “weak” tactile intensity according to the predefined “strong” and “weak” volume levels for the auditory stimuli. Intensity incongruent tactile stimuli had its “strong” and “weak” intensity levels assigned to each note randomly, however with the same overall distribution of “strong” and “weak” levels (Fig. 57).

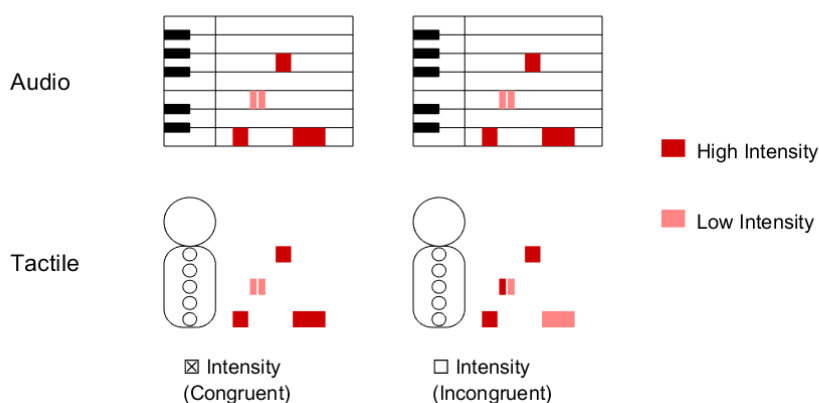


Figure 57. Graphic representation of intensity incongruence. Each of the four subplots has an x-axis showing time, a y-axis showing either pitch for the audio stimulus, or height for the tactile stimulus, and uses light red rectangles to represent low intensity notes and dark red rectangles to represent high intensity notes. The high and low intensities of the audio stimulus subplot and the tactile stimulus subplot on the left are congruent, represented by the checked timing box. On the right, the tactile stimulus

subplot is intensity incongruent with the audio stimulus subplot, represented by the unchecked box. Note that when the timing of the two stimuli are intensity incongruent, the number of high and low intensity notes are still constant.

c) Pitch-Height Congruence

The pitch-height congruence parameter was defined according to our initial hypothesis that participants, especially musicians, would recognize and appreciate when tactile stimuli higher up on their back were aligned with auditory stimuli higher in pitch, and vice versa. Pitch-height congruent tactile stimuli therefore correspond to either the “upright” pitch-height mapping (high:high, low:low), or the “upside down” pitch-height mapping (high:low, low:high). Including an opposite-organized pitch-height map (upside-down) in addition to the randomized, incongruent pitch-height map allows for further analysis of the potential effect of pitch-height congruence. However, if participants’ ratings show a benefit of the tactile stimuli which are congruent in terms of the upside-down pitch-height mapping, this would deny our initial hypothesis. Pitch-height incongruent tactile stimuli had the height of the tactile stimuli randomly assigned to each note, with no relationship to the corresponding auditory pitch, however with the same distribution. Examples of the three pitch-height maps can be seen in Fig. 58.

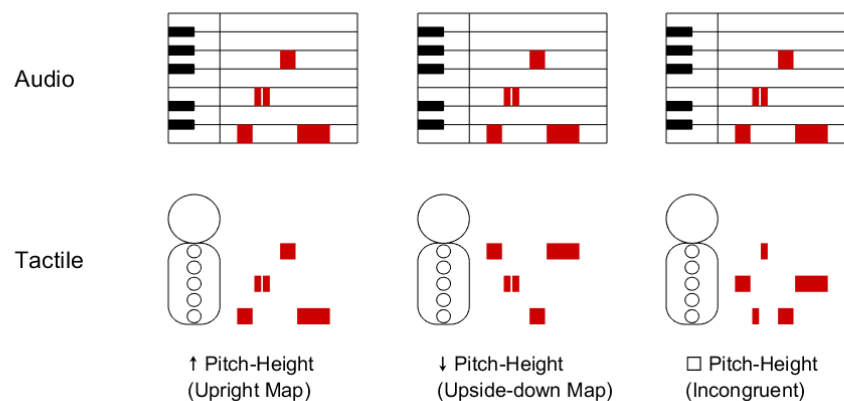


Figure 58. Graphic representation of pitch-height congruence. Each of the four subplots has an x-axis showing time and a y-axis showing either pitch for the audio stimulus. On the left-most subplot, the pitch of the audio stimulus and height of the tactile stimulus are congruent with a low-low and high-high mapping, represented by an up arrow (“upright map”). In the middle subplot, the pitch of the audio stimulus and height of the tactile stimulus are congruent with a low-high and high-low mapping, represented by a down arrow (“upside-down map”). On the right subplot, the height of the tactile stimulus is random and incongruent with the pitch of the audio stimulus. Note that when the height of the two stimuli are intensity incongruent, the number of high and low intensity notes are still constant.

C. Procedure

1. Intensity-Matching Task

The first task was an intensity matching task, which aimed to equalize the “strong” and “weak” vibratory signal intensity across all actuators according to participant’s individual sensitivity levels. The Multimodal Harness fits each participant differently. Variations in pressure between each participant’s body and the device can change how they perceive the vibratory signal intensity.

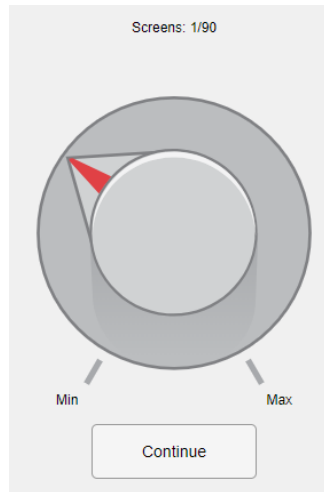


Figure 59. Intensity matching task GUI. The participants used the virtual knob to alter the intensity of the vibratory signal of the comparison stimulus.

In the intensity matching task, participants completed 90 trials in which they were presented with a virtual knob on a GUI on each trial (Fig. 59). Two alternating vibrotactile stimuli were presented to the participants in a trial: the reference stimulus and the comparison stimulus. The reference stimulus is fixed in level and always occurs on the bottom vibratory module. In half of the trials, the reference stimulus vibrated at “strong” intensity and in the other half at “weak” intensity. The comparison stimulus vibrated a different actuator for each trial, and the level could be adjusted via the virtual knob. Before manual adjustment, the comparison stimuli were always first displayed at the minimum intensity in order to ensure participants’ comfort.

All subsequent tactile stimuli were equalized to the strong or weak reference stimulus using individual data from the intensity matching task.

2. Control Experiment Tasks

In the control experiment, participants completed an order task to evaluate their ability to identify the different locations of the five tactile stimuli along the length of their back, transmitted by the five vibratory modules of the Multimodal Harness.

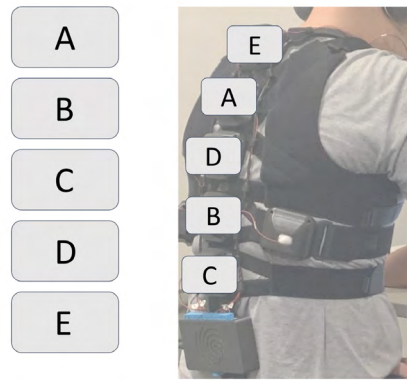


Figure 60. Order matching task. By clicking on each of the five buttons (left), participants activated a different transducer on the Multimodal harness (right). Unaware of the actual order on their back, their task was to list the letters according to descending order along their spine.

On the GUI, there were five buttons organized in a single vertical array. Each button triggered the display of a vibratory signal at one position of stimulation on the back of the wearable device. The signals displayed by each button did not trigger the corresponding position of stimulation in terms of top-to-bottom order along the spine (Fig. 60). Participants triggered each vibratory signal and attributed it to one of the five positions on their back, indicating their estimation of the correct top-to-bottom order. Participants' verbal responses were recorded to judge their ability to localize the stimuli on their back (see results in section III.A).

During the control experiment, we also conducted an informal intensity discrimination task, to verify that participants were able to clearly perceive the difference in the two tactile intensities which were calibrated during the previous intensity matching task (section II.C.1) at each position of stimulation on the back. Only three of 21 participants made any mistakes.

3. Rating Task

The final task was the rating task, in which participants were instructed to compare their preference between one reference audio-tactile stimulus and several test audio-tactile stimuli, judging whether each of the test stimuli were “better” or “worse” than the reference stimulus. The rating task was defined based on a MUSHRA-style experimental procedure. The evaluation scale ranged from -60 to 60, with -60 being “much worse” than the reference stimuli, 0 being identical, and 60 being “much better”. Hidden amongst the test stimuli was one “anchor” and one “reference,” which are stimuli that are expected to be rated a certain way: the hidden anchor should be rated poorly, and the hidden reference should be rated as identical to the reference stimuli. These known stimuli create a framework on the rating scale which serves to evaluate the level of consistency among the participants. Building off of Aker et al. (2022), the timing-incongruent audio-tactile stimuli was used as a hidden anchor.

The rating task consisted of six screens corresponding to six experimental conditions. In each condition, participants were presented with a GUI with six buttons, and six corresponding sliders from -60 to 60 (see Figure 61). Each button

would present an audio-tactile stimulus to the participant. Of the six stimuli, one was a labeled reference stimulus and five were test stimuli. The test stimuli's tactile components varied according to intensity-congruence, timing-congruence, and pitch-height mapping congruence (see Figures 56, 57, 58). Participants were instructed to rate each test stimulus based on their preference compared to the reference stimulus. To concentrate their sensory preference rating on the comparison between the reference and the test stimuli (not in between test stimuli), participants were forced to re-click on the reference stimulus in between every test stimulus. The participants could interrupt and re-play the stimuli as they wished. To move on to the next screen, they must have rated every test stimulus.

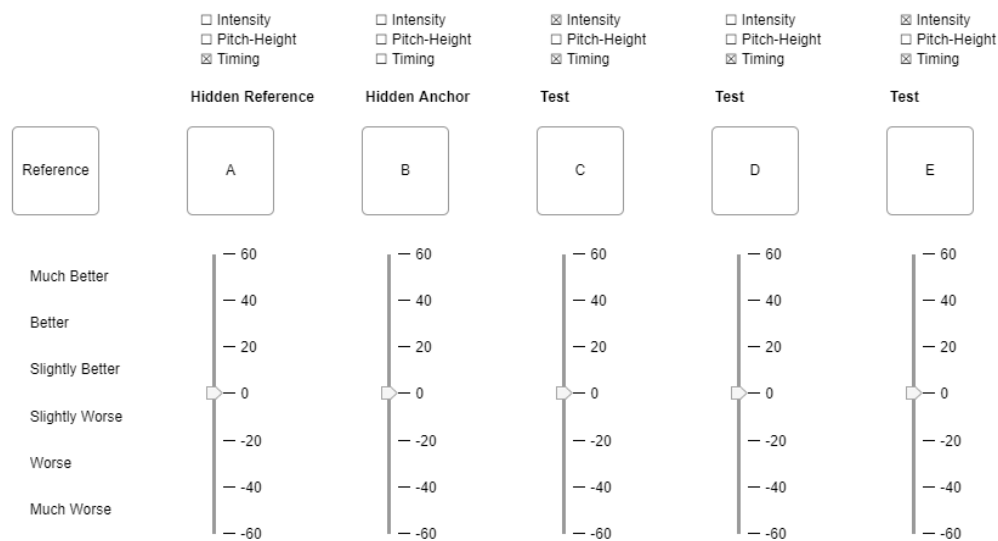


Figure 61. GUI setup for the rating task. Each of the six screens (one for each experimental condition) was composed of the same assortment of audio-tactile stimuli, based on their congruency parameters. The order of the five test stimuli was randomized for each of the six screens. The only stimulus that was timing-incongruent was the hidden anchor.

Results

III. Results

A. Control Experiment: Order Matching

Results for the control experiment, described in section II.C.2, are seen in Figure 62. The results showed a majority of participants making at least one mistake. While participants were generally able to differentiate the different tactile stimuli's locations on their back, the most confusion occurred between the top two transducers (E and A). One participant made three mistakes, mixing up the order for a majority of the stimuli placements.

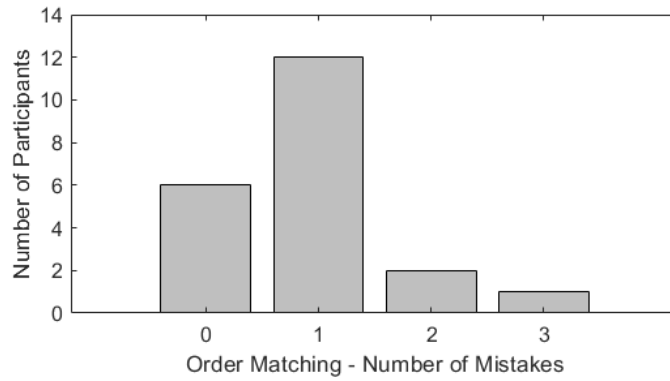


Figure 62. A histogram of the number of mistakes made by participants in the order training task. The order training task presented participants with five buttons corresponding to the five vibratory modules, however in a random order. Each button presented a vibration on one of the five vibratory modules. Participants were tasked with matching the buttons with the correct vibratory module from top to bottom. Mixing two buttons up counted as one mistake, three buttons as two mistakes, etc.

B. Rating Task

Averaged across results from all three songs, the participants' responses according to the upright pitch-height mapping can be seen in Fig. 63, and the upside-down mapping in Fig. 64. In both of these figures, we observe that the participants correctly identified the hidden reference amongst the five stimuli, rating it as identical to the reference in both mapping conditions. To evaluate the effects of each congruence parameter on participants' ratings, we analyzed the results using a linear model. To conduct the linear model analysis, each stimulus was first broken down into three independent variables: intensity congruence (yes or no), timing alignment (yes or no), and pitch-height mapping (incongruent, congruent and upright, congruent and upside-down).

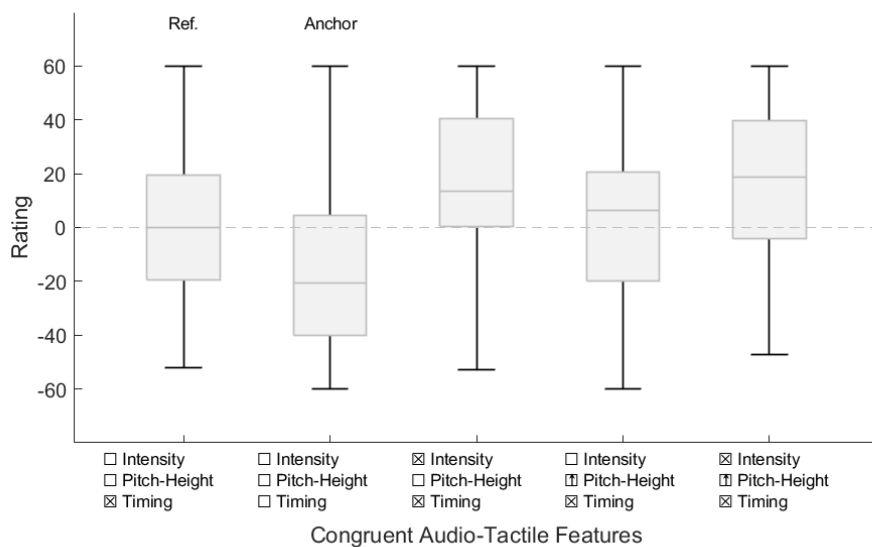


Figure 63. Inter-participant average results for each of the five audio-tactile stimuli, for the upright pitch-height mapping.

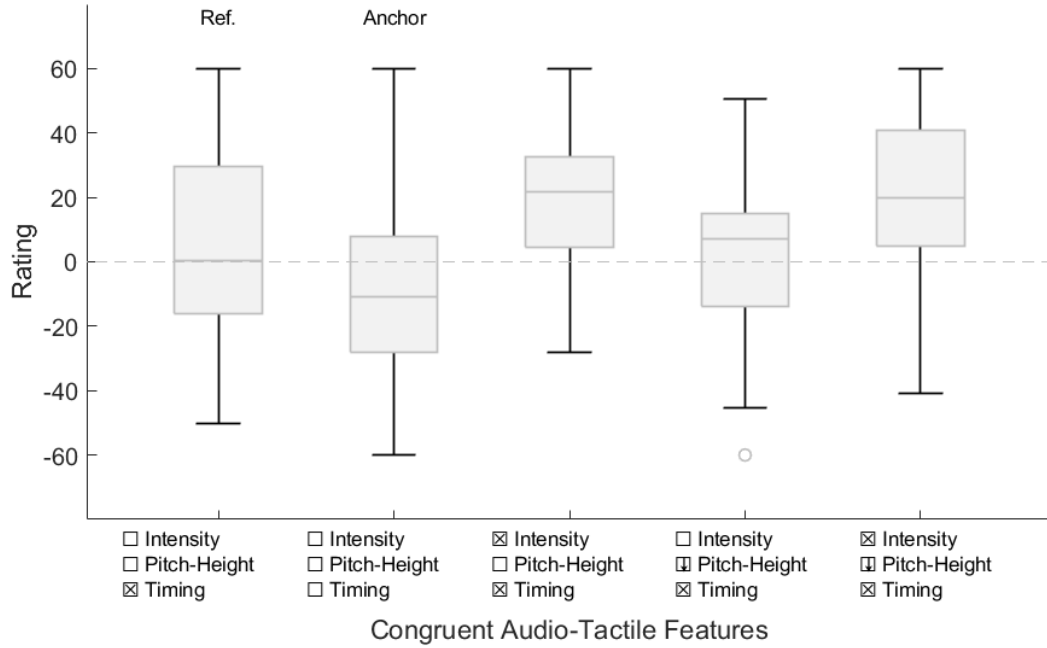


Figure 64. Inter-participant average results (across all three songs) for each of the five audio-tactile stimuli, for the upside-down pitch-height mapping.

1. Linear Model

The linear model intended to test the effect of intensity congruence, timing alignment, and pitch-height mapping on participant ratings. The model showed a statistically significant ($p < 0.05$) intensity congruence term, a timing alignment and musicianship interaction term, a Song 3 and upright pitch-height map interaction term, and a Song 3, upright pitch-height map, and musicianship interaction term. Results summarizing the reduced model can be seen in Table 6.

The model was initially created with intensity congruence, timing alignment, pitch-height map and musicianship as fixed effects, and participant as a grouping variable for a random slope of intensity congruence, timing alignment, and pitch-height mapping. The initial model resulted in a singular fit, therefore the random slope for the pitch-height map was removed as it accounted for the smallest amount of variance. The model was reduced further by removing interaction terms with a p-value of more than 0.05. The reduced model included intensity congruence, timing alignment, pitch-height map and an interaction between timing alignment and musicianship, and pitch-height map, song, and musicianship (Equation 1 below).

$$\begin{aligned}
 \text{Predicted Rating} = & \\
 & \beta_0 + \beta_1 * \text{Intensity Congruence} + \beta_2 * \text{Timing Alignment} + \beta_3 * \text{Pitch Height Map} + \\
 & \beta_4 * \text{Song} + \beta_5 * \text{Pitch Height Map} * \text{Song} + \beta_6 * \text{Musician} \\
 & \beta_7 * \text{Song} * \text{Musician} + \beta_8 * \text{Pitch Height Map} * \text{Musician} \\
 & \beta_9 * \text{Song} * \text{Musician} * \text{Pitch Height Map} \\
 & E(\text{Intensity Congruence} | \text{Participant}) + E(\text{Timing Alignment} | \text{Participant})
 \end{aligned}$$

Table 6: Linear model of participant ratings

Effect	Estimated Coefficient	Std. Error	p Value
<i>Intercept (Reference, Song 1, Non-musician)</i>	1.7316	4.2255	0.682840
Intensity Congruent	16.3712	3.8897	0.000432 ***
Timing Unaligned	-7.7571	5.1813	0.147779
Pitch-Height (Upright)	-8.4846	6.4951	0.191994
Pitch-Height (Upside-Down)	-3.0713	6.4951	0.636497
Song 2	2.0676	4.4999	0.646079
Song 3	-2.5333	4.4999	0.573693
Song 2 and Pitch-Height (Upright)	3.4562	8.9999	0.701110
Song 2 and Pitch-Height (Upside-Down)	-5.2021	8.9999	0.563485
Song 3 and Pitch-Height (Upright)	21.3250	8.9999	0.018157 *
Song 3 and Pitch-Height (Upside-Down)	15.7807	8.9999	0.080084
Musician and Timing Unaligned	-17.1577	7.1374	0.024604 *
Musician and Pitch-Height (Upright)	10.6900	8.9743	0.234094
Musician and Pitch-Height (Upside-Down)	0.2137	8.9743	0.981015
Musician and Song 2	-1.9876	6.2176	0.749341
Musician and Song 3	7.0265	6.2176	0.258921
Musician, Song 2, and Pitch-Height (Upright)	-4.3127	12.4351	0.728863
Musician, Song 2, and Pitch-Height (Upside-Down)	5.8750	12.4351	0.636793
Musician, Song 3, and Pitch-Height (Upright)	-29.3507	12.4351	0.018608 *
Musician, Song 3, and Pitch-Height (Upside-Down)	-6.3516	12.4351	0.609712

Table 6. Results of the linear model, with intensity congruence, timing alignment, pitch-height map and an interaction between timing alignment and musicianship, and pitch-height map, song, and musicianship (see Equation 1 above).

Results showed that the participants were more likely to rate intensity-congruent stimuli more positively than the reference. The upside-down pitch-height map had no significant positive or negative effect. The upright pitch-height map had a positive effect over all of the participants, but for musicians it had a negative effect. The timing-unaligned stimuli only had a negative effect on musicians.

Discussion and Conclusion

IV. Discussion

The results show a consistent and reliable benefit on preference of intensity congruence and timing alignment between the audio and tactile stimuli for vibrotactile music enhancement with the Multimodal Harness, however a less consistent benefit of pitch-height congruence.

The model shows a positive effect of intensity congruence and timing alignment for vibrotactile music enhancement. In general, the results coincide with Aker et al. (2022). Interestingly, the effect of timing alignment only appeared as an interaction term with musicianship. The interaction with musicianship implies that timing alignment only has a positive effect for musicians, contradicting Aker (ibid.)

whose results had shown a positive effect across all participants. This could be due to a difference in the definition of musicianship, or the relative salience of the timing-incongruent stimuli across studies.

A. Effect of Pitch-Height Map

The effect of pitch-height congruence was seen only in Song 3, and only for the upright pitch-map. The nature of its effect varied in terms of the participant category: it showed a positive effect on participants overall, whereas the interaction with musicianship showed a negative effect. There are several ways to interpret this finding. The only instance of a positive correlation between pitch-height mapping and participants' ratings is for Song 3, which has the slowest tempo and longest note durations (see Figure 55). Song 3 is also clearly a scale, which has an easily predictable sequence of pitch changes. Song 1 had a more complex melody, and faster tempo than Song 3. Song 2 contained only two notes, stimulated only the uppermost and lowermost positions on the back, and had a higher tempo than Song 3. While participants were given unlimited time to evaluate the positions of the different tactile stimuli during the order matching task, they may not have been able to recognize the correspondence between the pitch of the auditory tone and the elevation of the tactile stimulus at high tempos, or for more complex melodies. Song 3 was also unique in that the pitches had a clear directionality throughout the song. It is possible that the increase of effect for pitch-height maps is not due to a precise, relative pitch-to-height correspondence, but a dynamic, rising pitch direction corresponding to a vibration rising in height, and vice versa.

Even within Song 3, the effect of the pitch-height map was inconsistent among participants. There could be several reasons for this. First, we could cycle back to one of the articles discussed earlier: Kuchenbuch et al. (2014) mapped pitches to corresponding fingers on the participants' hand according to how each of those fingers would activate a range of notes on a stringed instrument. In our study, we did not choose a particular mapping that corresponds to how a musician activates different pitches on an instrument, instead evaluating the notion of pitch-elevation associations that are common to the audio-visual domain. The lack of instrumental relevance could have reduced the potential for our audio-tactile pitch-height mapping to influence participants' sensory preference ratings, in particular musicians. However, different instruments have different corresponding pitch-height mappings in terms of spatial elevation: double bass players play low notes high on their instrument, saxophone or clarinet players play low notes low on their instrument, and pianists have no notion of elevation as their tones are laid out horizontally. The rating task was built on the assumption that participants would appreciate the notion of congruence, or sensory alignment between two modalities, but physical sensation alone could have played a part in participants' ratings. We could infer that the lack of effect due to pitch-height mapping could be due to the participants' paying more attention to their preference regarding the position of the tactile stimuli, instead of their sensory preference regarding its correspondence to the auditory stimuli.

In general, the experiment was meant to be controlled for physical sensation. On a given screen, each tactile stimulus had similar physical properties. When parameters were randomized, like intensity, the intensities were only shuffled amongst the notes, keeping the distribution of intensities the same. The same was true

for the pitch-height map. For example, if a song activated the highest haptic module on the Multimodal Harness twice, all possible randomizations would still have the highest haptic module activated twice. This was why the upright and upside-down pitch-height maps never appeared on the same screen. Despite this, unprovoked statements from the participants hint that some may have evaluated their appreciation of the tactile stimuli based on their position on the body, and not based on how that position corresponded with the auditory signal. One participant remarked after the experiment that she did not appreciate any of the vibrations in the lower region of her back, while another mentioned that he enjoyed the vibratory sensations all along his back. As mentioned by Turchet et al. (2021), one of the main reasons that tactile signals are unappreciated by users in contexts of audio-tactile musical enhancement is due to their placement on the body.

B. Implications for Audio-Tactile Effect Design

1. Intensity

Our intensity congruence parameter was based on emphasis, not overall gain of the auditory and tactile stimuli. Based on the current study's results, when designing congruent audio-tactile effects for musical enhancement, the intensity levels of vibrotactile signals accompanying auditory melodies should match in terms of precise emphasis along the duration of the melody. However, we cannot infer from these results that the gain, in addition to note-by-note intensities, should be coupled across modalities.

2. Timing Alignment

The only parameter with a significantly negative effect on participants' sensory preference ratings was timing incongruence. This study's results suggest that crossmodal timing alignment is an important factor when designing for tactile music enhancement, and imply that latency should be imperceptible across the auditory and tactile modalities.

3. Audio-Tactile Mapping

The lack of consistent influence of the pitch-height mapping parameter, combined with participants' remarks concerning the positions of tactile stimulation, suggest that an ideal tactile signal mapping could have more to do with personal sensory preferences than the perception of pitch-based musical congruence. To better accommodate users, musical haptic wearables should be personalizable in terms of amplitude calibration, or enable deactivation of vibrations at specific parts of the body: two suggestions also offered by Turchet et al. (2021) in their review of musical haptic wearables.

V. Conclusion

In this study, we investigated the effect of crossmodal correspondence across auditory and tactile stimuli on participants' appreciation of music. We manipulated the experimental parameters of the tactile stimuli (intensity, timing and location/height on body) so that they were either congruent or incongruent in comparison to their

auditory counterparts (intensity, timing, and pitch, respectively). Despite the evidence for universal pitch-height associations in the audio-visual domain, in this specific experimental context we did not replicate similar effects of pitch-height congruence in the audio-tactile domain. Intensity and timing were confirmed as crucial parameters to align between the auditory and tactile modalities for musical enhancement: a relevant takeaway for designing tactile signals displayed by musical haptic wearables. While this study did not produce consistent effects of pitch-height congruence across all groups of participants, further research could reinterpret or elaborate our experimental paradigm. In future research, it could be interesting to repeat a similar test to look for potential effects of note duration on participants' appreciation of our proposed pitch-height congruence parameter, for effects of body part stimulated, or to repeat on several groups of musicians separated by instrument families.

VI. Contributions

C. Richards, S.C. Aker, N. Misdariis, J. Marozeau and D. Faux all contributed to experimental design. S.C. Aker conducted statistical data analysis. C. Richards and S.C. Aker contributed equally to writing.

VII. Acknowledgments

This research was supported by Actronika and the ANRT in the framework of a CIFRE industrial research contract, and by Demant. The authors would like to thank Prof. Vincent Hayward for fruitful discussions while preparing this study.

3. “Bimodal Judgment of Audio-Tactile Stimuli”

The following passage contains a draft version of a full-length article, including all content except the section detailing the multimodal harness to avoid redundancy.

The co-authors (Claire Richards, Nicolas Misdariis, Damien Faux and Roland Cahen) submitted a shortened version of the following content on December 16, 2022, to the 2023 World Haptics Conference for the IEEE Transactions on Haptics short papers track¹³. A copy of that 6-page submission can be found in the appendix, pages 207-212. At the time of final submission of the thesis manuscript, the authors were still in the revision phase. All references in this passage can be found in the thesis bibliography. The figures are numbered according to their position in the full manuscript.

Abstract

Multimodal perception research often proceeds sense-by-sense, probing interactions between modalities by using different, sense-specific stimuli. The current study approaches multimodal interactions in another manner, by simultaneously stimulating two modalities (hearing and touch) with one source: vibration. Within a specific range of frequencies (approx. 20-1000 Hz) and in direct contact with particular loci on the body (the spine, clavicles, and ribs), it is possible to both hear and feel a vibratory stimulus. With this in mind, the authors developed a wearable audio-tactile device: the multimodal harness. In this study, we used this device to better predict by how much the user may hear or feel each vibration depending on its signal parameters (intensity, frequency, and locus of stimulation). We evaluated participants’ perception along a continuum spanning hearing and touch. Participants’ ability to consistently distinguish between simultaneously perceived modalities despite an inherent temporal and frequential overlap demonstrates a unique case of multimodal interaction, and analysis of their bimodal judgments clarifies how the vibratory signal parameters affect the perceptual balance between senses.

Keywords: Audio-tactile, multimodal interaction, wearable technology, perceptual judgment

Article Content

Introduction and Background

I. Introduction

The auditory and somatosensory systems are unique in their mutual ability to detect and interpret vibratory information. When a vibrating motor is firmly placed on the surface of a bony structure on the skull or torso, the receiver can perceive the mechanical waves through both the senses of hearing and touch: the inner ear captures sound waves conducted internally through the musculoskeletal structure of the body (Adelman et al. 2015; Richards et al., 2021), and mechanoreceptors detect the vibrations on the surface of the skin within the approximate frequency range of 20 to 1000 Hz (Merchel & Altinsoy, 2020; Clemente et al., 2017). In this paper, we

¹³ <https://2023.worldhaptics.org/presenting/shortpapers/>

investigate the perceptual overlap between the modalities of hearing and touch when they are simultaneously excited in the manner described above. Wearing a specially-designed audio-tactile device, participants judged their perception of vibratory stimuli along a continuum between the two modalities, here described as the audio-tactile range. The patterns that emerge across their bimodal judgments contribute to our analysis of this perceptual overlap, with implications for audio-tactile effect design in similar wearable devices.

II. Background

In multimodal processing research, a “unified percept” refers to a combination of signals from different sensory modalities that occur in close temporal proximity (Holler & Levinson, 2019), integrated effortlessly by the brain into a coherent multimodal percept (Lalanne & Lorenceau, 2004). One commonly-cited example of a unified percept is the McGurk effect, a strong multisensory illusion where dubbing a voice saying “ba” onto a face articulating “ga” results in a third percept: the listener hears “da” (Gick & Derrick, 2009). The participant uses both the visual and auditory senses to form a new audio-visual percept, proving integration of the senses in that it differs from each individual sensory component. In reference to this audio-visual effect, Tiippana (2014) describes multisensory integration as a perceptual experience where the contributing sensory components cannot be perceived separately. Driver and Noesselt (2008) discuss interactions across modalities in terms of multisensory “interplay” instead of multisensory integration, creating a looser definition in order to include a broader range of multisensory effects. They explain that when two or more different senses contribute to the perception of a single external property, these modalities may affect one another, but might not always result in a single unified percept. Many examples of multisensory interplay refer to cases where two different types of stimuli are studied: vibration and light (Shams et al., 2000), facial expression and vocal tonality (Spence & Gallace, 2011), or texture and sound (Fuxe et al., 2002).

In the current study, we are interested in a specific type of multisensory interplay, where the perceiver’s senses of hearing and touch are stimulated simultaneously by one single source: vibration. Multimodal interactions between auditory and tactile perception have been studied in terms of crossmodal enhancement (Fuxe et al., 2002), co-activation (Schürmann et al., 2006; Caetano and Jousmäki, 2005) and modulation effects (Bresciani et al., 2005). The potential for interaction between these two modalities is also unique due to their common ability to process mechanical waves: among the three main perceptual groups (vision, audition, somatosensation) these are the only two modalities that can be associated in this way.

We created simultaneous interaction across hearing and touch by means of contact-based vibratory stimulation, which elicits auditory perception of the stimulus via extra-tympanic conduction (ETC) and tactile perception by stimulating the skin’s cutaneous receptors (Richards et al., 2021). Though it is commonly referred to as bone conduction, we refer to contact-based vibratory sound perception as “extra-tympanic”: sound perception that involves anything other than the eardrum. There is evidence that other, soft, bodily tissues are involved in the conduction of mechanical waves within the body, leading to sound perception (Adelman et al., 2015). Previous studies about the tactile aspect of ETC targeted individuals with profound sensorineural hearing loss (Dean & Martin 1997; Nober, 1968).

During the current study, we analyzed both the auditory and tactile perception of the vibratory stimuli, rather than each modality in isolation. In our previous research, we had only evaluated participants' auditory perception of vibratory signals displayed to the body via ETC (Richards et al., *ibid.*). However, participants often remarked that they also felt the signal, and at times expressed confusion about their perception, wondering if they were truly evaluating their audition, or their sense of touch, too. In this study, we therefore sought to bring more clarity to the audio-tactile perception resulting from simultaneous, single-source stimulation, and explore whether it can be qualified as multimodal integration (i.e. they create an inseparable percept).

Methods

III. Methods

Inspired by past research about perceptual confidence, we developed a “bimodal judgment” experimental paradigm to investigate participants' bimodal perception within and between the auditory and tactile modalities. In this method, participants must place a perceptual judgment of a vibratory stimuli somewhere on the scale between auditory and tactile, considering both senses at the same time.

Mamassian (2020) discussed the nuances of confidence in perceptual tasks, opening with the understanding that “perceiving is to commit to a decision based on sensory information that is often uncertain” (Mamassian, 2020, p. 616). He notably defined the confidence forced-choice paradigm, an experimental procedure that forces the participant to make an either/or judgment according to which of two perceptual stimuli is more likely to be correct. In the current study, we cannot judge participants' responses as correct or incorrect because of the nature of the perceptual task: participants were simply instructed to record their personal estimate of auditory vs. tactile perception. The main inspiration taken from Mamassian's paradigm is the notion of forced-choice. In our bimodal judgment paradigm (see section III.C.2), the participant must make a choice: they cannot rate the stimulus as being equally perceived in both modalities. They must therefore consciously ask themselves after each vibratory stimulus whether they heard it more than they felt it, or vice versa. Their resulting “bimodal judgment” tells us two things: whether they perceived the vibratory stimulus as “more auditory” or “more tactile”, and the precise degree to which they judge the strength of both modalities. This is not a measure of perceptual confidence, in Mamassian's terms. Evaluating their judgments does not tell us whether the participant viewed their response as correct, but rather whether the participant perceived the sensory modalities as more or less distinct.

Analysis of the bimodal judgments between and within participants demonstrated whether they were able to distinguish between hearing and touch when both senses were excited by the same source, thus clarifying whether this bimodal perception should be classified as multimodal integration or interplay. Finally, the perceptual patterns that emerge across participants allowed us to interpret our findings in terms of what they may reveal about audio-tactile interactions during simultaneous, single-source stimulation.

We designed our experiment according to three main hypotheses about participants' audio-tactile perception:

1. *Frequency dependence.* Between 200 and 800 Hz, the participants will rate their perception with a gradual shift from mostly-tactile to mostly-auditory, reflecting the peak of vibrotactile sensitivity at 250 Hz, and the decrease in tactile sensitivity with increasing frequency. At 1200 Hz, a frequency outside of the detectable range of vibrotactile sensitivity, participants will rate their perception as 100% auditory.
2. *Intensity effect.* Higher intensity of the vibratory signal will be correlated to a higher percentage of tactile rating at all tested frequencies except 1200 Hz.
3. *Response styles.* Participants will exhibit different styles of bimodal judgment, either preferring to stay on the edges or towards the center of the audio-tactile range.

A. Participants

A total of 23 participants took part in the study, (12 male, 11 female, average age 23.7, Standard deviation 2.9). The participants declared to have no known hearing impairments. In accordance with the Declaration of Helsinki, all participants provided informed, written consent prior to the study. The INSEAD IRB provided ethical approval of this study (Protocol ID 2022-52).

B. Procedure

The unique functionality of the multimodal harness inspired the context of the present study: it simultaneously stimulates both the senses of hearing and touch through vibrations that specifically target the musculoskeletal structure of the torso. While designing the experimental procedure, our main objective was to explore in detail the nature of the bimodal perception that it facilitates. In previous research involving the multimodal harness, the current authors developed creative interfaces for multimodal sensory effect composition, and spatialization of those effects on the body (Richards et al., 2022). Before developing the multimodal harness and its accompanying interfaces for sensory effect design, the authors also conducted a study on vibratory perception on the torso via ETC to ensure that users could indeed hear the sounds from within their body (Richards et al., 2021). To build on these prior works, in the current study we investigate the zone of overlap between auditory and tactile sensation. We propose to detail this zone of sensory overlap according to how much the participant is able to distinguish between their auditory and tactile perception when both of their senses are stimulated simultaneously by the same source of vibration.

Our current experimental procedure probes this perception according to two main measures, in two separate tasks: the vibratory intensity required to elicit perception at each position of stimulation on the multimodal harness (in the calibration task), and the participant's judgment of that perception along the range of audio-tactile sensation between 200 and 1200 Hz (in the bimodal judgment task).

1. The Calibration Task

As a first step in the experimental procedure, we calibrated the intensity of the vibratory signals according to the participants' personal levels of perception. Though auditory and tactile sensitivity vary across positions and frequencies, during this task the participants were instructed to set their levels of vibratory intensity by considering both senses at the same time.

We designed an individualized equalizer (EQ.I) tool which participants used to set an upper and lower limit for the intensity of a given frequency-position combination (five frequencies \times nine positions = 45 total calibrations). The calibration task lasted approximately 10 minutes, and was broken down into five sections: for each of the five frequencies, participants set a "maximum comfortable" and "minimum perceptible" level of vibratory intensity for all of the nine positions of stimulation (Fig. 65). The maximum comfortable level refers to a signal that is very easily perceived, but not unpleasant. The minimum perceptible level refers to the signal of lowest intensity that is possible to perceive. If the participants could neither hear nor feel the vibratory signal at a given position of stimulation, they unchecked a box underneath the equalizer for that position, effectively removing that stimulus from the next task. The maximum and minimum intensity values collected from the calibration task serve to determine the intensities of the individualized stimuli presented during the bimodal judgment task, whose amplitudes are calculated based on the average of these two values. We used this average value to define the stimuli amplitude instead of the maximum comfortable or minimum perceptible level in order to reduce the potential for straining and fatigue.

In addition to the amplitude values gathered from the EQ.I, another set of standardized amplitude values was also defined, in order to provide a control for the potential effect of amplitude on participants' bimodal judgments. This standardized equalizer (EQ.S) was calculated based on seven participants' results from the pilot testing phase. Its intensity values were calculated in order to ensure the best possible chance of stimulus perception. We first took the average of all seven participants' maximum and minimum intensities. These values were then adjusted so that none of the stimuli were less intense than any participant's minimum intensities. If participants had unchecked the box underneath a given frequency-position combination during their individual calibration, that combination was also removed from the standard equalizer's stimuli in the bimodal judgment task.

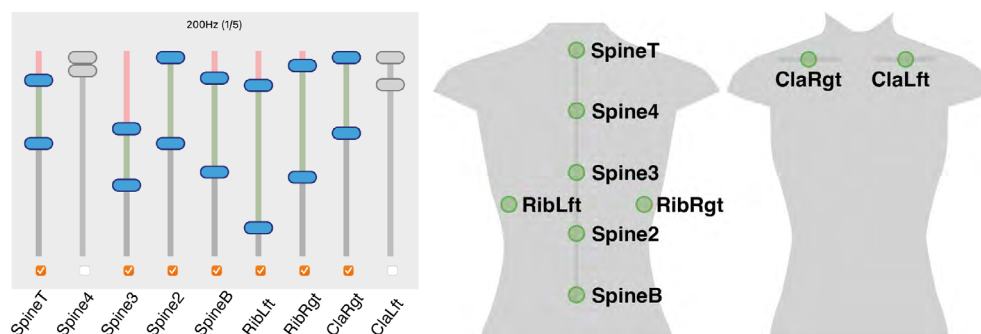


Figure 65: The intensity calibration task. Each vertical bar seen on the GUI interface (left) represents a position on the multimodal harness (right). For each of the nine positions, the participants set the maximum comfortable and minimum perceptible

levels of signal intensity. The intensity scale is set in dB. The bottom value on the scale corresponds to 0 V output, and the uppermost value corresponds to 2.6 V, the actuator's maximum admissible output.

2. The Bimodal Judgment Task

The bimodal judgment task employs the audio-tactile range, a Likert-style continuous scale ranging from 100% auditory perception (A) to 100% tactile perception (T). The scale ranges from -10 to 10, where -10 is 100% A and 10 is 100% T. Participants use this scale to place the judgment of how they perceived the vibratory signal (Fig. 66). The participants must make a choice between judging the signal's perceptual strength as more audio or more tactile by positioning the cursor on either side of the midline: the point marking a sensation that is equal parts auditory and tactile perception. Prior to this task, we informed the participants that, based on their frequency and their position on the body, perception of the vibratory signals may vary between auditory and tactile - sometimes the signal will be heard, sometimes heard and felt, and sometimes only felt.

We defined the audio-tactile (A-T) range according to these specific frequencies for a few key reasons: they represent the best effective range of the voice-coil motors integrated in the wearable device, they target both the auditory and tactile sensitivities, and this range of frequencies has been previously shown as being situated within the range of vibratory signals perceptible via ETC (Richards et al., 2021). Pacinian corpuscles, the mechanoreceptors in the skin responsible for detecting high-frequency vibrations between 50 and 1000 Hz, have a peak frequency of vibrotactile sensitivity of 250 Hz (Petry et al., 2018). Since different zones of the body have varying sensitivity, others have suggested a range of best vibrotactile sensitivity from approximately 50 to 500 Hz (Chafe, 1993). However, across the surface of the torso, it has been reported that there is no significant difference in vibrotactile sensitivity (Garcia-Valle et al., 2020). At the borders of the range, 200 Hz is just below the peak of vibrotactile sensitivity (250 Hz), and 1200 Hz is just outside of the range of vibrotactile sensitivity, but within the audible range of perception via ETC (Verrillo 1966, Boothroyd and Cawkwell 1970).

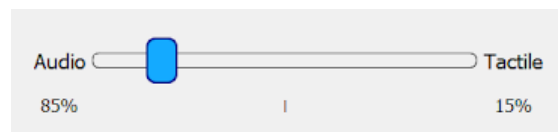


Figure 66: The audio-tactile (A-T) range: a section of the interface from the bimodal judgment task. As participants moved the cursor between “Audio” and “Tactile”, the percentage of the perception changed in order to reflect their judgment. The judgment cannot be positioned exactly at the range midline (50/50): participants must decide which modality was stronger than the other for each vibratory stimulus ($A > T$ vs $T > A$). The judgment can, however, be placed at the edge of the range (100% A or 100% T).

Results

IV. Results and Analysis

A. Frequency Dependence

The results of the bimodal judgment task support our first hypothesis (see section III), following a perceptual shift from mostly tactile ($T > A$) to mostly auditory ($A > T$) with increasing frequency. Figure 67 shows the bimodal judgment results and standard deviations, averaged across all participants' responses to the vibratory stimuli equalized according to their EQ.I (values shown in blue) and the EQ.S (shown in pink). Across participants, the average bimodal judgment values at 200 Hz are situated above the midline ($T > A$). At 400 Hz, participants' judgments begin to shift towards the other end of the range ($A > T$) up through 1200 Hz, the frequency at which participants showed the greatest consensus about bimodal judgment regardless of amplitude (see also Table 8). The shift of perceptual strength from tactile to auditory is partially dependent on the position of vibratory stimulation: at the clavicles and ribs, the judgments are located closer to the midline than at the five positions along the spine. The slope of the descent from $T > A$ to $A > T$ varies between exponential and linear depending on these two groups of positions: for both EQ stimuli, the shift between perceptual strength is more abrupt at the spinal loci than at the loci on the ribs and clavicles (see blue values shown in Fig. 67). Since the amplitude values associated with these judgments were averaged across all participants' EQ.Is, we cannot infer as much about the patterns in bimodal judgments from this data than the results in pink, whose stimuli amplitudes were identical across participants.

The pink values of bimodal judgments represent responses to stimuli of standardized amplitudes (Fig. 67). We can therefore conclude that these patterns in judgment across positions and frequencies corroborate our first hypothesis, and the variations reflect effects of other variables such as device fit and perceptual differences across participants. Analysed in comparison, the averaged bimodal judgment results of the EQ.I and the EQ.S show similar slopes: both calibrated and non-calibrated stimuli reflect similar patterns of bimodal judgments across participants. This finding solidifies the analysis of the patterns of bimodal judgment, in terms of both our first and second hypotheses.

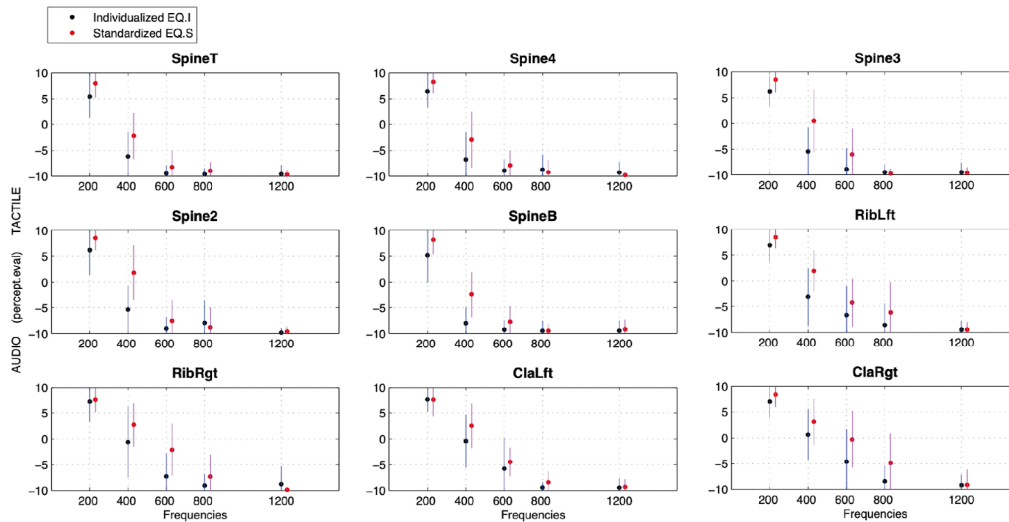


Figure 67. In pink, averaged participant judgments on the A-T range, EQ.I stimuli amplitude. In blue, averaged participant scores, EQ.S stimuli amplitude. The nine graphs reflect the positions of stimulation on the multimodal harness: SpineT is the highest vibratory module on the spine, Spine4 through Spine2 descend downwards to SpineB, the lowest. The data from the right and left ribs and clavicles are labeled accordingly. The y-axis values are arbitrary: -10 represents 100% auditory sensation, 0 represents equal parts auditory and tactile sensation, and 10 represents 100% tactile sensation.

The pink results from Fig. 67 reflect participants’ responses according to the same stimuli amplitudes. The EQ.S stimuli were higher in amplitude in comparison to the average EQ.I stimuli, the percentage increase varying based on position of stimulation and frequency (Table 8). The EQ.S provided a control for the potential effect of amplitude on participants’ bimodal judgments.

B. Intensity Effect

Comparing the results from the EQ.I and the EQ.S allows us to analyze the influence of intensity calibration on participants’ responses, and a potential effect of increased amplitude. The “intensity effect” hypothesis described our assumption that, within the range of frequencies detectable by the skin, increased vibratory signal amplitude will cause participants’ bimodal judgments to shift towards the tactile end of the A-T range. In Table 7, we observe that across all frequency-position combinations, signal amplitude increases from the average EQ.I to the EQ.S. The reason for this increase in amplitude is related to the calculation method used for the EQ.S (see end of section III.B.1), defined to ensure stimulus perception at the standardized amplitude values.

Table 7: Factor of Stimuli Amplitude Change between EQ.I and EQ.S

Loci	200 Hz	400 Hz	600 Hz	800 Hz	1.2 kHz
SP.T	4.13	2.33	2.76	1.88	2.48
SP.4	3.01	1.48	1.37	1.16	1.58
SP.3	3.60	2.39	1.68	1.70	2.24
SP.2	2.94	2.35	1.44	1.62	1.09
SP.1	2.14	2.15	2.71	2.08	0.82
L.Rib	2.03	2.47	1.99	1.31	1.10
R.Rib	1.60	2.61	1.84	1.13	0.94
L.Cla	3.39	1.47	2.03	1.81	1.46
R.Cla	3.67	1.83	1.82	1.97	1.11
Avg.	2.95	2.12	1.96	1.63	1.42
St.D.	0.86	0.42	0.49	0.35	0.58

Table 7: These values reflect the factor of increase in signal amplitude between the average EQ.I and the EQ.S. “Avg.” represents the inter-position average change, per frequency, and “St.D.” the standard deviation.

In Table 8, we observe the change in the average participant response during the bimodal judgment task, depending on the EQ.I versus the EQ.S. Comparing the values from Table 7 (signal amplitude % change) and Table 8 (bimodal judgment value change) shows that the relationship between increased signal intensity and bimodal judgment is dependent on frequency, but not only in the way suggested in our hypothesis. At 200 Hz, participants’ responses at all loci shifted towards the T>A end of the A-T range, whereas at 600 Hz, all responses shifted towards A>T. The degree of that shift also depends on the tested frequency: at 400 Hz, the shift between EQ.I vs EQ.S responses is approximately 16x stronger than that at 1200 Hz, when averaged across all loci.

Table 8: Bimodal Judgment: Value Change Between EQ.I and EQ.S

Loci	200 Hz	400 Hz	600 Hz	800 Hz	1.2 kHz
SP.T	2.52	3.96	1.22	0.61	-0.09
SP.4	1.83	3.87	1.09	-0.55	-0.52
SP.3	2.26	5.91	2.87	-0.22	-0.09
SP.2	2.30	7.18	1.48	-0.83	0.22
SP.1	3.00	5.57	1.48	0.00	0.27
L.Rib	1.52	5.09	2.43	2.43	0.00
R.Rib	0.39	3.35	5.22	1.74	-1.09
L.Cla	-0.04	3.00	1.35	1.00	0.14
R.Cla	1.35	2.52	4.30	3.61	0.09
Avg. (abs.)	1,69	4,49	2,38	1,22	0,28
St.D. (abs.)	0,98	1,54	1,49	1,17	0,34

Table 8: These values reflect the change between the average value of bimodal judgment of the vibratory stimuli from the EQ.I and EQ.S. The A-T range spans values from -10 (100% A) to 10 (100% T). Negative values (in red) represent a

change in judgment shifting towards A>T between the EQ.I and the EQ.S, while positive values (in green) represent shifts towards T>A. For scale, compare the shift to the scale's absolute range (20).

Table 8 brings more detail to the differences in bimodal judgments which were previously illustrated by the blue and pink data in Fig. 68 (section IV.A). Positive values represent a shift in judgment towards T>A (more tactile = green), and a negative value represents a shift in judgment towards A>T (more audio = red). The lowest line (Avg.) represents the inter-position average change, per frequency. The small change at 1200 Hz suggests that, no matter the signal amplitude, participants will perceive the vibrations in the same way (only auditory). The extreme variation at 400 Hz could suggest that the bimodal judgment of this frequency is highly dependent on amplitude, or that participants generally have difficulty distinguishing auditory from tactile sensations at this frequency. At 200 Hz, the increased vibratory signal amplitude amplifies the tactile sensation, possibly due to the skin's heightened vibrotactile sensitivity around this frequency. At 600 Hz and 800 Hz, the shift towards A>T suggests that increased signal amplitude aids participants' auditory perception of the signal, rather than increasing tactile perception.

Table 9 proposes another way to evaluate the effect of increased intensity on participants' bimodal judgments: the inter-participant coefficients of correlation between responses of the EQ.I and the EQ.S. The strongest degree of perceptual consensus occurs at 1200 Hz, while participants seem to show the least consensus between their judgments of the EQ.I and EQ.S stimuli at 400 Hz.

Table 9: Coefficient of correlation, Inter-participant: Comparing EQ.I vs EQ.S Responses

	200 Hz	400 Hz	600 Hz	800 Hz	1200 Hz
SpineT	0.35	-0.02	0.51	0.68	0.68
Spine4	0.69	0.02	0.59	0.61	0.67
Spine3	0.47	0.49	0.62	0.84	0.82
Spine2	0.46	0.16	0.26	0.80	0.94
SpineB	0.02	0.10	0.55	0.94	0.81
RibLft	0.40	0.26	0.59	0.68	0.61
RibRgt	0.30	0.21	0.45	0.20	0.45
Clalft	0.72	-0.17	0.43	0.52	0.91
Clargt	0.52	0.15	0.28	0.17	0.50

Table 9: Inter-individual differences in judgments, based on the comparison between each participant's EQ.S and EQ.I responses. High p-value/correlation signifies a high likelihood to judge the vibratory stimulus at the same position and frequency similarly according to both EQs, and vice versa for low p-value. Non-significant p-values are white, *brown, **red, ***green.

C. Response Styles

The third hypothesis is based on our assumption that, when given the bimodal judgment task, participants would exhibit two main response styles: they would either

rate most of the stimuli towards either majority of auditory or tactile perception (a majority “binary” response style), or they would mostly hover closely around the center of the range (a majority “central” response style). If participants placed a majority of their judgments towards the center of the range, this would partially refute our first hypothesis.

Table 10: Bimodal Judgment: % of “Central” vs. “Binary” Responses by Participant (EQ.S)

P	1	2	3	4	5	6	7	8	9	11	12	13	14	15	16	17	18	19	20	21	22	23
“C”	11	27	40	9	20	24	22	18	27	22	36	24	9	24	38	47	20	36	24	22	49	11
“B”	89	73	60	91	80	76	78	82	73	78	62	76	91	76	62	53	80	64	76	67	51	89

Table 10: Distribution of participants’ (P) bimodal judgments along the A-T range. The values are in %, representing the total number of responses from the EQ.S, over 45 trials. The left column corresponds to the “central” (C) distribution, or a rating on the A-T range between -5 and 5 (corresponds to a judgment between 75%T / 25%A and 25%A / 75%T). The right column corresponds to the “binary” (B) distribution, or a rating either between -6 and -10, or 6 and 10 (either between 20%T / 80%A and 100%A, or 20%A / 80%T and 100%T). (P10 was exempt due to incomplete data.)

Table 10 illustrates the participants’ response styles, indicating where each participants’ judgments were distributed along the audio-tactile range. The distribution of their responses globally confirms our hypothesis: most participants had a tendency to stay on the edges of the range, rating more than 75% of their bimodal judgments in the binary style (n=11). Another group of participants had a more uniform distribution of responses, placing their judgments approximately equally (50/50) according to the two response styles (P17 and P22). Other participants’ response distributions were situated somewhere in between these two groups (n=9). No participants had a majority of judgments in the central response style, which implies that nobody had extreme difficulty distinguishing between the two modalities.

Discussion and Conclusion

V. Discussion

In the current study, we analyzed the perceptual balance between the auditory and tactile modalities based on the variation of the stimulating signal’s intensity, frequency, and locus on the body. Following each vibratory signal, participants judged their perception according to the two modalities along a continuum, evaluating their perception of both senses at once rather than separately. Results show that participants’ bimodal judgments on the audio-tactile range consistently depend on frequency in a manner supporting our first hypothesis; from 200 to 1200 Hz, judgments gradually shift in perceptual balance from tactile to auditory perception. Participants’ bimodal judgments at 400 Hz were particularly close to the center of the audio-tactile range, implying that this particular frequency caused more difficulty when distinguishing between modalities. The effect of increased intensity, evaluated through the difference in judgments of calibrated and non-calibrated stimuli amplitudes, generally affects participants’ bimodal judgments by shifting the perceptual balance towards the tactile end of the audio-tactile range. However, the

degree of that shift depends on the frequency of the stimuli, and in higher frequencies, increased intensity sometimes caused an overall shift towards the auditory end of the range. Participants exhibited general styles of responses during the bimodal judgment task, according to the distribution of their ratings on either end, or towards the center of the audio-tactile range.

The cortical processing of auditory and tactile information are intertwined. Measuring transcranial magnetic stimulation during a temporal discrimination task, Bolognini et al. (2010) established that the brain's auditory cortex processes temporal information derived from both the auditory and tactile modalities. In a series of psychophysical experiments, Yau et al. (2009) analyzed the influence of auditory inputs on tactile frequency discrimination. They found that when participants judged two sequentially-presented tactile stimuli, the auditory distractor occurring during the second of the two tactile stimuli only had a detrimental effect on their responses when similar in frequency. Foxe (2009) reworded the significance of their findings, explaining that regardless of the anatomical differences between the cellular tissues of the ear and skin, the frequency of the processed vibrations is an integral dimension of multisensory interactions.

Driver and Noesselt (2008) defined multisensory interplay as the interaction when two or more senses contribute to the perception of a single external property. Multisensory integration, defined as the convergence of two modalities into one, unified percept, is a rarer phenomenon. As cited above, previous research suggests that audio-tactile interplay is especially likely to occur when the vibratory signals are aligned in terms of temporal- and frequency-related features, as was the case in our experiment. In terms of the effect of frequency-related features, our study's results suggest that certain vibratory frequencies affect participants' ability to distinguish between the auditory and tactile modalities more than others. In the zone of perceptual overlap between auditory and tactile perception (approx. 20-1000 Hz), our results demonstrate a potential peak of multimodal interaction between auditory and tactile perception at 400 Hz.

VI. Conclusion

Despite temporal and frequency alignment of the vibratory stimuli, the current study's participants consistently demonstrated the ability to distinguish between the two modalities of hearing and touch. The nuances of auditory and tactile discrimination were qualified in terms of dependence on signal frequency, and the evidence for an effect of increased signal intensity. Participants' ability to judge their perception of the two aligned sensations in terms of "more" or "less" auditory or tactile perception provides an argument that, in the context of the current study, the two modalities did not integrate into a unified percept at all tested frequencies. However, participants' bimodal judgments at 400 Hz were particularly close to the center of the audio-tactile range, at all tested positions on the torso. This demonstrates participants' uncertainty and inconsistency while distinguishing single-source audio-tactile perception of vibration at 400 Hz: a certain point of multimodal interplay, and a point of potential interest for future research about multimodal integration.

VII. Acknowledgements

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4. Conclusion

In this chapter, we probed the utility of the multimodal harness as an experimental instrument. Each of the two experiments revealed something new about audio-tactile perception, in terms of crossmodal correspondence and perceptual judgments.

In section 1, the multimodal harness helped us to investigate crossmodal congruency across auditory and tactile perception. The experiment was structured based on the assumption that the tactile enhancement of music will benefit from alignment across certain audio-tactile signal parameters. We explored our assumption that participants, especially musicians, would prefer tactile stimuli whose locations on the body corresponded to the pitch of the musical notes. Our proposed “pitch-height” congruency parameter produced inconsistent effects across conditions, while tactile musical enhancement clearly benefits from alignment across audio-tactile intensity and timing.

In section 2, we used the multimodal harness to analyze how participants perceive and distinguish between the auditory and tactile modalities during simultaneous single-source vibratory stimulation. We asked participants to place their “bimodal judgment”, or their personal estimation of how they perceived a vibratory signal, along a range ranging from tactile to auditory. Our hypothesis that the perceptual balance would shift from tactile to auditory with increasing frequency was confirmed. The effect of increased vibratory signal intensity is more nuanced: depending on frequency, increased amplitude can shift the participant’s perception towards one or the other modality.

While representing advancements in the field of multisensory research, these findings are also of particular significance when considering the creative use of the multimodal harness. The results from the study on crossmodal congruency between auditory and tactile stimulation highlights the importance of personalization while developing audio-haptic effects, and emphasizes the correlation between intensity and timing across modalities in order to create a more enjoyable sensory experience. The bimodal judgment study gives an introductory view on the effect of the position, frequency and intensity of vibratory stimuli on distinguishing between overlapping auditory and tactile stimulation. Reflection about these experiments, including the psychophysical study detailed in Chapter II, section 3, structured our creative approach in terms of effect spatialization on the body, personal parametrization, and factors for musical contexts: aspects of audio-tactile composition to be discussed in the following, and final, chapter.

Chapter V: Composing Sensory Experiences for the Multimodal Harness

1. Introduction

In this final chapter, we discuss the outputs of the multimodal harness (as defined in Chapter II, section 1) that were guided by our goal to explore its use as a vehicle for creative expression and functional use. These outputs span the new creative interfaces for sensory effect design, imagined applications of audio-tactile wearable technology, user feedback, and an artistic collaboration. The purpose of this art project in a design thesis, is to demonstrate and exemplify audio-tactile effects within a widely open use context, as well as exploring expressive applications. The creative output of this doctoral research is as much at the heart of our research objective as the experimental and theoretical output. Through a creative approach, we aimed to get closer to the heart of *why* we built the multimodal harness, and learn about what it can enable as a new creative medium. Through that medium, we may find a new way to connect to sound, to our own body and self. With the novelty of this medium also comes the necessity to actively generate research questions as we proceed, to test our assumptions about sensory effect design, and to collect feedback from users external to the project.

Our creative approach towards the multimodal harness has evolved throughout the research. We started off with a blank slate; before we had built the first iteration of the multimodal harness, we could not predict much about the sensations that it would produce for the user. We could assume with some certainty that it would be possible to perceive the sounds, thanks to the experimental results of the psychophysical evaluation (Chapter II, section 2.3.5). However, those results are also dependent on the experimental conditions and the specific device used to elicit auditory perception (the monopoint module).

To better understand the perceptual possibilities offered by the multimodal harness, we first designed some initial interfaces for audio-tactile effect design. We created these software tools and interfaces out of necessity, having judged that our goals for effect design could not be realized properly nor easily with standard features of digital audio workstations. We built them to spatialize vibrations, creating patterns of tactile movement across the surface of the body, and to explore the aesthetic potential of extra-tympanic conduction as an acoustic medium. Having tested our first hypotheses for sensory effect design, we reflected and reiterated, acknowledging that the accessibility of the compositional interface is a crucial factor to support collaboration and creative use. Finally, we found the collaborative context to build an artistic project with a composer whose previous works, methods and inspirations harmonized with our own.



2. Audio-Tactile Composition Workshop

In this section, we will discuss some of the first methods developed to explore our hypotheses about audio-tactile effect design. To immerse ourselves in the creation, reflection and testing of multisensory effects designed for the multimodal harness, we organized a collaborative, 2-week workshop in August 2021. Our goals for this first workshop were to explore three main themes for audio-tactile effect design on the body, using the first iteration of the multimodal harness:

1. Multimodal music listening experiences
2. Spatialization of audio-tactile signals on the body
3. Individual variations in vibratory sensitivity

Since it was impossible to understand the sensory experience of the multimodal harness prior to testing and developing the interfaces that would allow us to design effects for it, we did not enter this workshop with a strict organizational plan. Rather, we had broad objectives for what we hoped to accomplish in two weeks: brainstorm, test, demonstrate, and reflect. In the first week, we dedicated our time to brainstorming about how we would address each of the three above themes, and to developing the first drafts of the Max patches which would serve as initial exploratory audio-tactile design interfaces. In the second week, we shifted our focus towards the use of these first interfaces, testing preliminary effects and gathering feedback from any colleagues at Ircam and Actronika who were available at the time.

In section 2.1, we present an article in which we detail the main research questions and user feedback about the interfaces that we built to explore the three above themes of effect design. A principal, recurring theme of this article is that, while it is more or less easy to localize vibrotactile stimulations as coming from different points on the body's surface, auditory perception by means of bone conduction is essentially mono, since all sounds are conducted up from the torso, entering the inner ear from the conduit of the cervical spine. The law of transition between the audio-haptic positions is therefore complex, since it needs to take into account several factors: the auditory volume, the acoustic spectrum, vibrotactile sensation, and location of stimulation on the skin's surface. Finally, the conjunction of the two sensations constitutes a mixed audio-haptic perception. This mixed perception causes new, unique perceptive properties to emerge, which we explored during the August 2021 collaborative workshop by designing preliminary interfaces.

Throughout (and after) the workshop, there was one particular question that kept coming back: "what are the applications?" This question is a recurrent one when approaching design from new technology artifacts rather than precise usage requirements. The authoring tools for audio-tactile effect design developed during the workshop may also serve as a means to explore more functional uses: while exploring their use, many other ideas for use-case scenarios came to mind (meditation, sports, alerts...). However, to fit within the scope of our research, we limited our evaluation of the multimodal harness and its corresponding authoring tools to a musical context.

2.1. “Designing the Balance Between Sound and Touch: Methods for Multimodal Composition”

In this section, we present section excerpts of a published article presented at the 2022 Sound and Music Computing Conference (SMC), titled “Designing the Balance Between Sound and Touch: Methods for Multimodal Composition” (Richards et al., 2022). This article won the “Best Paper Award” of the conference¹⁴.

Based on what we have already elaborated in the previous chapters and sections of the thesis manuscript, we removed all redundant sections of the article. For reference, the full article can be found in the appendix, pp. 199-206. The article’s content has not been modified for this section, apart from the heading style, figure numbers, and citation style.

Introduction (Richards et al., 2022, p. 421)

The experiences of grazing one’s hand across a soft surface and listening to a concerto may not seem to have much in common. However, in both cases, the body is detecting and interpreting vibratory information, whether that vibration is a result of the friction produced by the movement of skin on a surface, by the movement of performers’ bows on the strings of violins, or by touching the surface of a speaker playing music. In our research, we seek to illuminate the physical aspect of sound perception, by bringing the vibrations directly in contact with the body.

In parallel to the development of our multimodal wearable device, we conducted a psychophysical study on extra-tympanic hearing thresholds of the human torso, with the aim to begin a definition of audio-haptic signal design guidelines for the wearable (Richards et al., 2021). In this study, instead of taking a psychophysical approach, we decided to start by applying the basic parameters obtained from the first study’s results within a more creative developmental framework: an intensive workshop.

Our intention in organizing this workshop was not to produce data, but to gain more clarity on the research questions we can ask. In the next sections, we first present the project context of exploring a set of audio-haptic forms of expression, followed by basic technical details of the multimodal harness. Then, we describe functionalities of authoring tools we developed, trial feedback, and the research questions generated by the sensory experience they permit (or not). Finally, we discuss our perspectives on future development, for both experimental and compositional purposes.

Design Workshop (Richards et al., 2022, p. 423)

The two-week workshop, organized by the co-authors, took place at IRCAM in Paris, France in August 2021. During the workshop, five participants (P.01, P.02, etc.) tested our tools based on their own interest or direct involvement in the project: they were neither specifically selected nor remunerated for their participation. During every trial of the multimodal harness, users wear ear plugs and a noise-canceling headset in order to mask the external noise created by the modules’ vibrations and focus on their hearing via extra-tympanic conduction.

¹⁴ <https://smc22.grame.fr/awards.html>

The main objective of the design workshop was to create first drafts of audio-haptic signal design interfaces. Creating these tools would allow us to refine our assumptions about the sensory experiences afforded by the multimodal harness, informed by our previous psychophysical study, haptic illusions of signal movement (Geldard & Sherrick, 1972), and existing research on vibrotactile musical experiences (Gunther & O’Modhrain, 2003; Baijal et al., 2012).

We hypothesize that the vibratory activation of tactile, auditory and bi-modal perception enables myriad possibilities for signal design: sensations that can travel in all directions to create illusions of movement, sound perception by vibratory transmission through musculoskeletal structures, and novel effects based on the multimodal integration of both sensations. While it is possible to approximately localize tactile stimuli on the body’s surface (Cholewiak, 1999), auditory perception by means of extra-tympanic conduction on the torso is essentially mono, since all sounds are entering the inner ear from the same pathway: the cervical spine. In other words, spatial audio information is lost, but we hypothesize that the localization of tactile stimuli could remain strong enough to transmit impressions of spatialized auditory source positions.

Authoring Tools for the Multimodal Harness (Richards et al., 2022, pp. 423-427)

Each of the following authoring tools offers a different possibility for designing audio-haptic effects. In this section, we describe each of the authoring tools in three parts: the interface design, feedback from trial sessions, and finally key questions and limitations related to interface functionalities and perceptive experiences.

Inner.Music: Multimodal Music Player (Richards et al., 2022, pp. 423-424)

Inner.Music is a music player, designed to test the perception of filtered source files transmitted to the multimodal harness. This tool features a body point-based equalizer tool, which allows the designer to calibrate the signals to each position of stimulation.

Interface Design and Composition Features

Inner.Music allows the designer to self set, adjust and balance the volumes of each actuator’s filter bands, while listening to music. The interface is also a preset manager: individual sensory profiles, created by saving the nine filter band settings in presets, can vary each person’s sensory preferences (see fig. 68).

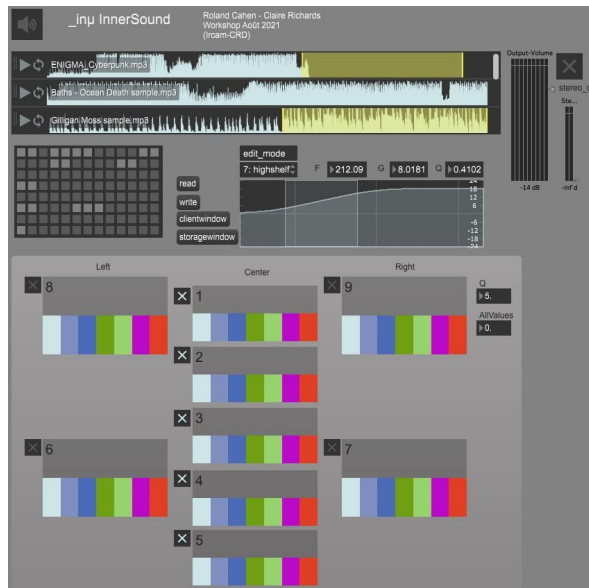


Figure 68: Inner.Music as seen in Max environment. Any sound file can be uploaded into the playlist object at the top of the interface. By default we propose a short list of rhythmic music with powerful bass content: electronic, disco-funk and pop. Left and right channels are routed to the left and right lateral actuators on the clavicles and ribs and mixed together on the vertical positions of the spine. A graphic equalizer and a mute button is available for each actuator, with different colored bars for 7 frequency bands spanning 50-4000 Hz. The user can save their equalizer settings in the grid below the playlist object, recorded and saved for future use. To the right of the preset grid, a high shelf filter object, applied to all channels, attenuates the bass frequencies with respect to the high frequencies due to the resonant frequency of the actuator (70 Hz).

Our initial intention for Inner.Music was to create a tool that adjusts each actuator's spectrum in order to obtain a homogeneous audio-haptic sensation across all stimulated positions. However, we understood during the trial sessions that the ranges and nature of the two modalities' perceptions vary across positions, and according to different types of effect design or scenarios of use. We therefore chose to exploit these variations, creating an interface that allows the user to tweak their own sensory experience instead of imposing a generic predetermined sensory calibration.

Trial Feedback

While toying with the Inner.Music interface, participants employed various strategies: balancing the signal to achieve a perception of homogeneity across the positions, attributing levels and spectrum bands to each position in order to focus their perception on either the tactile or auditory modality, or muting positions that they did not appreciate. For example, some favored a stronger tactile sensation of the bass in the lower back, and routed the trebles to the upper back and clavicles to hear via extra-tympanic conduction. A common remark was that the music is audible, but appears to be coming from a distant place within their body, and in order to hear more details, they have to focus their attention. P.03 said, "It's possible to hear the sound, but to feel practically nothing."

P.05 was especially sensitive to extra-tympanic auditory perception, saying: “I can hear the sound as if I were listening with headphones - maybe even better”. On the other hand, P.01 was disappointed by the quality of the auditory experience and resorted to actively touching the modules to enhance his tactile perception (fig. 69).



Figure 69: Photo of P.01, taken during the workshop. Since he wasn't satisfied with the quality of sound perception, he placed his fingers directly on the modules to enhance his tactile perception.

These differences in sound perception could be attributed to morphological differences affecting the transmission of the mechanical waves within the body (Adelman et al., 2015). A user's expectations may also impact how they judge their sensory experience: they might compare the quality of their auditory experience to other systems that were specifically designed for the ears, not the body.

Key Questions and Limitations

The strong morphological differences between each individual can be compared in a similar way to how differences in the structure of the outer ear can affect one's hearing. The Head Related Transfer Function (HRTF) is a physical transfer function that describes how a given sound coming from a specific point will reach the ear, in terms of spectral characteristics (Wightman & Kistler, 1989). In comparison, we wonder if we could develop a Body Related Transfer Function (BRTF), a functionality capable of adjusting the multimodal harness's response to each individual in order for them to perceive the same signal, based on their morphological differences (height, weight, musculoskeletal characteristics).

Mp2p: Body Spatialization Interface

We created the Mp2p (Mono point-to-point) interface as a creative tool for spatialization of multimodal signals on the harness, by manipulating the signals' positions and trajectories.

Interface Design and Composition Features

Within the design space, simple mono signals can be played on any single actuator or grouped set of actuators and panned¹⁵ between them according to a set 1D path. Spatialization of the multimodal signals in the Mp2p system works based on configuration presets which organize the points of stimulation along different paths. The signal can be routed to each independent point, one channel after another, or to several points at once, by grouping channel outputs together. In fig. 70, we see three possible configuration presets: these allow the designer to create different illusions of movement (sporadic in the first preset, side-to-side in the middle preset, top-to-bottom in the right preset). The actuators' positions on the lateral and vertical axes of the body allow for directional and alternating effects. We defined a set of configurations, providing a diverse selection of routing structures for the spatialized effects. The designer can manipulate the signal's position, duration, waveform (sine, saw tooth or noise), frequency (50 Hz to 4 kHz), and linear amplitude (0. to 1. float multiplier), and play their composition looped or one-shot (see fig. 71). By manipulating these variables, the sensory effects can be perceived as having continuous or discrete inter-position transitions: the signal can move gradually, or switch abruptly along its path.

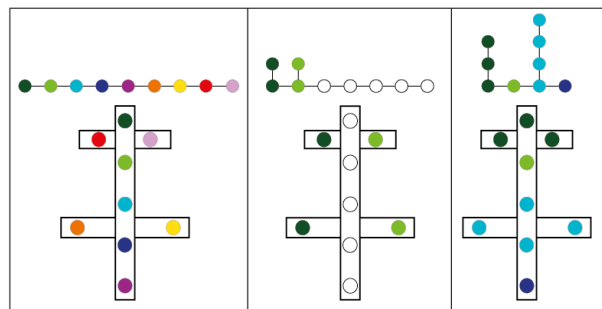


Figure 70: Diagrams of three possible Mp2p spatialization path configurations. On the top of the figure, arrays of colored dots represent the signal path: each different color is a different channel. Below each signal path is a graphic representation of the nine positions on the harness structure: the upper horizontal line is the clavicles, the lower is the ribs, and the vertical line is the spine. In the left-most configuration, each position has its own independent channel. The middle configuration uses only two channels (light and dark green), with two positions paired to each channel - the five spine points are inactive. The right-most configuration groups the positions among four channels: the clavicles and top spine point (dark green), the second spine point (light green), the middle spine and ribs (cyan) and the lowest spine point (navy).

¹⁵ Linear panning with Max [mc.mixdown~ @pancontrolmode 2] object gave the best results.

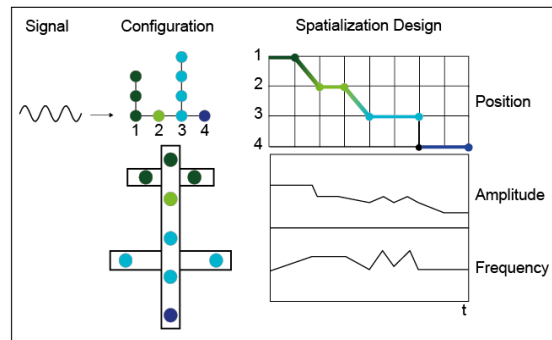


Figure 71: Graphic representation of the Mp2p interface functionality. A sine-wave signal follows a 1D path according to the chosen configuration preset (see fig. 74). To the right of the figure is the spatialization design, with three curves for position, frequency and amplitude. By modifying the curve, the designer can fine-tune the signal's duration at each group of positions, and its variations in amplitude and frequency across the composition.

Trial Feedback

The Mp2p interface is slightly more complex than the other two tools, so after learning about the basic parameters, participants generally chose to tweak our predefined patterns rather than create their own from scratch. P.03 was particularly impressed by the sensation created by the signal moving up and down the spine. If the signal moved quickly enough along the points, he felt a continuous sensation, like a "hand running up and down [his] back." The slower the movement of the signal along the points, the easier it was to localize from which position it came. The illusion we tried to create of a front-to-back shifting sensation between the front actuators (clavicles and ribs) and back (spine) was less convincing, perhaps due to the slightly central position of the actuators on the ribs, and because the sensation of something crossing one's body is a rather alien concept.

The duration of the experience as a whole also impacted the sensory experience: after trying the patterns, P.02 said:

I need more time to become familiar with the sensations I'm feeling on and in my body, since they are so new. Just a few minutes is not enough for my brain to really understand what is happening. I think with more time I'd be able to appreciate the sensations a bit more.

Participants made more comments on their "outer" body (tactile perception) than their "inner" body (extra-tympanic sound perception) during the spatialization experience. For most participants, the signal was only audible when displayed to certain positions (upper back and clavicles, i.e. those closest to the inner ear). The bi-modal aspect of the spatialization experience may therefore depend not only on a signal's position, intensity and spectral characteristics, but also on the user's conscious attention to either modality.

Key Questions and Limitations

When we started to design Mp2p, we tried to use an existing 3D spatializer tool: a vector-based amplitude panning (VBAP) algorithm (Pulkki, 1997). However, our configuration did not permit this because the listening point (the head) was off-center, i.e. not based on diffusion points (speakers) placed around the origin (listener). If we use a classic calculation of spatial decay ($\text{gain} = 1/\text{distance}^2$) according to airborne sound transmission, the signal disappears as soon as we move the point of diffusion away from the actuators' exact positions. Realistically, we would need to create a more specific spatialization model which takes into account the body's responses to extra-tympanic conduction and tactile stimulation of the skin. The listening point (i.e. listener's position) would be the head, while the haptic sensations would be distributed: they would not refer to any central reference or origin point, since tactile perception is decentralized and perceived all over the surface of the skin (i.e. each actuator's position would have its own sensory reference).

One key limitation of Mp2p is the static nature of the configuration preset system. The signal path configurations are saved within presets and are static within a single composition. In other words, the designer cannot use multiple configuration presets in one spatialization time frame, limiting each composition to a single path that the signal can follow. One possible solution is to create a state-based programming interface which would include a configuration for each state, and a sequencer that allows the designer to edit each successive state and concatenate them with discrete or progressive transitions between states. In its current state, Mp2p does not integrate the equalizer profile function of Inner.Music, so in order to calibrate the signal intensity for the different sensitivities of each point of stimulation, designers must manually tweak and adjust the amplitude levels along the duration of the displayed signal. It is time-consuming to find the right nuances of intensity and frequency values for a given point in order to obtain the intended perceptive results. A final limitation of this tool is that the signal is mono: we cannot create "harmonies" of different sounds and movements. In section 6, we discuss some steps to address this constraint.

Drummer: Body-based Drum Machine

While we discussed musical metaphors during the workshop, we decided to create a basic nine-track step sequencer and drum machine.

Interface Design and Composition Features

Each track on the interface corresponds to one actuator and plays one selected sound file, imported from the user's library. The designer creates their drumming pattern by activating buttons on the sequencer, creating repetitive patterns of stimulation in which each actuator/position performs a sequence of an instrument (see fig. 72). The patterns can be saved as presets.



Figure 72: The Drummer interface seen in the Max environment. The sequencer tracks each correspond to one actuator position on the harness. Above the sequencer, there is a preset grid for saving specific drumming patterns.

Trial Feedback

Participants described using the Drummer tool as a fun experience: the interface is simple and user-friendly, patterns can be quickly designed, and the ability to assign different instruments to the different points of stimulation is unique to this tool. Participants tended to move around while testing it, in sync with the rhythm. We heard several remarks about enhanced awareness of one's own body, and the presence of the wearable device. P.02 said, "I feel like the different instruments are playing directly on my body, or like I am the instrument!" She added that, since she heard the different sounds at the same time as she felt the stimuli at the different positions, the sound seemed to be coming directly from those points. This comment suggests that, even though the spatial audio information is lost in extra-tympanic conduction, the localized perception of tactile stimuli can contribute to impressions of auditory source positions. This comment also branched off into a discussion about sensory effects for physical rehabilitation, perhaps to help target the user's attention on a specific part of their body.

Key Questions and Limitations

In the Drummer interface, the opportunities to create musical patterns remain basic: the designer can select the output channels, choose sound files, alter the tempo and number of columns, but cannot change relative signal intensity according to the point of stimulation. The interface functionalities could be enriched with multichannel or MIDI sequences, an equalized distribution of the signals so that their intensities can be tailored to each point of stimulation, or a more dynamic variation of each track's intensity.



Figure 73: Photo taken during the workshop. P.02 bends forward to change her perception of the transmitted vibrations.

One could also imagine guiding the user's movements by distributing different sensations to different parts of the body. However, body movements and changes in posture interfere with audio-haptic perception. The pressure of the modules against the body changes based on the way the user stretches their joints and limbs (see fig. 73). For example, when the user bends downwards, or stretches their arms in front of them, they pull the modules closer against their spine. The added pressure on the points of stimulation, along with the difference in the curvature of the spine, facilitates good contact of the modules and thus good transmission of the vibratory signals. However, if the user raises their arms above their head, the upper back arches inwards, creating more distance between the modules and the skin and reducing the vibratory transmission. This aspect of use of the multimodal harness could be seen as a limitation but also as an advantage: though the body's movements cause variations in audio-haptic perception, those variations are part of the physical interaction between the user and the wearable, and could be a source of perceptual cues for movement-related use cases. Modifying accents, rhythm or instrument positions according to the user's movements would be interesting to explore, but this implies the integration of motion and pressure sensors which is currently out of the project's scope.

Discussion (Richards et al., 2022, p. 427)

During the two weeks of the workshop, we were able to address each theme of audio-haptic composition (multimodal music, sensory equalization, and signal spatialization). However, we experienced developmental setbacks due to time constraints and a lack of knowledge about user perception. Evidence of these current limitations can be found in several aspects of the interface functionalities: a sensory equalizer function is present in only one of the authoring tools (Inner.Music), the spatialized audio-haptic signals are mono and limited to basic wave types, and we are restrained to one-dimensional position configurations. Although they contain some similar elements, the authoring tools are distinct from one another, and the resulting sensory experiences are limited to each interface's distinct functionalities.

These constraints are temporary: we aim to streamline and optimize our authoring tools. For example, in future iterations, features could be consolidated into

one interface: the sensory equalizer in Inner.Music, the curves in Mp2p for modulation of position, frequency and amplitude, and the position-specific sound selector in Drummer. For example, in a unified interface, the designer could use the sensory equalizer to first determine a baseline audio-haptic calibration that suits their perceptual preferences. They could then use Drummer's function to select specific sound files to display at each position, and then use Mp2p's curves for spatialization pattern design to map the signal display at each position, along with more fine-tuned variations in amplitude and frequency across the duration of the composition. Inspired by existing tools for audio spatialization (Pottier, 2000), we have already begun to optimize the mono-source design constraint of Mp2p in a separate interface (called "MC-Curv"). Instead of one single spatialized source, the designer could edit and spatialize up to four sources on the body at the same time, creating harmonies of movement across the stimulation points instead of single-path sensations.

Regarding the design of the multimodal harness, we hope to improve many aspects in the next iteration: sound transmission quality, comfort, and ease of adjustability. The second iteration of the harness involves changes for both the wearable structure and the module. The actuators will be integrated in an orthogonal position relative to the surface of the body, instead of parallel. Though they will protrude from the surface of the device, this will allow the voice-coil actuator's lengthwise-directed vibrations to penetrate the surface of the body rather than rubbing horizontally across the skin. We hypothesize the change in orientation will increase sound perception in the mid/high frequency range, bringing more clarity to certain instrumentals and vocal sounds, without impacting the quality of tactile stimulation.

Conclusions (Richards et al., 2022, pp. 427-428)

Since there is no generic go-to tool for audio-haptic composition, we faced the same developmental challenges as past composers and researchers: we wanted to create and study multisensory effects, but we didn't have the tools to do so. In (Gunther & O'Modhrain, 2003), the authors complain of the "awkwardness" of designing the vibrotactile sensory effects using Protools, a standard Digital Audio Workstation. Nine years later, in (Baijal et al., 2012), the authors used Premiere Pro to create "vibetracks" for a film, by placing clips of different sine waves one-by-one at precise points along the video track. Today, researchers acknowledge that tactile composition is still "largely unexplored", that composers need to "take into account haptic perceptual effects" and that they develop their own design tools for this purpose (Turchet et al., 2021). Resorting to these painstaking methods drastically slows down the design process, and makes it difficult for progress to happen in the domain.

Another obstacle to overcome is the general lack of guidelines about variations in both auditory and tactile sensitivity across different sites on the body, and across individuals. Established ranges of sensitivity according to each position of stimulation could help provide compositional suggestions, or presets according to each modality. To this end, in an upcoming study we will follow up on our past psychophysical research (Richards et al., 2021) and evaluate participants' responses regarding both tactile and auditory perception while using the multimodal harness.

The authors call for smoother workflow design for audio-haptic composition, accessible to the research community. We hope that the products of our workshop can

foster discussions about what features and guidelines might contribute to an ideal audio-haptic composition interface.

Acknowledgements (Richards et al., 2022, pp. 427-428)

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2.2. User Feedback

The week after the workshop during which we developed the Inner.Music, M.p2p and Drummer interfaces, we invited colleagues to give feedback regarding their first impressions of the audio-tactile effects. Spending about 10 minutes testing each of the interfaces, 14 participants (P01, P02, etc.) played effects designed by us, and some created their own effects. The transcribed feedback was verbal and open, meaning that we asked for an unfiltered personal account of their experience, rather than according to any specific questions relating to our perspective and project objectives. We can categorize the feedback by theme in the following categories:

Multimodal Perception

P02: “It’s possible to hear the sound, but to feel practically nothing”

P11: “I feel the tactile effects on my body, but the sound is coming from my head - it’s strange”

P09: “Having a different sound based on the different points of tactile stimulation is a very interesting concept, since I become accustomed to what point is related to which instrument”

Tactile Perception and Spatialization

P13, P03: “Upwards movement of the signal on the spine is very interesting”

P12: “The vibrations give my body the sensation of shivers, so I feel cold if the vibrations are on my ribs or my back”

P12: “There is a clear sensation of discontinuity”

P08: “When the signal travels, it doesn’t feel like individual actuators are being activated, it’s more like there was continuous stimulation across all of the points”

P10: “The tactile sensation is more predominant on my back than on my clavicles”

P08: “The vibrations coming from lowest actuator on the back spread through the body the best”

P01, P11: “It makes a tickle sensation”

Auditory Perception

P12: “I couldn’t tell you where the sound is coming from, other than from inside of me”

P11: “I feel the same sound differently on each part of my body”

P14: “I can hear the sound as if I were listening with headphones - maybe even better”

P07: “I like having the bass on my clavicles, it makes me feel like the sound is coming from in front of my body, it gives the feeling of being in the same room as the sound, instead of a room away from the sound”

Applications of Use

P05: “Rhythmic music is the most pleasant to experience using the device, since I can really feel the bass”

P10: “Would it be interesting to use the device for musicians, so that they can localized different instruments on their body?”

P06: “What if we added a visual representation of spatialization to the experience? I’d like to see this used for meditation, to visualize the movement of sounds through the body”

P12: “A relaxation use case would be interesting”

Interface

P05: “I didn’t understand the linear spatialization paths, so I didn’t use that interface” (M.p2p)

P06: “The spatialization interface could be more user friendly”

P08: “The equalizer tool is very user-friendly and easy to understand”

P12: “I prefer to use the Drummer tool, because with the punctual vibrations my senses don’t become saturated” (Translated from French)

Inconveniences

P12: “The sensation of circular motion is interesting, but the front/backwards movement is less convincing” (Translated from French)

P06: “The pressure on my clavicles is uncomfortable”

P01: “The experience is ‘complete’, but very constraining, I feel deaf and a little bit suffocated”

2.2.1. Discussion of User Feedback

The users’ feedback about the interfaces and their multimodal sensations tell us a few key things about the experience of the multimodal harness. Firstly, the balance of remarks between the users’ auditory and tactile sensations speaks to the dual perception of the vibrations via the two modalities.

Regarding comments about their auditory perception, the users knew that the sound was coming from inside of their body, since they had been briefed on the principle of extra-tympanic conduction, and their outer ear canals were covered and plugged. However, certain users still compared the sound they heard with a position in space (“having the bass on my clavicles ... makes me feel like the sound is coming from in front of my body”), or with a more familiar listening style (“I can hear the sound as if I were listening with headphones”). Users also demonstrated an awareness of how the part of the body that was stimulated affected their perception of the sound (“I feel the same sound differently on each part of my body”).

The tactile sensation of the vibrations was also sometimes compared to other types of sensations such tickling or a cold/shiver sensation. The users made other comments about the perception of spatialization or movement of the tactile sensations across the surface of their body (“...like there was continuous stimulation across all of the points”, “Upwards movement of the signal on the spine is very interesting”), the difference in perception of intensity according to the position of stimulation, and the “spreading” sensation of vibrations inside of the body.

Considering potential applications involving the spatialized audio-tactile sensations was another natural point of discussion with most users. The mixed feedback about the use of the multimodal harness involved some aspects of the

interfaces, the physical discomfort of wearing the device, and dissatisfaction with the auditory or tactile sensations. Concerning the interfaces, users' complaints generally targeted the M.p2p interface, which was the most complex of the three developed during the workshop. We addressed their comments while developing the iterations of the second audio-tactile composition workshop, discussed in the following section (section 3). The tight fit and hard contact of the device makes it, understandably, uncomfortable after users have spent a certain period of time wearing it. To address the discomfort at the clavicles, we integrated a thin, firm layer of foam on top of the clavicle modules in the second iteration of the multimodal harness. Finally, to attempt to address this discomfort, along with certain users' dissatisfaction concerning the volume of their auditory experience while wearing the device, we specifically implemented design changes for the second iteration of the multimodal harness (see Chapter II, section 3.2.2).

3. Audio-Tactile Composition Workshop: II

The three main interfaces developed during the first workshop (Inner.Music, M.p2p, and Drummer) allowed creative exploration of audio-tactile effects, clarified the research questions which we examined through the experiments detailed in Chapter IV, and allowed us to refine our objectives for a future, integrative interface which would combine features from each preliminary interface.

Following the first audio-tactile workshop in August 2021, we reflected on user feedback (section 2.3) along with the limitations of the preliminary interfaces referenced in the article discussion (section 2.1). While these three interfaces were ideal for studying our ideas for effect design in isolation, the separation between their functionalities limited the possibilities for effect composition. To further explore the potential of the multimodal harness as a vehicle for artistic expression, we organized the second audio-tactile composition workshop for August 2022. During the second workshop, we used the second iteration of the multimodal harness. (The differences between the two iterations are detailed in Chapter II, section 3.2.2.)

3.1. Workshop Objectives

Our objectives for this second workshop can be separated into two categories: simplification and integration of the audio-tactile interface functionalities into the Ableton Live environment to give access to a larger number of users/designers, and the creation of audio-tactile demos. We wanted to integrate the features of multichannel distribution, spatialization, and sensory equalization into one comprehensive interface. We decided to integrate custom Max for Live¹⁶ patches into the Ableton Live digital audio workstation. One advantage of using Ableton Live as a composition interface is that it grants access to a diverse range of instruments already existing in Live's software environment and community, any of which would be possible to use to create an audio-tactile composition. Ableton also has a multichannel functionality, and despite its relative unreliability, it would be possible to incorporate methods for multichannel distribution and spatialization of the vibratory effects, through a custom Max for Live architecture. Our choice to implement our ideas into Ableton Live was also inspired by the program's accessibility and prevalence of use in the music community. In terms of the creation of audio-tactile demos, one main objective of this workshop was to produce a practical tool that composers could use to create new sensory compositions for the multimodal harness. These compositions would serve as demonstrations to explore ideas about multisensory perception, such as the interpolation between auditory and tactile modalities, overlapping trajectories of audio-tactile effects across the body, or the cohabitation between both auditory and tactile stimulation.

3.2. *iNsO4L (iNsOund for Live) Toolbox*¹⁷

The *iNsOund for Live* toolbox is a set of Max for Live devices, integrated within the digital audio workstation Ableton Live for use with the multimodal harness. The first

¹⁶ <https://www.ableton.com/en/live/max-for-live/>

¹⁷ ©2022 Developed by Roland Cahen, Centre de Recherche en Design (CRD) ENSCi les Ateliers - ENS Paris-Saclay

of these devices is the iNsO_Router, a multichannel signal distributor whose functionality is inspired by the linear spatialization methods employed in the previous M.p2p Max patch. The second main device in the toolbox is the iNsO_AH_Filter is a filter that allows the designer to calibrate the balance between auditory and tactile (haptic) sensation.

Sound spatialisation usually refers to a listener situated inside an array of speakers, all sound positions being calculated so that they best reach the listener. Wearing the multimodal harness, the listener’s head is located outside of the array of vibrotactile actuators on the device. While haptic perception is localized on different body positions, the multimodal harness facilitates audio perception via extra-tympanic conduction, where the mechanical waves are routed through the body to the user’s inner ears solely through the cervical spine. In order to ensure spatial sound transition from one activator to another while minimizing the loss of gain, the iNsO4L toolbox features basic multichannel panning, and follows one-dimensional linear paths. Like the M.p2p interface created during the first workshop, audio-tactile signal paths are still the main concept and setting of the spatialization system in the iNsOund for Live toolbox.

3.2.1. iNsO_Router

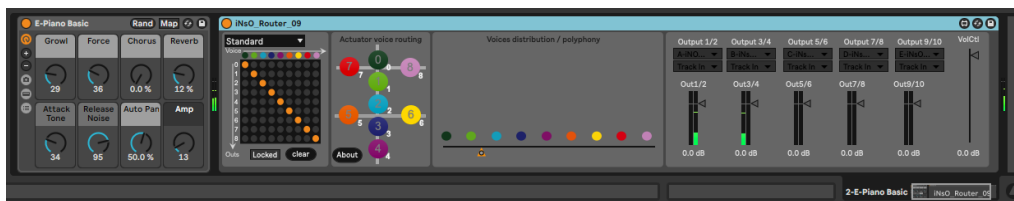


Figure 74: The iNsO_Router has 1 input (audio or instrument) and 9 outputs routed separately to 5 stereo Return tracks. Actuators are numbered from 0 to 8 , as represented by the “Standard” distribution/path seen in the image: 0 to 4 down the spine, 5 and 6 on the left and right ribs, 7 and 8 on the left and right clavicles.

The iNsO_Router device (Fig. 74) spatializes the incoming signal onto the nine vibratory modules on the harness. In the context of our objectives, one of Ableton’s limitations is that it only allows stereo in and out tracks. Therefore, multichannel spatializers must be split into two channels. Max for Live allows to create wormholes with more than two channels, but they must be routed to stereo outputs anyways. In addition, it is not possible to address directly to physical channels and any routing must refer back to Ableton Live’s existing channels, whose outputs depend on the present audio clients.

3.2.2. iNsO_AH_Filter

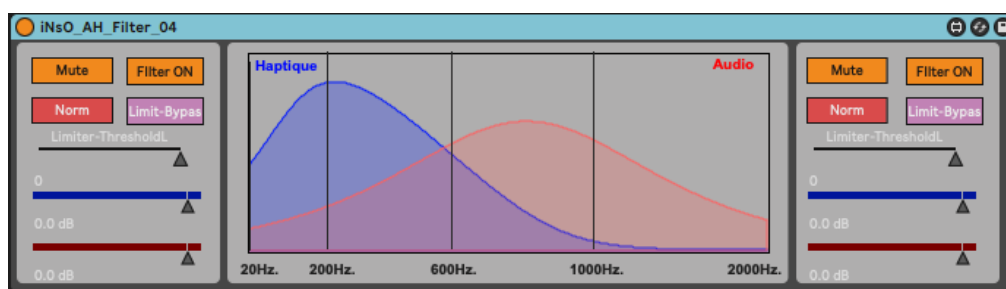


Figure 75: The iNsO_AH_Filters are meant to be placed on each Return/Output stereo track. They allow the designer to calibrate the vibratory effect on each stereo track, according to the perceptual balance they wish to achieve at a given point in their composition.

The designer can use the iNsO_AH_Filter (Fig. 75) to shift the balance between auditory and tactile perception for each Return/Output stereo track. By placing this device on each track, the designer can attribute single or mixed modality perception according to a given instrument, for example. The dB values and frequencies of the filter are estimated based on the experimental results of the psychophysical study (see Chapter II, section 2.3.5) and the study of bimodal judgment (see Chapter IV, section 2).

For in-depth details on use of the iNsO_Router, iNsO_AH_Filter and utilities in Ableton Live, along with alternative third party applications that could also be used for audio-tactile composition, please refer to the iNsOund for Live Toolbox Manual found in the appendix, pages 227-235.

4. Musical Collaboration: A Creative Case Study of the Multimodal Harness

A serendipitous encounter made this musical collaboration possible, studied in the framework of an instrumental case study. We used a particular case (the study of the composer's workflow) to gain insight into a specific issue (the use of the multimodal harness and its corresponding interfaces for audio-tactile composition). Alberto Gatti is an Italian composer, sound designer and sound engineer. He likes to think about sound from the point of view of other modalities, especially touch. Alberto Gatti composed audio-tactile études, or creations developed specifically for the multimodal harness in October to December 2022. In this section, all citations in italics represent exchanges with Alberto Gatti, the composer with whom we collaborated during this case study - either as direct verbatim from transcribed interviews, or from his written notes.

Here he explains his interest in working with new mediums for acoustic expression:

Ever since I discovered electroacoustic music, my research as an artist and composer has always been about the relationship between object and sound related to it, focusing my music on the more 'tactile' aspects of sound because they are connected to the subjective sound experience of each of us. I often work with vibrating transducers, and I have designed a series of sound sets and an armchair that vibrates to perceive both the tactile and auditory aspects of sound. The opportunity to collaborate on this project was really exciting as I discovered that transducers can also work on the bone system not only of the head.

4.1. Case Study Objectives

We structured this collaboration according to our creative research narrative, which speaks to the design of creative interfaces and composing multisensory effects for the body. Our objective was to approach the composition process as a case study, where we conduct an in-depth analysis of the multimodal harness as a tool for artistic expression. During this case study, our goal was to gather qualitative information from the point of view of the composer about how he used the multimodal harness (Chapter II, section 3.2) and the iNsOund Max for Live Toolbox (Chapter V, section 3.2). The goals of the case study were defined to clarify the reach of our research in an uncontrolled creative setting:

- **Produce content for demonstrations, in the form of short (max 3 minute) compositions. We refer to these compositions as 'Études', in the way Pierre Schaeffer uses this concept, meaning experimental/artistic exploration/demonstration of a concept with the studied artifact itself.**

Evaluating and demonstrating the content developed for the multimodal harness will serve as an essential way to communicate in a tangible way about the doctoral research.

- **Develop and test hypotheses about what type of audio-tactile composition will best exploit the sensory experience of the multimodal harness.**

The hypotheses, each interrogating the aesthetic potential of the audio-tactile experience, were discussed and agreed upon between the research team and the composer during the initial discussions about the collaboration. The composer tested each hypothesis throughout the composition of the audio-tactile *études*, which will be detailed in section 4.4.

- **Use the tools developed during the research for audio-tactile effect design.**

If these tools are inaccessible, or difficulty of use requires alternative design processes, we asked the composer to detail the reasons why, and explain the personal processes that he used in their place.

The composer was at full liberty to determine how to interpret and use the provided tools and mutually-defined objectives. We followed the creative process of the composer as he interpreted the hypotheses of audio-tactile composition, and appropriated our tools according to his personal approach. We then evaluated the outcome of his musical interpretation according to his experience, judging the viability of the iNsOund Max for Live Toolbox, the multimodal harness, and the sensory experience they facilitate as a means for creative expression.

To allow us to follow his creative process, Albero kept a working journal in which he wrote about any difficulties he encountered, and outlined his methods for addressing each of the *études*' corresponding hypotheses. Once he had made considerable progress on each of the *études*, we conducted an interview with him, during which we discussed his use of Ableton Live and the iNsOund for Live Toolbox for composing, the most remarkable aspects of the composition process, and his impressions about the physical and sensory experience of the wearable device. In section 4.4, we will provide a summary of his feedback, and our observations. In all following sections, the quotations are directly adapted from interviews with Alberto, or excerpts from the working journal kept during his composition process. We also defined some validation criteria : a) making the best of both audio and tactile perception, without favoring one or the other and b) making it possible for the jury to experiment some of these demos on the day of the defense.

4.2. Audio-Tactile Études

The themes of each audio-tactile *étude* were suggested by Alberto after an initial discussion with the research team about the functionality and perceptual qualities of the multimodal harness, experimenting with trends we already made and exploring in depth the possibilities offered by the iNsOund for Live Toolbox. Here, we describe the *études* in terms of their respective themes and hypotheses, and not the final perceptual experience: they were still in the process of being composed at the end of the doctoral research.

I believe it is not a demonstration but a new method of creating content and investigating new forms of emotion and feelings. The three studies focus on thinking differently about the enjoyment of sound. I started from what I

perceived during the first tests. I immediately noticed how especially the frequency range from 300 Hz down was really physical. We are used to thinking of low frequencies as 'those that move the belly', with this method it is amazing how different and truly physical it can be. Another aspect is that sound is usually perceived from the outside, whereas in this case the sound travels from the centre of our body (on our axis) to our head, a new and never before perceived experience. The aspects that certainly inspired me the most develop on two levels: a constant sound as a perceived physical-tactile force and how a sound that is diffused and therefore heard from one part of the body rather than another is heard differently, not only from a tactile point of view but also from an auditory one.

Audio-tactile étude 1: *Tenuto*

The first étude seeks to explore Alberto's question, asking "How can someone feel the sensation of continuity and internal space?" In this audio-tactile étude, the sound moves along different points on the multimodal harness, causing the listener to feel and hear different things at different points of the body within continuous sound evolution.

The idea behind [Tenuto] is how a sustained sound can be a tactile force instead of a perceived pitch. At the same time the usual sound is heard from one precise part of the body and shifted in its sustain period to another; the 'pairwise' shift is introduced by the use of audio samples of different attacks with different timbral qualities in order to stimulate auditory and tactile memory at the usual time.

Audio-tactile étude 2: *Tactile obstinate*

For the second étude, Alberto experiments with "rhythmic effects and a detuned cycle to see what it becomes: the pulses shift along with pitch perception".

'Tactile obstinate' aims to cause the listener to perceive point events that tend to sound objects with poor spectral components in order to work on the construction of a timbre that has a perceived medium frequency mixed with a low frequency sound. The idea is to hear small sounds in different parts of the body that create a 'touching sound' effect, i.e. a sound that can be perceived both audibly and tactilely. As with 'Tenuto', the same sound perceived at different points of the body often results in a different sound perception. The rhythm is stable and is progressively "spatialised" in the body, causing the ostinato to be perceived in portions of the corpus that are progressively distributed throughout the body.

Audio-tactile étude 3: *The womb*

This étude was initially inspired by the idea of spatializing human voices, natural or foley sounds on the body coming from inside but as if they were coming from a body linked to ours. Alberto asked: "Is the voice the perception of corporeality? If so, what is a voice when heard through vibration?" He explained his motivation as being more related to the sonic characteristics of the voice than the comprehension of the words

or the language. In this étude, the goal was to create an experience of sound from the womb - internal, filtered sound - then create the experience of leaving the womb by modifying the perception of voices throughout the piece. In the first section of this étude, Alberto would try to recreate a known experience or source of sound, either in traditional terms (such as the cello) or from concrete music: *“door creaking, water flowing, other simple things”*.

4.3. Summary: Working Process and Feedback

When beginning the process, Alberto was faced with a totally new system and perceptual experience of sound. While he acknowledged that this was an opportunity to explore his artistic approach, he also quickly recognized that there would be a learning curve for using the wearable device and interface. In his journal, he wrote *“I realized that I need time to try the device and experience it a lot to get to know its performance better.”* This remark brings the question: is it necessary to be trained or earn knowledge about this experience to fully appreciate it?

In his first test of the iNsOund for Live Toolbox, he was unfortunately not able to use the Max for Live patches due to his version of Ableton Live. After several tries and errors with our iNsOund Ableton Live components, he felt more comfortable using a different DAW to test the multichannel effects, and saw that the errors he encountered were not related to the multimodal harness. Therefore, for his initial tests, Alberto developed his own approach within Ableton, spatializing the effects on the different channels by using several overlaid tracks. He was eventually able to troubleshoot the problem with Roland, and used the iNsOund for Live Toolbox for his later works. The first attempt of using the device was complicated, as he wrote: *“The first 'artistic test' performed was complex. Setting up the equipment myself and setting up the sound card is not trivial but not impossible either.”*

Another interesting remark from his first days of using the multimodal harness with Ableton Live was the notion of mixing and vibrotactile rendering. A sound designer and composer, Alberto was not already so familiar with the creation of tactile effects. He noted that it is particularly difficult because *“you don't perceive what is being composed beforehand”*. To be able to have an idea of a given effect design in terms of its multimodal perception, the composer needs to have already gotten used to the range of perception while using the multimodal harness, or they need to wear the device while composing. As this happens in all sound design works which involve expression through objects and artifacts, Alberto was quite well prepared for this because of his experience with vibrating objects. However, as Alberto pointed out and we already noticed, wearing the device for long periods of time is not practical and can be even painful after a few hours: he described the harness as *“very immersive but not comfortable for use more than one hour”*. He also noticed that he lost sensitivity to the vibrations after his longest periods of use (2 hours). Therefore, ensuring a proper perception of the études as he was composing them was the hardest part of the process. While he acknowledged that the device was uncomfortable to wear, he still sees its potential for novel listening experiences: *“In terms of design, I don't think it's too much of a problem to wear this exoskeleton, also because, as already mentioned, what it does is a new thing and will certainly have a future.”*

During interviews, Alberto also remarked that the multimodal harness needs “*real equalization*”, to avoid fatigue or straining to perceive either the auditory or tactile sensations. He recommended that there be a way for the user to create a self calibration: “*We all hear differently, so perhaps a self-calibration system should be included.*” Part of our research objective was based on the study of calibration of the different positions of stimulation for audio-tactile perception. We implemented the iNsO_AH_Filter tool so that the designer could adjust the balance between auditory and tactile perception during any point of the composition. However, it was up to the designer to use this tool, and at that point in interface development, we did not take the time to implement any standardized sensory equalization tool. Alberto’s comment about sensory calibration has defined the main priority in future development of the iNsOund for Live Toolbox: the integration of a standardized and/or personalizable equalization feature.

When asked for feedback about the sensation of using the multimodal harness, Alberto said that his favorite part was the novelty of using the device, and the fact that it can also “*guide*” him as a composer, to feel the music in a different way and focus on the tactile sensations as well as internal auditory perception. He described the auditory perception as like a “*strange loudspeaker*”, strange because the sound is coming from inside of you, instead of from external space. He said, “*with the harness, you are aware that the high frequencies are in your heads, while the low vibrations are perceived lower in the body.*” Alberto also noted that the limit in working only with lower frequencies (< 2000 Hz) was not a problem, and that he was able to find creativity by appreciating the associated sensations and sound.

For extensive, first-hand insight into Alberto’s process, experience, and impressions while creating the audio-tactile études, please refer to his responses in the follow-up questionnaire, included in the appendix (p. 236).

4.4. Future Work

Live musical collaborations are another source of inspiration for audio-tactile composition, but we did not have time during the doctoral research to pursue this type of project.

Following the thesis, we therefore plan to continue our work with Alberto Gatti to explore the sensory relationship between the cellist, their instrument and the listener wearing the multimodal harness. Alberto’s main motivation behind this concept is to explore what type of perception the listener has when they feel what is happening to the instrument.

He explained his reasons for finding inspiration in the musician-cello-listener relationship:

The choice of the cello was intuitive, at first I had thought of a double bass, but for reasons of convenience and also for the relationship with chamber music we chose the cello. The idea was the visual transposition into the tactile sense: seeing someone stimulating a body and perceiving this stimulus with one's own body could take the perception of the gesture and the sound produced by it to another level, a level that besides being sonorous is

gestural, representing the strength of the gesture and the commitment of the movement to 'feel' something.

During a preliminary test, we used a standing microphone to capture the sounds of the cello, which were then routed to all channels on the multimodal harness (Fig. 76). In the future of the project, we plan to integrate contact microphones directly onto targeted zones of the instrument's surface. We invited a cellist to play her instrument in a series of basic exercises: tapping the body of the cello, loud plucking and snapping of the strings, drumming, long, sweeping notes, the production of low and high tones, and interpolations between tones. (Note: As we did not have the time to conduct a full report on these audio-tactile sensations, we cannot say much more about the experience other than general remarks.)



Figure 76: During a test session, we worked with a cellist to explore the potential of the sensory experience: the listener, wearing the multimodal harness, feels and hears the vibrations of the instrument in real time.

Listening to and feeling the vibrations, we felt an uncanny sense of connection to the musician, as if we became the cello itself. Cutting off pathways of external hearing and limiting the auditory perception to extra-tympanic perception is one option: the listener only hears the sound transmitted to the multimodal harness. Another option would be to only partially block the pathways of external hearing, allowing the listener to perceive both air- and ETC-transmitted sound. By manipulating the sound perceived through the multimodal harness, the listener could receive two simultaneous streams of auditory input: both the “true” sound of the instrument, and the modified/filtered internal sound. The tactile sensation reinforces the illusion of becoming “one” with the instrument. For example, as the listener watches the musician move the bow across the cello strings, the vibrations are felt on the body as if the bow slid across the skin. We wonder if it is necessary to block the external auditory pathway (air-conducted sound) to produce the full experience and functionality of the harness. This question has emerged regularly during workshops and discussions with subjects and users during the thesis project. We cannot decide right now, but according to the user and between different situations or approaches to sensory experiences, either option may be preferable.

5. Conclusion

In this chapter, we reviewed the most creative outcomes of the multimodal harness: the interfaces and tools, workshops, compositions and collaborations each closely tied to the aesthetic audio-tactile experience of the wearable device. These creative advancements represent an essential part of integrative project structure. They allowed us to position the human sensory experience not only as an experimental or theoretical concept to explore, but also as a real, living matter to work with.

During the first audio-tactile composition workshop, we tested our initial ideas about effect design by developing several exploratory interfaces: Inner.Music, Drummer, and M.p2p. These interfaces provided us with the necessary foundations to gather qualitative feedback, and plan for the second edition of the audio-tactile co-development workshop held one year later. We also illustrated some imaginary scenarios of use of spatialized audio-tactile effects, inspired by discussions with participants about the place of this genre of wearable technology beyond the domain of music. The outputs of the second audio-tactile co-development workshop (section 3) integrated our initial Max/MSP interfaces into the Ableton Live environment, facilitating their use by composers familiar with this existing digital audio workstation workflow.

The products of the second workshop enabled us to therefore propose these tools (the iNsOund for Live toolbox and the multimodal harness) to a musical composer in a collaborative framework. The work of the composer, Alberto Gatti, was completed during the last semester of the thesis, and probed the full potential of the wearable device and its accompanying interfaces in their latest stage of development. The audio-tactile *études* composed by A.Gatti (section 4.4) were the main subject of our case study. The composer's working process and appropriation of our research exposed its pertinence in terms of novel methods and materials for musical composition. Emboldened by the results of this musical collaboration, we believe now more than ever that there is a bright future for inclusive musical expression and perception through spatialized audio-tactile effects and device design even if it is not as simple as one may at first imagine.

Chapter VI: Discussion, Conclusions and Perspectives

During this doctoral research, our main goal was to expand and contribute to alternative methods for listening experiences. “Alternative” is the key word here – neither substitute, assistive, augmented nor complementary describe our objective for the novel audio-tactile device developed during this thesis: the multimodal harness. We developed a novel wearable technology which would allow the user to perceive vibrations with their skin via vibrotactile stimulation, and with ears via extra-tympanic conduction (ETC). The multimodal harness introduces a different, alternative way of appreciating sound as vibration. It exploits the power of traveling mechanical waves to excite the surface and the inside of the body, to produce a simultaneous auditory and tactile experience of vibration.

1. Context and Structure

This thesis was organized according to the guiding purpose, developmental process, and the outputs generated by two audio-tactile devices: the monopoint module, and the multimodal harness. We used the terms “purpose”, “process”, and “outputs” in order to provide the overall organizational framework of the thesis. They helped us to define our investigative approach not only according to the concrete results related to the audio-tactile devices, but also by analyzing the steps along the path to their conception. Clarifying the purpose of each audio-tactile device illustrated the multidisciplinary nature of our research approach. The monopoint module was destined solely for psychophysical experimentation. The multimodal harness’ purpose spanned the theoretical, experimental and creative. Beyond clarifying the relationship between the audio-tactile device’s guiding purpose and its resulting form, consciousness of their process of development allowed us to take a step back and articulate the many facets of our research as an integrative whole. The outputs of the audio-tactile devices reach beyond the devices themselves, and relate to tangential outcomes such as experimental data, methods and data, scenarios of use, sensory effects. The concept for an industrializable product, Ryzm™, was also presented as an output of the multimodal harness. The three terms appeared throughout the thesis, helping to situate each aspect of our design project according to its position in the integrative whole presented in Chapter III.

2. The Monopoint Module: Purpose, Process, Outputs

In Chapter II, following the presentation of the thesis structure, we presented the purpose and process of designing the monopoint module. The purpose of the monopoint module was to serve as an experimental tool, used to address the following question: How do three main parameters of the vibratory stimulation signal (position on the body, frequency and amplitude) relate to the listener’s thresholds of auditory perception via extra-tympanic conduction? During the process of development, we defined five main design criteria: reliable readings of pressure against the body, consistent contact on the skin, minimal friction, and protected wires. The outputs of the monopoint module refer to the experimental results about the auditory detection thresholds of hearing via extra-tympanic conduction (ETC) on the

torso. The results of the psychophysical study would then provide the foundation on which we would base the development of the multimodal harness.

Through a psychophysical procedure adapted from Walker and Stanley (2005) and McBride et al. (2008), we analyzed participants' auditory perception of vibratory signals displayed to key points of the torso's musculoskeletal structure (the spine, clavicles, and sternum). Our hypothesis posited that certain signal parameters would impact auditory perception via ETC, and that tactile sensation of the auditory signal would potentially impact auditory signal detection. The results confirmed the possibility of hearing frequencies from 50 Hz to 1900 Hz at sites of stimulation on the torso, distant and isolated from the skull. The lowest auditory detection thresholds of our study were situated around 250 Hz, which corresponds to the peak of vibrotactile sensitivity. We have two theories for the low auditory thresholds at 250 Hz: either the tactile sensation may have influenced participants' ability to detect the auditory signals, or the length of the traveling wave within the body could have influenced its ability to reach the inner ear. Stenfelt (2011) noted the possibility for tactile sensation to cause lower thresholds at low frequencies, explaining that multimodal interaction when stimuli are perceived via ETC results in a "greater growth in loudness compared to [air-conducted] sound for equal increase in sound intensity" (p.11). Adelman et al. (2015) conducted a study on auditory perception at sites on the torso, using the term "soft-tissue conduction" (STC) when referring to auditory perception from within the body.

Both our study's results and those of Adelman et al. (ibid.) reflect a positive relationship between the threshold value and distance from the skull: the more distant the vibratory stimulation, the higher the auditory threshold of detection. However, our study's focus on measuring thresholds from a range of frequencies (seven pure-tone frequencies from 50 to 4000 Hz vs only 2000 Hz in Adelman et al.) illustrated that auditory detection of vibratory signals displayed on the torso varies not only based on their position of stimulation and amplitude, but also a third parameter of frequency.

3. The Multimodal Harness: Purpose and Process

The results from this first experiment solidified our motivation to create a second audio-tactile device: a wearable device called the "multimodal harness". The purpose of the multimodal harness addressed multiple facets of our research: to serve as an experimental tool for the analysis of audio-tactile perception, to encourage the user to revisit their assumptions about sound perception, and to provide a concrete anchor representing the integrated disciplines present in this project. Finally, we also built the multimodal harness with the motivation to demonstrate, through the creation of audio-tactile compositions, that the experience of sound is really about the experience of vibrations - something that everybody can perceive, and appreciate in their own way. It is a wearable device designed in order to stimulate the inner ear via vibratory excitation of specific positions of the musculoskeletal structure of the torso: the spine, ribs, and clavicles. We chose to substitute the positions of stimulation on either side of the ribs, instead of the sternum, in order to provide more potential for spatialized audio-tactile effect design. The sternum was also removed from the positions of stimulation due to the zippered front closure of the multimodal harness.

In section 3 of Chapter II, we discussed the process of creating the first and second iterations of the multimodal harness (MH.1 and MH.2). We defined the design

criteria of the multimodal harness in collaboration with Les Vertugadins, a costume design studio. The MH.1 was designed according to five main design criteria, based on the quality of the vibratory signal transmission, and user comfort: consistency of vibratory transmission, isolated vibratory sensation, ergonomics and efficiency, tight fit without discomfort, and lightweight yet durable. The MH.2's design criteria were defined in order to improve auditory perception via ETC, and to simplify the usability of the harness and user comfort. They build on the previous five design criteria, with added emphasis on: optimized sound perception, minimal adjustments, maximum comfort, and minimized external sound.

4. Theoretical and Industrial Outputs of the Multimodal Harness

Starting with Chapter III, the thesis dealt with the outputs of the multimodal harness. In Chapter III, we discussed its industrial and theoretical outputs (in the sense of the thesis framework term). The industrial outputs of the multimodal harness refers to Ryzm™, a concept for a commercial product inspired by the perceptual experience of the multimodal harness. While developing Ryzm™, reorienting our research towards product design pushed us to consider its implications from a different point of view: one that puts user acceptability at the heart of device development, instead of the perceptual experience itself. Developing the product born of the industrial context of our research¹⁸, Ryzm™, was an instrumental step towards concretizing this project's perspective. As a first step in defining our own approach, we examined the similarities, differences, and reciprocity between two distinct categories of design: product and speculative design. Our contributions related to this reflection deal with the positive project impacts when merging speculative and product design processes. Fallman (2007) placed research-informed product design and scientific research about design on opposite ends of a range. He distinguished design-oriented research, which deals with research first and design second, and research-oriented design, which prioritizes clients and the production of new products. While he acknowledged that these design research methods often find themselves intertwined, he concluded by arguing that it “is too much to both do a good design, with a happy client – answering to all the real-world challenges one will face – and do a good research, with happy peers” (p. 200). The results of our research provide one example where the industrial and scientific sides of design research may coexist, providing benefits to all project stakeholders.

During the last section of Chapter III, we positioned our research in the midst of its diverse contributions from many disciplines. Integrative design is a perspective on design research that we defined to bring clarity to our own project approach. We look at all of the components of our project—the scientific methods, the creative processes and outputs, the disciplines and contributors—and we see them as parts as a cohesive whole, similarly to a Gestalt. We defined integrative design according to six criteria: it is multidisciplinary, it aims to integrate, it integrates and interprets the design-science dynamic, each contributing element is unique, they disseminate

¹⁸ The research was conducted as part of an industrial sponsorship with Actronika SAS, funded in part by the ANRT (Association Nationale de la Recherche et de la Technologie) in a CIFRE contract.

variations on a central narrative, and the design process creates connections between disciplines. Each experimental, creative, industrial or theoretical element of our project brings with it its own narrative, each of which reflect one interpretation of the core, integrative narrative as articulated in Chapter III, section 5: “The experience of sound is really about the experience of vibrations - something that everybody can perceive, and appreciate in their own way.” Telling the story of the research objective according to the point of view of each actor allowed us to frame the project in their terms, which facilitated communication and also allowed us to reorient ourselves according to the different project goals.

5. Experimental Outputs of the Multimodal Harness

Chapter IV was dedicated to the experimental outputs of the multimodal harness: two studies which analyzed the perceptual experience it facilitates. In the first study, we explored how to best code an audio signal into a haptic device for music enhancement. Specifically, we looked at how tactile height could be used to code auditory pitch. We manipulated the alignment between tactile and auditory musical stimuli in terms of the tactile intensity, timing and a third parameter of ‘pitch-height mapping.’ The pitch-height mapping parameter was based on the common association between visual height and auditory pitch, seeking to determine whether we may transpose the same phenomenon to the audio-tactile domain and thus positively affect participants’ multimodal appreciation of music. Despite the evidence for universal pitch-height associations in the audio-visual domain (Dolshied et al., 2014; Parkinson et al., 2012), we did not replicate similar effects of pitch-height congruence in the audio-tactile domain. Our results showed that intensity and timing are essential parameters to align for tactile music enhancement, but the lack of significant effect of the pitch-height mapping parameter on participants’ ratings showed that the association between auditory pitch and tactile ‘height’ is perhaps more complex than in the visual domain.

The second study presented in Chapter IV aimed to explore how simultaneous stimulation of the two senses of hearing and touch via vibratory contributes to multimodal interaction in the frequency range of 200-1200 Hz. We designed the study based on three hypotheses, assuming that participants’ perceptual judgments of the vibratory stimuli would depend on frequency, vary based on signal intensity, and be grouped into different styles of responses. Participants first calibrated the intensity levels of the vibratory stimuli according to their individual preferences. Then, in a second task, they evaluated their audio-tactile perception of the vibratory stimuli, assigning a “bimodal judgment” based on how much they felt and/or heard each signal. The fact that participants could consistently judge their perception of the two aligned sensations in terms of “more” or “less” auditory or tactile perception provides an argument that, in the context of the current study, the two modalities did not integrate into a unified percept at all tested frequencies: this mode of bimodal excitation cannot, therefore, be described as multimodal integration in the sense defined by Driver and Noesselt (2008). However, participants’ bimodal judgments at 400 Hz were particularly close to the center of the audio-tactile range, at all tested positions on the torso. This demonstrates participants’ uncertainty while distinguishing single-source audio-tactile perception of vibration at 400 Hz: a point of potential interest for future research about multimodal integration. This uncertainty

can be interpreted in at least two ways, as a difficulty to decide, or as the fact that the two modalities coexist and merge.

6. Creative Outputs of the Multimodal Harness

The creative outputs of the multimodal harness elaborated in Chapter V have given us the chance to demonstrate the real potential for spatialized audio-tactile compositions as a medium for aesthetic expression. During our first audio-tactile workshop in August 2021, we used Max/MSP to design a set of three preliminary interfaces based on our initial assumptions about the perceptual experience that the wearable device may afford. Inner.Music provided the possibility to filter any audio input, and route different frequency bands to different positions on the device. With Mp2p, we used different configurations of channels, grouped together to create paths that the vibratory signal followed, spatializing the vibration on the body from one module to another. The Drummer interface allowed us to test the simultaneous sensations of different signals at different parts of the body, and play around with different rhythms. During feedback sessions, certain users complained of unsatisfactory auditory perception; we had also hoped for more from the device in terms of extra-tympanic conduction. While we wouldn't have been able to do much in terms of audio-tactile effect design without them, the preliminary interfaces were not extremely user-friendly, and would benefit from overall simplification in order to facilitate full-length sensory compositions.

Based on this constructive feedback, we created new versions of both the wearable device and its associated interface. In 2022, we led a second audio-tactile workshop, during which we used the new iteration of the multimodal harness. Instead of limiting ourselves to the Max/MSP environment, we reinterpreted the preliminary interfaces with Max for Live in order to implement some of their main functionalities in Ableton Live, inspired by the program's accessibility and prevalence of use in the music community. The iNsOund for Live toolbox is a set of Max for Live devices for Ableton Live. The toolbox notably contains the iNsO_Router, a multichannel signal distributor, and the iNsO_AH_Filter, which allows the user to calibrate the balance between auditory and tactile sensation.

To test the usability of the toolbox from the point of view of a musician, we collaborated with Alberto Gatti, a composer with experience working with tactile effects. We analyzed his working processes and hypotheses in the framework of an instrumental case study, where the case of Alberto's composition process provided valuable insight into the use of the multimodal harness and the iNsOund for Live toolbox for musical expression. Going into the composition process, we had defined three main objectives: to produce content for demonstrations of the multimodal harness, to develop and test hypotheses about its associated sensory experience, and to test the iNsOund for Live toolbox in an uncontrolled creative setting. After we agreed on which hypotheses he would explore through his compositions, Alberto created three audio-tactile études: *Tenuto*, *Tactile obstinate*, and *The womb*. In *Tenuto*, Alberto composed a sound that moves along different points on the multimodal harness, causing the listener to gain awareness of how the sound changes depending on the part of the body which is stimulated with the vibration. *Tactile obstinate* experiments with the combined audio-tactile perception of vibration, where the listener hears a sound at the same time as they feel a rhythm spatialized on their body.

The multimodal sensations in *The womb* evoke the experience of being inside a body, and transitioning to the outside world.

The descriptions of these études can only communicate so much about the sensations they create for the listener: to fully understand the experience of perceiving vibrations composed for the body in this way, it is necessary to test them for oneself. This is an inherent limitation of the multimodal harness, but it is also part of its uniqueness and its novelty, its strength as a tool for perception and expression. The experience of these audio-tactile compositions is extremely personal: all of the listener's attention is focused *inwards*, towards the body, the sounds and sensations coming only from within themselves. It is an intrinsically isolated experience. The relationship between the composer and the listener takes on a new and physical aspect. The composer communicates not only through the sounds perceived via ETC, but also the way that their composition literally touches the user's body.

7. Conclusion

The diversity, scope, and potential of audio-tactile compositions as an aesthetic musical medium are limited only by the technology that enables us to create and to perceive them. We wonder, could spatialized audio-tactile effects gain as much emotional significance and communicative power as 'traditionally'-perceived sounds and music? Schmitz et al. (2015) suggested that wearable tactile devices aiming to display emotional aspects of music should display vibrations in a wide range of frequencies, to many positions on the body. Nanayakkara et al. (2009) explained that the vibratory experience of music was more enjoyable, and elicited stronger emotional responses, when the audio signal was spatially separated on the body, theorizing one reason could be that "in natural environments, vibrotactile stimulation from multiple signals is typically already spatially segregated" (p. 345). During the doctoral research, we did not yet explore the experience of the multimodal harness in terms of its potential to elicit diverse emotional responses to the body-spatialized audio-tactile compositions. In terms of future perspectives, we see a clear interest in studying the more emotional character of the experience of the multimodal harness. There is also a strong potential for the multimodal harness to serve as a tool to further study and develop inclusive and accessible vibratory listening experiences during future collaborations with users who are deaf or hard-of-hearing.

The sensory experience of the multimodal harness may inspire one to reconsider how the body is, or may become, capable of perceiving sound through vibration. We hope that this work will inspire researchers, designers, researcher-designers, sound designers, and composers alike to seek out their own alternative sensory experiences of sound, whether that is through theoretical reflection, experimentation, technological development, creative expression, or an integrative mixture of the above.

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Appendix

Standard Actuator - Datasheet

Our **Standard Actuator** is the first generation of the HapForce, High Definition Haptic Actuators product line. We bring to the market a very innovative actuator capable of providing a wide variety of touch sensations. We use high quality components to provide the best in class high definition haptic effects for its size.

We see the **Standard Actuator** as the perfect fit for a large variety of devices, game-pads, joysticks, mice, screens and many more. With its inertial drive design, any device can provide vibrations with an easy integration, it is simply vibrating everywhere.

The vibrations could even make you believe you are touching leather or paper on the top of your smartphone screen. Haptics for years have been dull and loud, by using a wide bandwidth of frequencies from 10 Hz to 1000Hz we are able to make anyone feel the digital world in a whole new way.

Forget the basic "Buzz" of haptics and discover the possibilities of having any type of button you know and more, very immersive road sensations in games, socialize as never before with Hapmoji's... The Possibilities are endless.

Our **Unitouch platform** is the best way to create these sensations. Allow your designers to create their own haptic interactions using a simple SDK to call our HD Libraries or even let them create directly through our **Unitouch Engine**. We provide our engine and libraries either with our own Tacronik electronics or directly through a portable version of our Unitouch platform.

The **Standard Actuator** provides the best entry into the high definition haptic world. Get a hand on our Kits and try out your new high definition interactions, provide your customers a new way of touching any digital environments, refine your branding by implementing highly recognizable effects and make your own haptic signature.



Figure 1: **HFBA121238** - Standard Actuator

Recommended Applications	
• HM interfaces	• Gaming
• Smart wearable	• Industrial devices
• Hedonic devices	• Healthcare

Table 1: **HFBA121238** recommended applications

Parameter	Specification
Resonant frequency	65 Hz
Dimensions	11.5 × 12 × 37.7 mm ³
Typical acceleration	11.4 g-pp

Table 2: **HFBA121238** key features

Feature	Benefit
Haptic	<ul style="list-style-type: none"> • High frequency bandwidth, 98% of the haptic and most of the audio bandwidth • Low resonant frequency • High speed response time
Connections	<ul style="list-style-type: none"> • Standard pin header, pitch 0.05 in • Trough hole soldering
Design	<ul style="list-style-type: none"> • Miniature size • Easy attachment point

Table 3: Key benefits of **HFBA121238** - Standard Actuator

1 Technical description

Haptic characteristics

Parameter	Specification	Conditions
Resonant frequency	65 Hz	As specified in section 5, load 100 gr
Acceleration (AC)	8 g-pp	As specified in section 5, load 100 gr, at max. AC voltage
Acceleration (impulse)	11.4 g-pp	As specified in section 5, load 100 gr, at max. impulse voltage
Lag time	6 ms	Delay to reach 10% of impulse acceleration
Rise time	14 ms	Delay to reach 90% of impulse acceleration

Mechanical characteristics

Parameter	Specification	Conditions
Dimensions	11.5 × 12 × 37.7 mm ³	
Movement direction	\vec{X}	As specified in section 4
Total mass	8.7 gr	
Moving mass	4.4 gr	

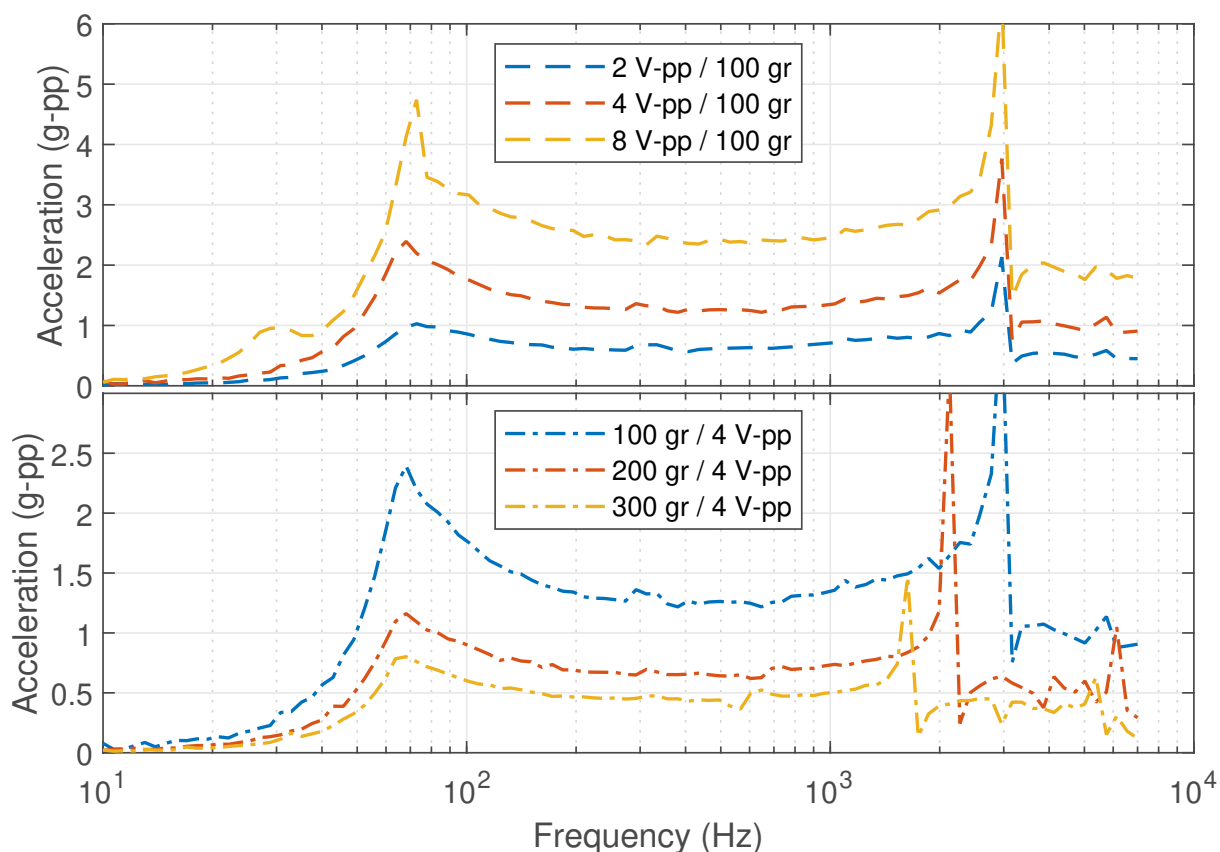
Electrical characteristics

Parameter	Specification	Conditions
Resistance	4.5 Ω	At 20 °C
Inductance	128 μH	
Rated voltage	1.41 V-rms	
Rated current	147.8 mA-rms	At rated voltage and resonant frequency
Min. voltage	0.25 V-Op	Threshold level for minimum perceptible signal
Max. DC voltage	2 V-Op	At 20 °C
Max. AC voltage	9 V-Op	At 20 °C
Max. impulse voltage	12 V-Op	At 20 °C

Environmental characteristics

Parameter	Specification	Conditions
Operating temp.	[−20 °C, 40 °C]	
Storage temp.	[−40 °C, 70 °C]	

2 Acceleration bandwidth measurement



3 Example of typical consumption data

Effect	Typical duration (ms)	Norm. mean current (mA/V) ¹	Norm. peak current (mA/V) ¹
Standard UI (e.g. click)	30	0.5 ²	250
Advanced UI (e.g. scroll)	30	10 ³	200
Standard gaming (e.g. shotgun)	300	1.5 ⁴	250
Advanced gaming (e.g. fire)	> 500	5 ⁵	250

¹ Current normalized according voltage input

² Single effect played every 5 s

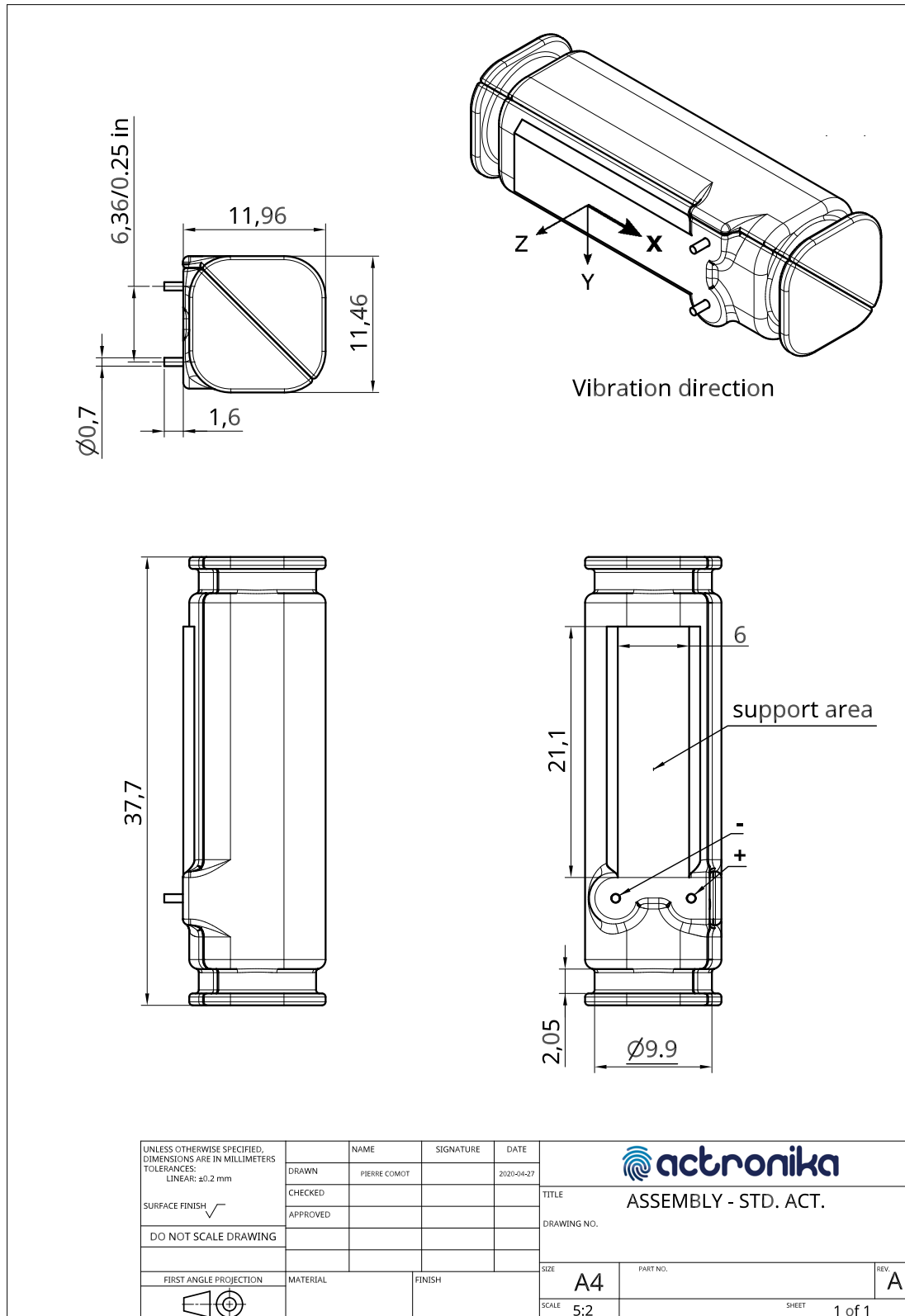
³ Multiple effect repetition (duration > 500 ms) every 5 s

⁴ Single effect played every 1 s

⁵ Effect played continuously

Mean current values are given for consumption calculation, wiring design and heating calculation. Maximum current values are given for electronic components choice.

4 Dimensional description



5 Measurement method description

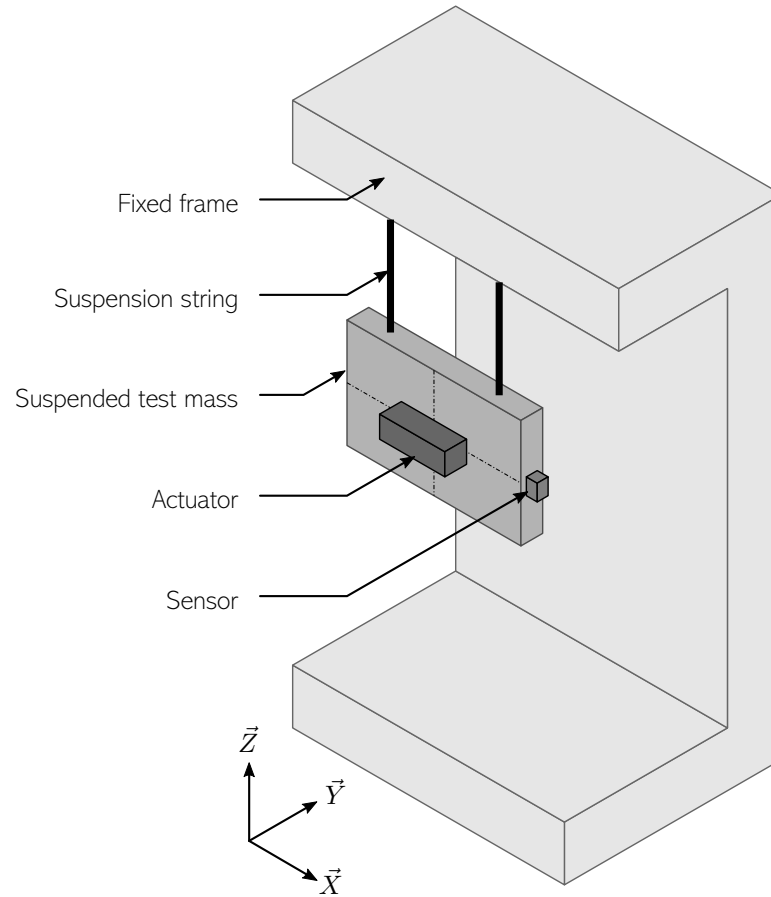


Figure 2: Actuator test bench description

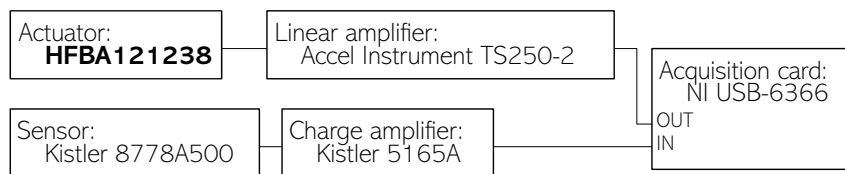


Figure 3: Actuator test bench architecture

6 Disclaimer

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DESIGNING THE BALANCE BETWEEN SOUND AND TOUCH: METHODS FOR MULTIMODAL COMPOSITION

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ABSTRACT

In this paper, we discuss key research questions generated from a collaborative workshop, during which our aim was to explore the potential of a wearable device to produce novel audio-haptic sensory experiences. The main intention of this research is to enable users with any type of hearing profile to appreciate a body-centered listening experience. The multimodal harness, developed by the co-authors, integrates nine voice coil actuators into a wearable structure, stimulating both the auditory and tactile senses via extra-tympanic sound conduction and vibrotactile stimulation of the skin on the upper body (spine, clavicles, ribs). We need to create our own interfaces in order to judge its capacity to elicit three modes of vibratory sound perception: auditory, tactile and bi-modal. To this end, we used the Max environment to make several preliminary authoring tools, whose compositional features allow us to explore three main themes of sensory composition: multimodal music listening experiences, spatialization of audio-haptic signals on the body, and sensory equalization. Feedback from trial sessions, along with current constraints due to the wearable and interface design, give us direction for our future work: iterate to improve the sensory experience of the multimodal harness, and apply these tools experimentally in order to contribute to multi-sensory processing research.

1. INTRODUCTION

The experiences of grazing one's hand across a soft surface and listening to a concerto may not seem to have much in common. However, in both cases, the body is detecting and interpreting vibratory information, whether that vibration is a result of the friction produced by the movement of skin on a surface, by the movement of performers' bows on the strings of violins, or by touching the surface of a speaker playing music. In our research, we seek to illuminate the physical aspect of sound perception, by bringing the vibrations directly in contact with the body. In parallel to the development of our multimodal wearable device, we conducted a psychophysical study on extra-tympanic hearing thresholds of the human torso, with the aim to begin a definition of audio-haptic signal

design guidelines for the wearable [1]. In this study, instead of taking a psychophysical approach, we decided to start by applying the basic parameters obtained from the first study's results within a more creative developmental framework: an intensive workshop.

Our intention in organizing this workshop was not to produce data, but to gain more clarity on the research questions we can ask. In the next sections, we first present the project context of exploring a set of audio-haptic forms of expression, followed by basic technical details of the multimodal harness. Then, we describe functionalities of authoring tools we developed, trial feedback, and the research questions generated by the sensory experience they permit (or not). Finally, we discuss our perspectives on future development, for both experimental and compositional purposes.

2. CONTEXT AND MOTIVATIONS

The perceptual ranges and discriminatory limits of hearing and touch are compatible and overlapping. Understanding the body's ability to interpret vibrotactile information can be broken down into several key characteristics of the presented stimulus: its frequency, intensity, duration, waveform and position on the skin's surface. The elements of vibrotactile signal design have much in common with those of auditory signal design (pitch, amplitude, duration, timbre, distance), but the two senses do not process the sensory information in the same way [2]. Opposed to hearing, which is centralized to the head, we perceive vibrations all over our body [3]. The perception of vibrations in the frequency range between approximately 10-1000 Hz overlaps the detection capacities of the two senses.

Though there are distinct differences in processing capacities between the two sensory organs, researchers have found that auditory stimulation can affect tactile perception [4, 5], and vice versa [6, 7]. Beyond influencing the perception of presented auditory stimuli, tactile stimuli alone have been found to activate the auditory cortex, both in normal-hearing and congenitally deaf adults. Researchers have found this effect to be greater for deaf versus hearing participants [8]. The mutual facilitation of one sense on the perception of the other can be attributed to



processes of multimodal integration and cross-modal enhancement [9].

The perception of hearing and touch can therefore be influenced separately and simultaneously, by using the same source of stimulation: vibration. In this paper, we discuss the excitation of the two modalities by means of extra-tympanic conduction of sound and vibrotactile stimulation of the skin. The existing literature on extra-tympanic conduction provides an essential foundation towards understanding how we are able to hear sounds that do not stimulate the outer ear. However, notable past investigations of these mechanisms are primarily based on the anatomy of the skull [10]. Commonly described as bone conduction, this paper refers to contact-based sound transmission as “extra-tympanic”, because there is speculation that soft tissue is involved in transmission mechanisms, and researchers have found that sound can be conducted from other parts of the body [11].

Many researchers have therefore investigated the use of vibration technology to augment auditory experiences by creating interfaces for the body. A large portion of these interfaces were specifically created for the improvement of musical experiences, and within this category, many devices have been developed specifically for the back and upper body. The model human cochlea [12] is a tactile device that separates audio signals into frequency bands from 20-1000 Hz, displayed to the back via 16 voice-coil actuators, arranged on the back of an armchair. The *Hapbeat* and *Vibeat* both integrate motors that vibrate in time with music, worn as a necklace or bracelet. The *Sound-shirt* integrates 30 micro-actuators (type unspecified) in a thin, flexible garment created for hearing-impaired individuals to have a tactile experience of philharmonic music. Users feel lower frequencies in the lower abdomen, while higher frequencies are displayed across the upper body. This frequency-based organization of tactile stimulations draws comparison to the model human cochlea while it differs from the *Subpac*, a backpack-style vest that enhances bass frequencies via two large voice coil actuators located on the back.

Our research differentiates itself from the prior art through our approach to mixed-modality effect design. The resulting experience of sound, perceived either by means of extra-tympanic hearing, tactile stimulation of the skin or a mixture of both modalities, is accessible to all hearing profiles. Hearing loss comes in many shapes and sizes, differing based on the frequencies affected, severity, symmetry, and type of lesion (conductive, sensorineural or mixed) [13]. Someone with severe sensorineural hearing loss could appreciate tactile sensations, while an individual with conductive hearing loss could hear the wide range of acoustic frequencies displayed via extra-tympanic conduction. Beyond catering to diverse hearing profiles, our project addresses normal hearing profiles as well, and is inspired by the principles of universal design: conception whose aim is to include all users, regardless of ability.



Figure 1. Image of the multimodal harness. There are nine actuators integrated on the structure: two on the clavicles, two on the ribs, and five along the spine. The straps are velcro-adjustable, two of which go around the legs to secure the last module against the body. The multichannel audio-haptics card is connected to the harness, situated below the last module on the spine.

3. THE MULTIMODAL HARNESS

3.1. Conception and Functionality

Before beginning the design process¹, we defined two key constraints for the multimodal harness: adhesion of the module against the body, and user comfort. In order to achieve effective sound transmission and avoid signal attenuation, the vibrating module should be made of hard material, secured tightly against the body. Balancing tightness and comfort, two contradictory qualities, became a principal design challenge which we addressed with the flexibility of the modules and the ergonomic aspects of the harness structure (fig. 1).

The technical aspects of the module (fig. 2) allow them to adapt to the body’s form at the different points of stimulation (spine, clavicles, and ribs). The hard plastic parts in direct contact with the user are ergonomically shaped (wide and flat on the ribs, extruded on the lower spine, rounded on the clavicles) in order to maximize the ratio of comfort to auditory signal transmission. The harness structure (fig. 1) has adjustable Velcro straps attached to all corners of the modules, pulling them against the body. Nine of Actronika’s *proprietary voice coil actuators* are connected to the *Mk-1 20-channel audio-haptic card*. The Max environment interfaces with the USB Audio output on the Mk-1 board, which is detected as a sound card.

¹ A co-development organized with *Actronika*, industrial and research partner, and *Les Vertugadins*, a Parisian costume design studio.



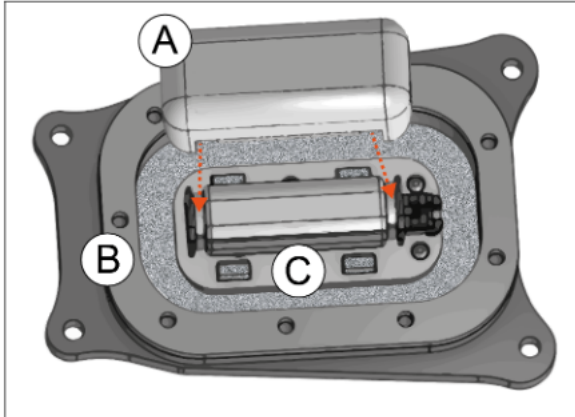


Figure 2. Schema of the module, which integrates the actuator. The module snaps onto extended fabric so it can “breathe” up and down on its frame (B), attached via the PCB clip (C). The 3D-printed clip-on piece (A) attaches onto the indented edges of the actuator, and comes into contact with the body, transmitting the vibrations to the user.

Each of the nine actuators on the multimodal harness has its own channel on the multichannel audio-haptic card. In its current wired design, users’ movements are restricted to the length of the 9V power supply and audio signal transmission cables.

4. DESIGN WORKSHOP

The two-week workshop, organized by the co-authors, took place at IRCAM in Paris, France in August 2021. During the workshop, five participants (P.01, P.02, etc.) tested our tools based on their own interest or direct involvement in the project: they were neither specifically selected nor remunerated for their participation. During every trial of the multimodal harness, users wear ear plugs and a noise-canceling headset in order to mask the external noise created by the modules’ vibrations and focus on their hearing via extra-tympanic conduction.

The main objective of the design workshop was to create first drafts of audio-haptic signal design interfaces. Creating these tools would allow us to refine our assumptions about the sensory experiences afforded by the multimodal harness, informed by our previous psychophysical study, haptic illusions of signal movement [14], and existing research on vibrotactile musical experiences [2, 12].

We hypothesize that the vibratory activation of tactile, auditory and bi-modal perception enables myriad possibilities for signal design: sensations that can travel in all directions to create illusions of movement, sound perception by vibratory transmission through musculoskeletal structures, and novel effects based on the multimodal integration of both sensations. While it is possible to approximately localize tactile stimuli on the body’s surface [15], auditory perception by means of extra-tympanic conduc-

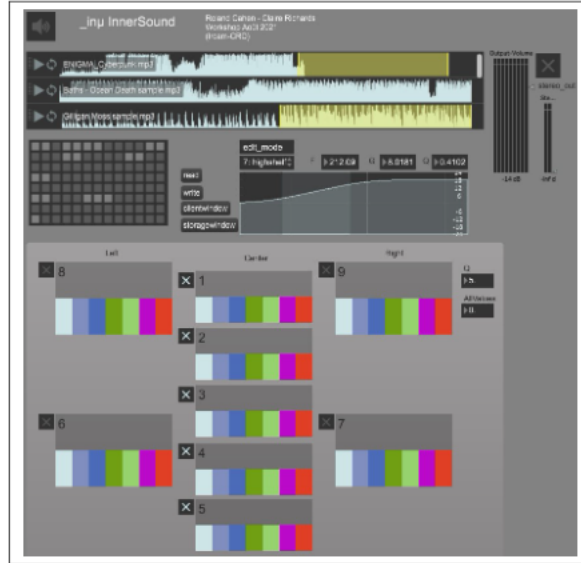


Figure 3. Inner.Music as seen in Max environment. Any sound file can be uploaded into the playlist object at the top of the interface. By default we propose a short list of rhythmic music with powerful bass content: electronic, disco-funk and pop. Left and right channels are routed to the left and right lateral actuators on the clavicles and ribs and mixed together on the vertical positions of the spine. A graphic equalizer and a mute button is available for each actuator, with different colored bars for 7 frequency bands spanning 50-4000 Hz. The user can save their equalizer settings in the grid below the playlist object, recorded and saved for future use. To the right of the preset grid, a high shelf filter object, applied to all channels, attenuates the bass frequencies with respect to the high frequencies due to the resonant frequency of the actuator (70 Hz).

tion on the torso is essentially mono, since all sounds are entering the inner ear from the same pathway: the cervical spine. In other words, spatial audio information is lost, but we hypothesize that the localization of tactile stimuli could remain strong enough to transmit impressions of spatialized auditory source positions.

5. AUTHORING TOOLS FOR THE MULTIMODAL HARNESS

Each of the following authoring tools offers a different possibility for designing audio-haptic effects. In this section, we describe each of the authoring tools in three parts: the interface design, feedback from trial sessions, and finally key questions and limitations related to interface functionalities and perceptive experiences.

5.1. Inner.Music: Multimodal Music Player

Inner.Music is a music player, designed to test the perception of filtered source files transmitted to the multimodal

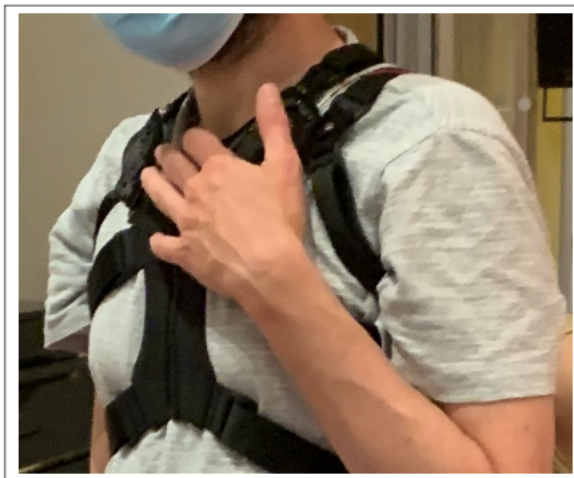


Figure 4. Photo of P.01, taken during the workshop. Since he wasn't satisfied with the quality of sound perception, he placed his fingers directly on the modules to enhance his tactile perception.

harness. This tool features a body point-based equalizer tool, which allows the designer to calibrate the signals to each position of stimulation.

5.1.1. Interface Design and Composition Features

Inner.Music allows the designer to self set, adjust and balance the volumes of each actuator's filter bands, while listening to music. The interface is also a preset manager: individual sensory profiles, created by saving the nine filter band settings in presets, can vary each person's sensory preferences (see fig. 3).

Our initial intention for Inner.Music was to create a tool that adjusts each actuator's spectrum in order to obtain a homogeneous audio-haptic sensation across all stimulated positions. However, we understood during the trial sessions that the ranges and nature of the two modalities' perceptions vary across positions, and according to different types of effect design or scenarios of use. We therefore chose to exploit these variations, creating an interface that allows the user to tweak their own sensory experience instead of imposing a generic predetermined sensory calibration.

5.1.2. Trial Feedback

While toying with the Inner.Music interface, participants employed various strategies: balancing the signal to achieve a perception of homogeneity across the positions, attributing levels and spectrum bands to each position in order to focus their perception on either the tactile or auditory modality, or muting positions that they did not appreciate. For example, some favored a stronger tactile sensation of the bass in the lower back, and routed the trebles to the upper back and clavicles to hear via extra-tympanic conduction. A common remark was that the music is audible,

but appears to be coming from a distant place within their body, and in order to hear more details, they have to focus their attention. P.03 said, "It's possible to hear the sound, but to feel practically nothing." P.05 was especially sensitive to extra-tympanic auditory perception, saying: "I can hear the sound as if I were listening with headphones - maybe even better". On the other hand, P.01 was disappointed by the quality of the auditory experience and resorted to actively touching the modules to enhance his tactile perception (fig. 4). These differences in sound perception could be attributed to morphological differences affecting the transmission of the mechanical waves within the body [11]. A user's expectations may also impact how they judge their sensory experience: they might compare the quality of their auditory experience to other systems that were specifically designed for the ears, not the body.

5.1.3. Key Questions and Limitations

The strong morphological differences between each individual can be compared in a similar way to how differences in the structure of the outer ear can affect one's hearing. The Head Related Transfer Function (HRTF) is a physical transfer function that describes how a given sound coming from a specific point will reach the ear, in terms of spectral characteristics [16]. In comparison, we wonder if we could develop a Body Related Transfer Function (BRTF), a functionality capable of adjusting the multimodal harness's response to each individual in order for them to perceive the same signal, based on their morphological differences (height, weight, musculoskeletal characteristics).

5.2. Mp2p: Body Spatialization Interface

We created the Mp2p (Mono point-to-point) interface as a creative tool for spatialization of multimodal signals on the harness, by manipulating the signals' positions and trajectories.

5.2.1. Interface Design and Composition Features

Within the design space, simple mono signals can be played on any single actuator or grouped set of actuators and panned² between them according to a set 1D path. Spatialization of the multimodal signals in the Mp2p system works based on configuration presets which organize the points of stimulation along different paths. The signal can be routed to each independent point, one channel after another, or to several points at once, by grouping channel outputs together. In fig. 5, we see three possible configuration presets: these allow the designer to create different illusions of movement (sporadic in the first preset, side-to-side in the middle preset, top-to-bottom in the right preset). The actuators' positions on the lateral and vertical axes of the body allow for directional and alternating effects. We defined a set of configurations, providing a

² Linear panning with Max [mc.mixdown @pancontrolmode 2] object gave the best results.



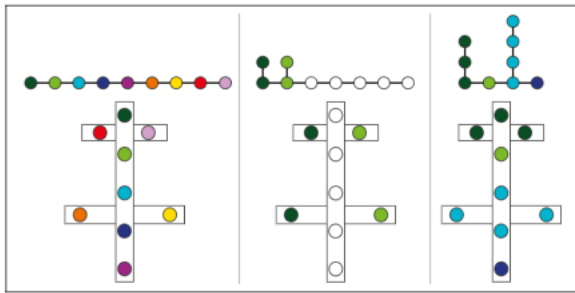


Figure 5. Diagrams of three possible Mp2p spatialization path configurations. On the top of the figure, arrays of colored dots represent the signal path: each different color is a different channel. Below each signal path is a graphic representation of the nine positions on the harness structure: the upper horizontal line is the clavicles, the lower is the ribs, and the vertical line is the spine. In the left-most configuration, each position has its own independent channel. The middle configuration uses only two channels (light and dark green), with two positions paired to each channel - the five spine points are inactive. The right-most configuration groups the positions among four channels: the clavicles and top spine point (dark green), the second spine point (light green), the middle spine and ribs (cyan) and the lowest spine point (navy).

diverse selection of routing structures for the spatialized effects. The designer can manipulate the signal's position, duration, waveform (sine, saw tooth or noise), frequency (50 Hz to 4 kHz), and linear amplitude (0. to 1. float multiplier), and play their composition looped or one-shot (see fig. 6). By manipulating these variables, the sensory effects can be perceived as having continuous or discrete inter-position transitions: the signal can move gradually, or switch abruptly along its path.

5.2.2. Trial Feedback

The Mp2p interface is slightly more complex than the other two tools, so after learning about the basic parameters, participants generally chose to tweak our predefined patterns rather than create their own from scratch. P.03 was particularly impressed by the sensation created by the signal moving up and down the spine. If the signal moved quickly enough along the points, he felt a continuous sensation, like a "hand running up and down [his] back." The slower the movement of the signal along the points, the easier it was to localize from which position it came. The illusion we tried to create of a front-to-back shifting sensation between the front actuators (clavicles and ribs) and back (spine) was less convincing, perhaps due to the slightly central position of the actuators on the ribs, and because the sensation of something crossing one's body is a rather alien concept. The duration of the experience as a whole also impacted the sensory experience: after trying the patterns, P.02 said:

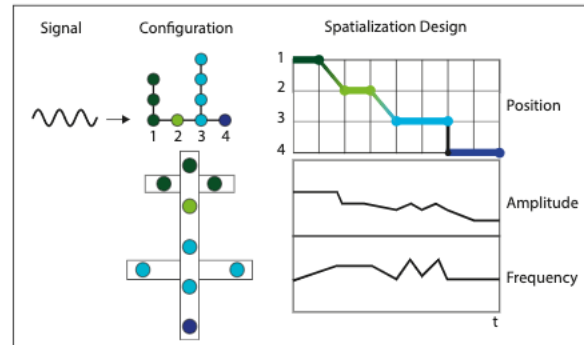


Figure 6. Graphic representation of the Mp2p interface functionality. A sine-wave signal follows a 1D path according to the chosen configuration preset (see fig. 5). To the right of the figure is the spatialization design, with three curves for position, frequency and amplitude. By modifying the curve, the designer can fine-tune the signal's duration at each group of positions, and its variations in amplitude and frequency across the composition.

I need more time to become familiar with the sensations I'm feeling on and in my body, since they are so new. Just a few minutes is not enough for my brain to really understand what is happening. I think with more time I'd be able to appreciate the sensations a bit more.

Participants made more comments on their "outer" body (tactile perception) than their "inner" body (extra-tympanic sound perception) during the spatialization experience. For most participants, the signal was only audible when displayed to certain positions (upper back and clavicles, i.e. those closest to the inner ear). The bi-modal aspect of the spatialization experience may therefore depend not only on a signal's position, intensity and spectral characteristics, but also on the user's conscious attention on either modality.

5.2.3. Key Questions and Limitations

When we started to design Mp2p, we tried to use an existing 3D spatializer tool: a vector-based amplitude panning (VBAP) algorithm [17]. However, our configuration did not permit this because the listening point (the head) was off-center, i.e. not based on diffusion points (speakers) placed around the origin (listener). If we use a classic calculation of spatial decay ($\text{gain} = 1/\text{distance}^2$) according to airborne sound transmission, the signal disappears as soon as we move the point of diffusion away from the actuators' exact positions. Realistically, we would need to create a more specific spatialization model which takes into account the body's responses to extra-tympanic conduction and tactile stimulation of the skin, as described in section 4.1.3. The listening point (i.e. listener's position) would be the head, while the haptic sensations would be distributed: they would not refer to any central reference or origin point, since tactile perception is decentralized and perceived all over the surface of the skin (i.e. each



Figure 7. The Drummer interface seen in the Max environment. The sequencer tracks each correspond to one actuator position on the harness. Above the sequencer, there is a preset grid for saving specific drumming patterns.

actuator’s position would have its own sensory reference).

One key limitation of Mp2p is the static nature of the configuration preset system. The signal path configurations are saved within presets and are static within a single composition. In other words, the designer cannot use multiple configuration presets in one spatialization time frame, limiting each composition to a single path that the signal can follow. One possible solution is to create a state-based programming interface which would include a configuration for each state, and a sequencer that allows the designer to edit each successive state and concatenate them with discrete or progressive transitions between states. In its current state, Mp2p does not integrate the equalizer profile function of Inner.Music, so in order to calibrate the signal intensity for the different sensitivities of each point of stimulation, designers must manually tweak and adjust the amplitude levels along the duration of the displayed signal. It is time-consuming to find the right nuances of intensity and frequency values for a given point in order to obtain the intended perceptive results. A final limitation of this tool is that the signal is mono: we cannot create "harmonies" of different sounds and movements. In section 6, we discuss some steps to address this constraint.

5.3. Drummer: Body-based Drum Machine

While we discussed musical metaphors during the workshop, we decided to create a basic nine-track step sequencer and drum machine.

5.3.1. Interface Design and Composition Features

Each track on the interface corresponds to one actuator and plays one selected sound file, imported from the user’s library. The designer creates their drumming pattern by activating buttons on the sequencer, creating repetitive patterns of stimulation in which each actuator/position per-

forms a sequence of an instrument (see fig. 7). The patterns can be saved as presets.

5.3.2. Trial Feedback

Participants described using the Drummer tool as a fun experience: the interface is simple and user-friendly, patterns can be quickly designed, and the ability to assign different instruments to the different points of stimulation is unique to this tool. Participants tended to move around while testing it, in sync with the rhythm. We heard several remarks about enhanced awareness of one’s own body, and the presence of the wearable device. P.02 said, “I feel like the different instruments are playing directly on my body, or like I am the instrument!” She added that, since she heard the different sounds at the same time as she felt the stimuli on the different positions, the sound seemed to be coming directly from those points. This comment suggests that, even though the spatial audio information is lost in extra-tympanic conduction, the localized perception of tactile stimuli can contribute to impressions of auditory source positions. This comment also branched off into a discussion about sensory effects for physical rehabilitation, perhaps to help target the user’s attention on a specific part of their body.

5.3.3. Key Questions and Limitations

In the Drummer interface, the opportunities to create musical patterns remain basic: the designer can select the output channels, choose sound files, alter the tempo and number of columns, but cannot change relative signal intensity according to point of stimulation. The interface functionalities could be enriched with multichannel or MIDI sequences, an equalized distribution of the signals so that their intensities can be tailored to each point of stimulation, or a more dynamic variation of each track’s intensity.

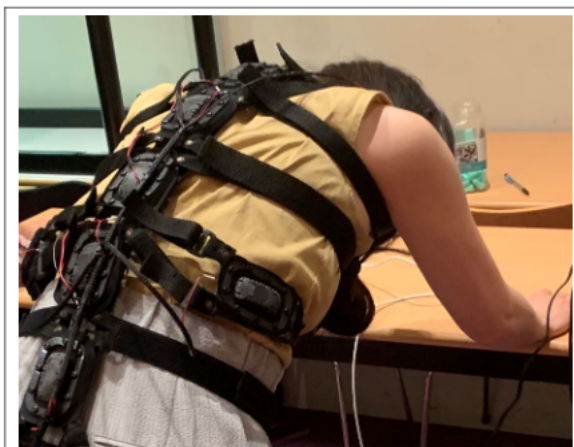


Figure 8. Photo taken during the workshop. P.02 bends forward to change her perception of the transmitted vibrations.

One could also imagine guiding the user's movements by distributing different sensations to different parts of the body. However, body movements and changes in posture interfere with audio-haptic perception. The pressure of the modules against the body changes based on the way the user stretches their joints and limbs (see fig. 8). For example, when the user bends downwards, or stretches their arms in front of them, they pull the modules closer against their spine. The added pressure on the points of stimulation, along with the difference in the curvature of the spine, facilitates good contact of the modules and thus good transmission of the vibratory signals. However, if the user raises their arms above their head, the upper back arches inwards, creating more distance between the modules and the skin and reducing the vibratory transmission. This aspect of use of the multimodal harness could be seen as a limitation but also as an advantage: though the body's movements cause variations in audio-haptic perception, those variations are part of the physical interaction between the user and the wearable, and could be a source of perceptual cues for movement-related use cases. Modifying accents, rhythm or instrument positions according to the user's movements would be interesting to explore, but this implies the integration of motion and pressure sensors which is currently out of the project's scope.

6. DISCUSSION

During the two weeks of the workshop, we were able to address each theme of audio-haptic composition (multimodal music, sensory equalization, and signal spatialization). However, we experienced developmental setbacks due to time constraints and a lack of knowledge about user perception. Evidence of these current limitations can be found in several aspects of the interface functionalities: a sensory equalizer function is present in only one of the authoring tools (Inner.Music), the spatialized audio-haptic

signals are mono and limited to basic wave types, and we are restrained to one-dimensional position configurations. Although they contain some similar elements, the authoring tools are distinct from one another, and the resulting sensory experiences are limited to each interface's distinct functionalities.

These constraints are temporary: we aim to streamline and optimize our authoring tools. For example, in future iterations, features could be consolidated into one interface: the sensory equalizer in Inner.Music, the curves in Mp2p for modulation of position, frequency and amplitude, and the position-specific sound selector in Drummer. For example, in a unified interface, the designer could use the sensory equalizer to first determine a baseline audio-haptic calibration that suits their perceptual preferences. They could then use Drummer's function to select specific sound files to display at each position, and then use Mp2p's curves for spatialization pattern design to map the signal display at each position, along with more fine-tuned variations in amplitude and frequency across the duration of the composition. Inspired by existing tools for audio spatialization [18], we have already begun to optimize the mono-source design constraint of Mp2p in a separate interface (called "MC-Curv"). Instead of one single spatialized source, the designer could edit and spatialize up to four sources on the body at the same time, creating harmonies of movement across the stimulation points instead of single-path sensations.

Regarding the design of the multimodal harness, we hope to improve many aspects in the next iteration: sound transmission quality, comfort, and ease of adjustability. The second iteration of the harness involves changes for both the wearable structure and the module. The actuators will be integrated in an orthogonal position relative to the surface of the body, instead of parallel. Though they will protrude from the surface of the device, this will allow the voice-coil actuator's lengthwise-directed vibrations to penetrate the surface of the body rather than rubbing horizontally across the skin. We hypothesize the change in orientation will increase sound perception in the mid/high frequency range, bringing more clarity to certain instrumentals and vocal sounds, without impacting the quality of tactile stimulation.

7. CONCLUSIONS

Since there is no generic go-to tool for audio-haptic composition, we faced the same developmental challenges as past composers and researchers: we wanted to create and study multisensory effects, but we didn't have the tools to do so. In [2], the authors complain of the "awkwardness" of designing the vibrotactile sensory effects using Protools, a standard Digital Audio Workstation. Nine years later, in [14], the authors used Premiere Pro to create "vibetracks" for a film, by placing clips of different sine waves one-by-one at precise points along the video track. Today, researchers acknowledge that tactile composition is still "largely unexplored", that composers need to "take into



account haptic perceptual effects" and that they develop their own design tools for this purpose [19]. Resorting to these painstaking methods drastically slows down the design process, and makes it difficult for progress to happen in the domain.

Another obstacle to overcome is the general lack of guidelines about variations in both auditory and tactile sensitivity across different sites on the body, and across individuals. Established ranges of sensitivity according to each position of stimulation could help provide compositional suggestions, or presets according to each modality. To this end, in an upcoming study we will follow up on our past psychophysical research [1] and evaluate participants' responses regarding both tactile and auditory perception while using the multimodal harness.

The authors call for smoother workflow design for audio-haptic composition, accessible to the research community. We hope that the products of our workshop can foster discussions about what features and guidelines might contribute to an ideal audio-haptic composition interface.

Acknowledgments

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Bimodal Judgment of Audio-Tactile Stimuli

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Abstract—Multimodal perception research often proceeds sense-by-sense, probing interactions between modalities by using different, sense-specific stimuli. The current study approaches multimodal interactions in another manner, by simultaneously stimulating two modalities (hearing and touch) with one source: vibration. Within a specific range of frequencies (20-1000 Hz) and in direct contact with particular loci on the body (the spine, clavicles, and ribs), it is possible to both hear and feel a vibratory stimulus. With this in mind, the authors developed a wearable audio-tactile device: the multimodal harness. In this study, we used this device to better predict by how much the user may hear or feel each vibration depending on its signal parameters (intensity, frequency, and locus of stimulation). We evaluated participants' perception along a continuum spanning hearing and touch. Participants' ability to consistently distinguish between simultaneously perceived modalities despite an inherent temporal and frequency overlap demonstrates a unique case of multimodal interaction, and analysis of their bimodal judgments clarifies how the vibratory signal parameters affect the perceptual balance between senses.

Index Terms—Audio-tactile sensation, bone conduction, multimodal interaction, wearable technology

I. INTRODUCTION

THE auditory and somatosensory systems are unique in their mutual ability to detect and interpret vibratory information. When a vibrating motor is firmly placed on the surface of a bony structure on the skull or torso, the receiver can perceive the mechanical waves through both the senses of hearing and touch: the inner ear captures sound waves conducted internally through the musculoskeletal structure of the body [1], [2], and mechanoreceptors detect the vibrations on the surface of the skin within the frequency range of 20 to 1000 Hz [3], [4]. In this paper, we investigate the perceptual overlap between the modalities of hearing and touch when they are simultaneously excited in the manner described above. Wearing a specially-designed audio-tactile device, participants judged their perception of vibratory stimuli along a continuum between the two modalities, here described as the audio-tactile range. The patterns that emerge across their bimodal judgments contribute to our analysis of this perceptual overlap, with implications for audio-tactile effect design in similar wearable devices.

II. BACKGROUND

In multimodal processing research, a “unified percept” refers to a combination of signals from different sensory modalities that occur in close temporal proximity [5], integrated effortlessly by the brain into a coherent multimodal percept [6]. One commonly-cited example of a unified percept is the McGurk effect, a strong multisensory illusion where dubbing a voice saying “ba” onto a face articulating “ga”

results in a third percept: the listener hears “da” [7]. The participant uses both the visual and auditory senses to form a new audio-visual percept, proving integration of the senses in that it differs from each individual sensory component. In reference to this audio-visual effect, Tiippana (2014) describes multisensory integration as a perceptual experience where the contributing sensory components cannot be perceived separately. Driver and Noesselt [8] discuss interactions across modalities in terms of multisensory “interplay” instead of multisensory integration, creating a looser definition in order to include a broader range of multisensory effects. They explain that when two or more different senses contribute to the perception of a single external property, these modalities may affect one another, but might not always result in a single unified percept. Many examples of multisensory interplay refer to cases where two different types of stimuli are studied: vibration and light [9], facial expression and vocal tonality [10], or texture and sound [11]. Here, we are interested in a specific type of multisensory interplay, where the perceiver's senses of hearing and touch are stimulated simultaneously by one single source: vibration. Multimodal interactions between auditory and tactile perception have been studied in terms of crossmodal enhancement [11], co-activation [12], [13] and modulation effects [14]. The potential for interaction between these two modalities is unique due to their common ability to process mechanical waves: among the three main perceptual groups (vision, audition, somatosensation) these are the only two that can be associated in this way.

In the current study, we analyzed both the auditory and tactile perception of the vibratory stimuli, rather than each modality in isolation. In our previous research, we had only evaluated participants' auditory perception of vibratory signals displayed to the body via extra-tympanic conduction (ETC) [2]. However, participants often remarked that they also felt the signal, and at times expressed confusion about their perception, wondering if they were truly evaluating their audition, or their sense of touch, too. In this study, we therefore sought to bring more clarity to the audio-tactile perception resulting from simultaneous, single-source stimulation. In doing so, we explore whether it can be qualified as multimodal integration, or if they create an inseparable and thus indistinguishable percept.

III. METHODS

Inspired by past research about perceptual confidence, we developed a “bimodal judgment” experimental paradigm to investigate participants' bimodal perception within and between the auditory and tactile modalities. In this method, participants must place a perceptual judgment of a vibratory



stimuli somewhere on the scale between auditory and tactile, considering both senses at the same time. In our bimodal judgment paradigm (see section 3.D), the participant must make a choice: they cannot rate the stimulus as being equally perceived in both modalities. They must therefore consciously ask themselves after each vibratory stimuli whether they heard it more than they felt it, or vice versa. Their resulting “bimodal judgment” tells us two things: whether they perceived the vibratory stimulus as “more auditory” or “more tactile”, and the degree to which they judge the strength of both modalities. This is not a measure of perceptual confidence, as defined by Mamassian [15]. Evaluating their judgments does not tell us whether the participant viewed their response as correct, but rather whether the participant perceived the sensory modalities as more or less distinct. Analysis of the bimodal judgments between and within participants demonstrated whether they were able to distinguish between hearing and touch when both senses were excited by the same source, thus clarifying whether this bimodal perception should be classified as multimodal integration or interplay. Finally, the perceptual patterns that emerge across participants allowed us to interpret our findings in terms of what they may reveal about audio-tactile interactions during simultaneous, single-source stimulation.

We designed this experiment according to one principal hypothesis of frequency-dependence: between 200 and 800 Hz, the participants will rate their perception with a gradual shift from mostly-tactile to mostly-auditory, reflecting the peak of vibrotactile sensitivity at 250 Hz, and the decrease in tactile sensitivity with increasing frequency. At 1200 Hz, a frequency outside of the detectable range of vibrotactile sensitivity, participants will rate their perception as 100% auditory.

A. Participants

A total of 23 participants took part in the study, (12 male, 11 female, average age 23.7, Standard deviation 2.9). The participants declared to have no known hearing impairments. In accordance with the Declaration of Helsinki, all participants provided informed, written consent prior to the study. The INSEAD IRB provided ethical approval of this study (Protocol ID 2022-52).

B. Stimulating Device

To transmit the tactile and auditory stimuli to the participants, we used a wearable device called the multimodal harness (Fig. 1). This device was created with the specific intention to stimulate the spinal column, clavicles in ribs in order to elicit both auditory perception of sound via extra-tympanic conduction (ETC), and tactile perception of vibration via vibrotactile stimulation of the skin’s surface (see [16]). The wearable device integrates nine vibratory modules: five situated along the length of the spine, one on each rib, and one on each clavicle. We estimated that, depending on the position of stimulation, the frequency of the signal, and the intensity of the vibration, the user’s perception of those vibrations while wearing the multimodal harness will vary along both the auditory and tactile dynamic of sensitivity. Research shows that the sensitivity to vibratory stimuli varies strongly based on



Fig. 1. The multimodal harness elicits both auditory and tactile perception, via extra-tympanic (bone) conduction and vibrotactile stimulation of the skin surface. The wearable device was designed with adjustable velcro straps, which suit users with waist dimensions between 64 and 90 cm. Photo credit: Véronique Huyghe.

the loci of stimulation on the body [17], [18], and perception of sound via ETC on the torso has been shown to depend on distance of the position of stimulation from the inner ear, along with the signal’s intensity and frequency [1], [2].

The multimodal harness elicits auditory perception via vibratory excitation of the user’s musculoskeletal structure: the mechanical waves enter the body at each position of stimulation and follow the ligaments and articulations through the inside of the body, up towards the inner ear. Users wearing the device may also be able to feel the vibrations on the surface of their body in the frequency range between approximately 20 and 1000 Hz [3]. These frequencies represent the sensitivity range of mechanoreceptors located within the skin, therefore representing a range of bimodal (audio-tactile) overlap, where both the ear and the skin can participate in the perception of the same vibratory source stimulus.

During the experimental procedure, participants wore ear plugs and an industrial-grade noise-cancelling headset (3M Peltor X5A) in order to cancel the external auditory pathway and ensure that their hearing was limited to the internal ETC sound perception elicited by the multimodal harness.

C. Procedure Part I: The Calibration Task

As a first step in the experimental procedure, we calibrated the intensity of the vibratory signals according to the participants’ personal levels of perception. Though auditory and tactile sensitivity vary across positions and frequencies, during this task the participants were instructed to set their levels of vibratory intensity by considering both senses at the same time.

Participants used an individualized equalizer (EQ.I) tool to set an upper and lower limit for the intensity of each

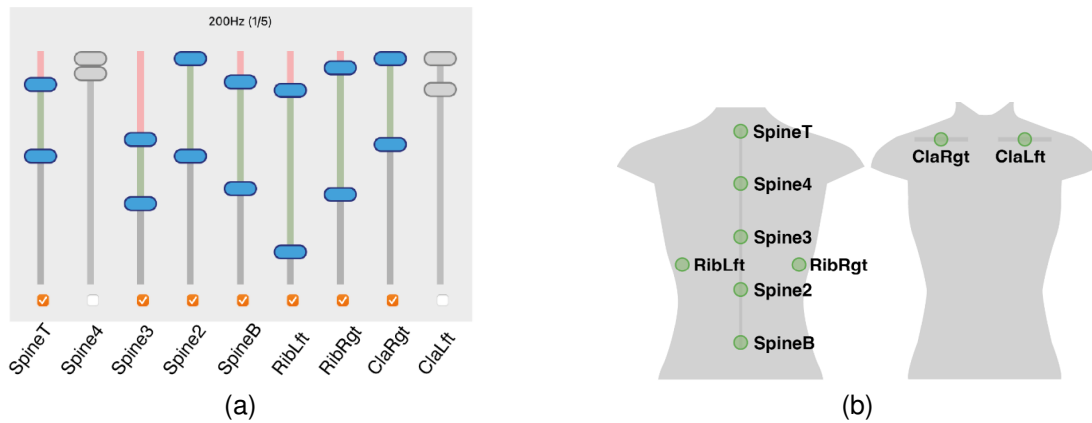


Fig. 2. The intensity calibration task. Each vertical bar seen on the GUI interface (a) represents a position on the multimodal harness (b). For each of the nine positions, the participants set the maximum comfortable and minimum perceptible levels of signal intensity. The intensity scale is set in dB. The bottom value on the scale corresponds to 0 V output, and the uppermost value corresponds to 2.6 V, the actuator’s maximum admissible output.

frequency-position combination, for the five tested frequencies (200, 400, 600, 800 and 1200 Hz) at the nine positions of stimulation (Fig. 2 b). The calibration task lasted approximately 10 minutes, and was broken down into five sections: for each of the five frequencies, participants set a “maximum comfortable” and “minimum perceptible” level of vibratory intensity for all of the nine positions of stimulation (Fig. 2 a). The maximum comfortable level refers to a signal that is very easily perceived, but not unpleasant. The minimum perceptible level refers the signal of lowest intensity that is possible to perceive. If the participants could neither hear nor feel the vibratory signal at a given position of stimulation, they unchecked a box underneath the equalizer for that position (see Fig. 2a), effectively removing that stimulus from the next task.

The maximum and minimum intensity values collected from the calibration task serve to determine the intensities of the individualized equalizer (EQ.I) stimuli presented during the bimodal judgment task, whose amplitudes are calculated based on the average of these two values. We used this average value to define the stimuli amplitude, instead of the maximum comfortable or minimum perceptible level, in order to reduce the potential for fatigue or straining.

In addition to the amplitude values gathered from the EQ.I, another set of standardized amplitude values was also defined, in order to provide a control for the potential effect of amplitude on participants’ bimodal judgments. This standardized equalizer (EQ.S) was calculated based on seven participants’ results from the pilot testing phase. Its intensity values were calculated in order to ensure the best possible chance of stimulus perception. We first took the average of all seven participants’ maximum and minimum intensities. These values were then adjusted so that none of the stimuli were less intense than any participant’s minimum intensities. If participants had unchecked the box underneath a given frequency-position combination during their individual calibration, that combination was also removed from the standard equalizer’s stimuli in the bimodal judgment task.

D. Procedure Part II: The Bimodal Judgment Task

The bimodal judgment task employs the audio-tactile (A-T) range, a Likert-style scale ranging from 100% auditory perception (A) to 100% tactile perception (T). The scale ranges from -10 to 10, where -10 is 100% A and 10 is 100% T (Fig. 3). The participants judge their perception along the range of audio-tactile sensation, according to the five tested frequencies of vibratory stimuli ranging 200-1200 Hz and the nine tested positions of stimulation (Fig. 2b).

We defined the audio-tactile (A-T) range according to these specific frequencies for a few key reasons: they represent the best effective range of the voice-coil motors integrated in the wearable device, they target both the auditory and tactile sensitivities, and this range of frequencies has been previously shown as being situated within the range of vibratory signals perceptible via ETC [2]. Pacinian corpuscles, the mechanoreceptors in the skin responsible for detecting high-frequency vibrations between 50 and 1000 Hz, have a peak frequency of vibrotactile sensitivity of 250 Hz [19]. Since different zones of the body have varying sensitivity, others have suggested a range of best vibrotactile sensitivity from approximately 50 to 500 Hz [20]. However, across the surface of the torso, it has been reported that there is no significant difference in vibrotactile sensitivity [21]. Providing the borders of the A-T range, 200 Hz is just below the peak of vibrotactile sensitivity (250 Hz), and 1200 Hz is just outside of the range of vibrotactile sensitivity, but within the audible range of perception via ETC [19], [22].

Participants use the A-T range to place the judgment of how they perceived the vibratory signal. The participants must make a choice between more audio or more tactile by positioning the cursor on either side of the midline: the point marking a sensation that is equal parts auditory and tactile perception. Participants cannot place their bimodal judgment at the midline. Prior to this task, we informed the participants that, based on their frequency and their position on the body, perception of the vibratory signals may vary between auditory and tactile - sometimes the signal will be heard, sometimes heard and felt, and sometimes only felt.

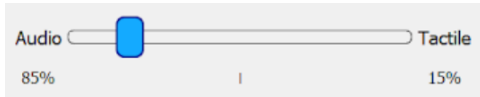


Fig. 3. The audio-tactile (A-T) range: a section of the interface from the bimodal judgment task. As participants moved the cursor between “Audio” and “Tactile”, the percentage of the perception changed in order to reflect their judgment. The judgment cannot be positioned exactly at the range midline (50/50): participants must decide which modality was stronger than the other for each vibratory stimulus (A>T vs T>A). The judgment can, however, be placed at the edge of the range (100% A or 100% T).

IV. RESULTS AND ANALYSIS

The results of the bimodal judgment task support our frequency-dependence hypothesis (see end of Methods section), following a perceptual shift from mostly tactile (T>A) to mostly auditory (A>T) with increasing frequency. Figure 4 shows the bimodal judgment results and standard deviations, averaged across all participants’ responses to the vibratory stimuli equalized according to their EQ.I (values shown in blue) and the EQ.S (pink). Across participants, all average bimodal judgment values at 200 Hz are rated above the midline (T>A). At 400 Hz, participants’ averaged judgments are closest to the midline. They then begin to shift towards the other end of the range (A>T) up through 1200 Hz, where participants showed the greatest consensus in perception, for both EQ.I and EQ.S stimuli gains.

The shift of perceptual strength from tactile to auditory also appears to be partially dependent on the position of vibratory stimulation: at the clavicles and ribs, the judgments are located closer to the midline than at the five positions along the spine. The slope of the descent from T>A to A>T varies between exponential and linear depending on these two groups of positions: for both EQ stimuli gains, the shift between perceptual strength is more abrupt at the spinal loci than at the loci on the ribs and clavicles.

The pink values of bimodal judgments represent responses to stimuli of standardized amplitudes (Fig. 4), which provided a control for the potential effect of amplitude on participants’ bimodal judgments. Based on the results, we can conclude that these patterns in judgment across positions and frequencies corroborate our first hypothesis. The variations in judgments, represented by standard deviations, reflect potential effects of other uncontrolled variables such as device fit and perceptual differences across participants.

The EQ.S stimuli gains were higher in amplitude in comparison to the average EQ.I stimuli gains, the factor of increase in amplitude varying based on position of stimulation and frequency (see Table 1). The reason for this increase in amplitude is related to the calculation method used for the EQ.S gains (see end of section 3.C), defined to ensure stimulus perception at the standardized amplitude values. Despite the dissimilarity in amplitude, the averaged bimodal judgment results with the EQ.I gains and with the EQ.S gains show similar slopes: both calibrated and non-calibrated stimuli reflect similar patterns of bimodal judgments across participants.

We cannot infer as much from the averaged bimodal judgments of the EQ.I stimuli, as the individually calibrated

TABLE I
THESE VALUES REFLECT THE FACTOR OF INCREASE IN SIGNAL AMPLIFICATION COEFFICIENT BETWEEN THE AVERAGE EQ.I GAINS AND THE EQ.S GAINS. “AVG.” REPRESENTS THE INTER-POSITION AVERAGE CHANGE, PER FREQUENCY, AND “ST.D.” THE STANDARD DEVIATION.

LocI	200 Hz	400 Hz	600 Hz	800 Hz	1200 Hz
S.P.T	4.13	2.33	2.76	1.88	2.48
SP.4	3.01	1.48	1.37	1.16	1.58
SP.3	3.6	2.39	1.68	1.70	2.24
SP.2	2.94	2.35	1.44	1.62	1.09
SP.1	2.14	2.15	2.71	2.08	0.82
L.Rib	2.03	2.47	1.99	1.31	1.1
R.Rib	1.6	2.61	1.84	1.13	0.94
L.Cla	3.39	1.47	2.03	1.81	1.46
R.Cla	3.67	1.83	1.82	1.97	1.11
Avg.	2.95	2.12	1.96	1.63	1.42
St.D.	0.86	0.42	0.49	0.35	0.58

amplitude values vary across participants. The stimuli amplitudes of the EQ.S are aligned across all participants, which solidifies the analysis of bimodal judgment patterns in support of our hypothesis. However, comparing the bimodal judgments between the stimuli adjusted according to the EQ.I and EQ.S gains shows similar patterns in responses across positions and frequencies, regardless of vibratory amplitude calibration.

V. DISCUSSION

In the current study, we analyzed the perceptual balance between the auditory and tactile modalities based on the variation of the stimulating signal’s intensity, frequency, and locus on the body. Following each vibratory signal, participants judged their perception according to the two modalities along a continuum, evaluating their perception of both senses at once rather than separately. Results show that participants’ bimodal judgments on the audio-tactile range consistently depend on frequency in a manner supporting our hypothesis; from 200 to 1200 Hz, judgments gradually shift in perceptual balance from tactile to auditory perception. Participants’ bimodal judgments at 400 Hz were particularly close to the center of the audio-tactile range, implying that this particular frequency caused more difficulty when distinguishing between modalities. Intensity, evaluated through the difference in judgments of calibrated and non-calibrated stimuli amplitudes, is also an influential factor.

The cortical processing of auditory and tactile information are intertwined. Measuring transcranial magnetic stimulation during a temporal discrimination task, Bolognini et al. [23] established that the brain’s auditory cortex processes temporal information derived from both the auditory and tactile modalities. In a series of psychophysical experiments, Yau et al. [24] analyzed the influence of auditory inputs on tactile frequency discrimination. They found that when participants judged two sequentially-presented tactile stimuli, the auditory distractor occurring during the second of the two tactile stimuli only had a detrimental effect on their responses when similar in frequency. Foxe [25] reworded the significance of their findings, explaining that regardless of the anatomical differences between the cellular tissues of the ear and skin, the frequency of the processed vibrations is an integral dimension of multisensory interactions.

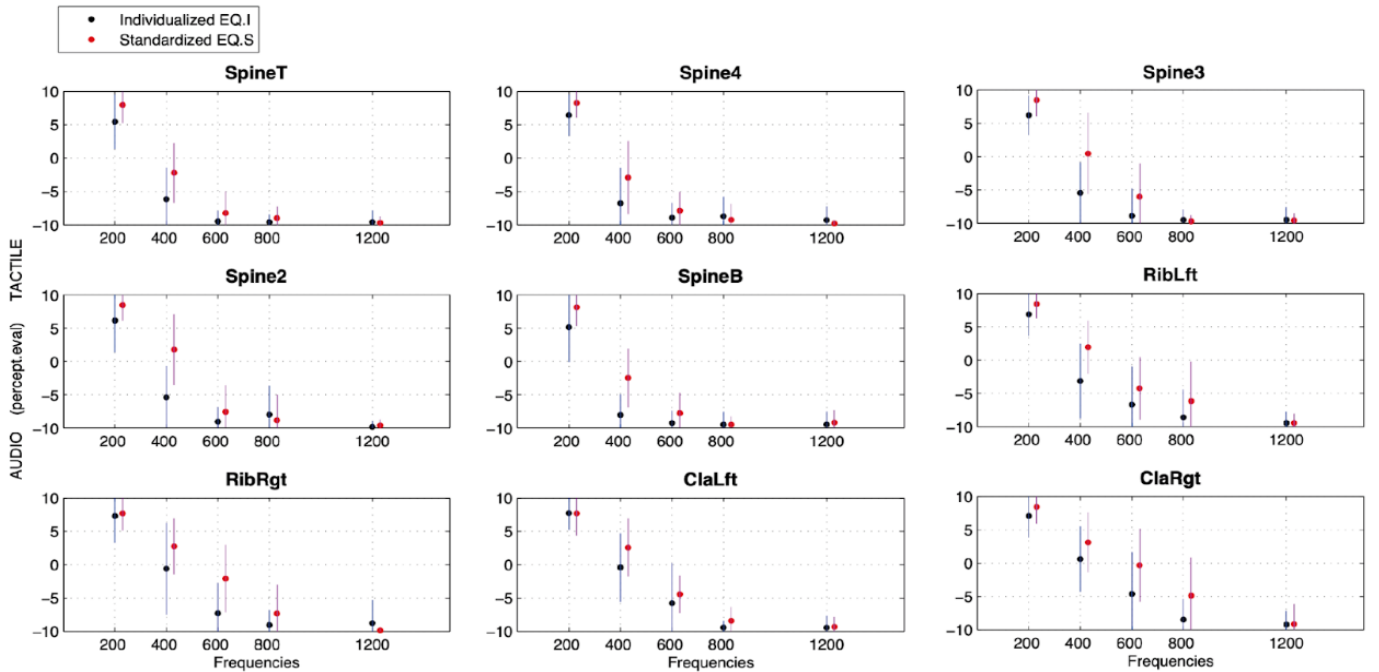


Fig. 4. In pink, averaged participant judgments on the A-T range, EQ.I gains. In blue, averaged participant scores, EQ.S gains. The nine graphs reflect the positions of stimulation on the multimodal harness: SpineT is the highest vibratory module on the spine, Spine4 through Spine2 descend downwards to SpineB, the lowest. The data from the right and left ribs and clavicles are labeled accordingly. The y-axis values are arbitrary: -10 represents 100% auditory sensation, 0 represents equal parts auditory and tactile sensation, and 10 represents 100% tactile sensation.

Driver and Noesselt [8] defined multisensory interplay as the interaction when two or more senses contribute to the perception of a single external property. Multisensory integration, defined as the convergence of two modalities into one, unified percept, is a rarer phenomenon. As cited above, previous research suggests that audio-tactile interplay is especially likely to occur when the vibratory signals are aligned in terms of temporal- and frequency-related features, as was the case in our experiment. In terms of the effect of frequency-related features, our study's results suggest that certain vibratory frequencies affect participants' ability to distinguish between the auditory and tactile modalities more than others. In the zone of perceptual overlap between auditory and tactile perception (approx. 20-1000 Hz), our results demonstrate a potential peak of multimodal interplay, potentially leading to multimodal integration, between auditory and tactile perception at 400 Hz.

VI. CONCLUSION

Despite temporal and frequency alignment of the vibratory stimuli, the current study's participants consistently demonstrated the ability to distinguish between the two modalities of hearing and touch. The nuances of auditory and tactile discrimination were qualified in terms of dependence on signal frequency, and the evidence for an effect of increased signal intensity. Participants' ability to judge their perception of the two aligned sensations in terms of "more" or "less" auditory or tactile perception provides an argument that, in the context of the current study, the two modalities did not integrate into a unified percept at all tested frequencies. However, participants' bimodal judgments at 400 Hz were particularly

close to the center of the audio-tactile range, at all tested positions on the torso. This demonstrates participants' uncertainty and inconsistency while distinguishing single-source audio-tactile perception of vibration at 400 Hz: a certain point of multimodal interplay, and a point of potential interest for future research about multimodal integration.

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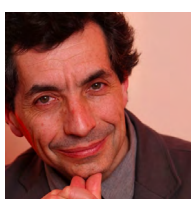


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The Reciprocity of Speculative and Product Design Research in an Industrial Framework

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Abstract. Wearable audio-tactile devices can be evaluated not only in terms of the perceptual experiences they elicit, but also how they come to exist. In this project case study, we show how the industrial environment influenced the design processes that have structured both the purpose and the form of two wearable audio-tactile devices, here described as design artifacts. We elaborate two design artifacts in terms of speculative and product design processes: the speculative design artifact (the multi-modal headset) which was conceived to challenge the user's assumptions about hearing, and the product design artifact (Ryson™) to bring the user an improved listening experience. In turn, we reveal the reciprocity of our speculative and product design processes: the creative interactions that bound the two artifacts' development created a connection between otherwise distinct scientific and commercial objectives.

Keywords: Wearable technology · Audio-tactile · Design research.

1 Introduction

Our research centers on the creation and study of wearable audio-tactile devices, built to transmit vibrations that stimulate both the senses of touch and hearing. To better understand the potential for body-based listening and the occupational possibilities it affords, we focus on three main axes: the exploration of sensory capacities [1], wearable device design processes, and audio-tactile sensory effect composition [2]. Here, we focus on the second axis: understanding how design processes have shaped the purpose and form of two wearable audio-tactile devices, defined as design artifacts. Both of the artifacts manifest the main objective behind our research: push the possibilities for including more of the body in the listening experience. However, at the start of their development, the devices had contrasting purposes: one aimed for novel experimental possibilities, while the other centered on commercial applications.

In this case study, we position these artifacts of our research in terms of speculative and product design. Our goal in reorganizing our work and retrospectively evaluating these design processes is to demonstrate the value of articulated scientific and commercial work, which has ultimately advanced our research objective and better integrated our project within its industrial environment.

2 Context and Motivations

2.1 Speculative and product design: What's the difference?

Before we explain the approaches of speculative design and product design, we note that design research differs from pure scientific research: rather than focusing on *products* of an investigation, design research centres on the *process* of investigation itself [3]. In this paper, we explain the separate outputs of our research in terms of the design processes that supported their creation.

In a nutshell, product design is about a project's targeted market, and speculative design the discourse surrounding it [4,5]. Product designers find creativity from within the "problem space", a working space confined by the constraints of the project's industrial environment: temporal, ergonomic, material, regulatory, etc. [4]. The product designer's goal is to draw a future product's path to the market, but an iterative problem-solving process of development and testing must first occur. With our industrial partner, Aotearoa, we have worked within these real-world constraints in order to find a practical application of our speculative research. The purpose of speculative design is to provoke thought and stimulate debate among designers and consumers by "exploring new aesthetic, functional and cultural possibilities for technology" [6]. Its approach allows us to consider both what we do not want and what we do want in our tech-infused future [7]. Speculative designs can appear impractical and idealistic because they live in a world with no marketplace constraints. Instead, they seek to express alternatives and challenge the status quo of the things we build.

2.2 Related Research: State-of-the-Art

Before we detail our design artifacts, we'll first give some context and introduce some of the research in the auditory and tactile domains that informed their creation. The perceptual ranges and discriminatory limits of hearing and touch are compatible and overlapping. The skin's ability to interpret vibrotactile information can be broken down into several key characteristics of the presented stimulus: its frequency, intensity, duration, waveform and position on the body. These parameters of vibrotactile signal design have much in common with those of auditory signal design (pitch, amplitude, duration, timbre, spatialisation), but the two senses do not process vibrations in the same way [8]. Opposed to auditory perception, which is centralised in the head, our tactile perception of vibrations is dispersed all over the surface of our body [9]. The tactile perception of vibrations in the frequency range between approximately 20-1000 Hz overlaps auditory sensitivity between 20-20kHz. Despite differences in the two sensory organs' processing capacities, researchers have found that auditory stimulation can affect tactile perception [10,11], and vice versa [12].

Researchers and product designers have therefore naturally investigated the use of vibrotactile technology for augmented sensory experiences of sound by creating body-based interfaces. The "neural human cochlea" system, integrated in an armchair-form tactile device called the Emoti-Chair, separates audio signals

into frequency bands from 20-2000 Hz, displayed to the user via 16 voice-coil actuators, arranged in two vertical rows [13]. The Hapheat and Vibrotact were both designed to vibrate in time with music, worn as a necklace or bracelet [14,15]. The Soundshirt, originally designed for deaf individuals to experience placements music, integrates 30 micro-actuators (type unspecified) in a thin, flexible garment [16]. The Soundshirt's frequency-based organization of tactile stimulations differentiates it from the Subpac, a vest that filters bass frequencies (8-126 Hz) from the audio of a connected device via two large voice coil actuators located on the back [17]. Finally, wearable devices such as the Soundbouncer Pulse and the Body:Suit:Score were developed as tactile musical aids, helping to keep time or follow the score [18,19]. Based alone on their varying dimensions of scale of development, context of use, and underlying theory, the above-listed devices also provide a diverse range of examples in speculative and product design. However, for the context of this paper, we restrict our analysis to a case study of our own research.

Inspired by the works listed above, we distinguish our audio-tactile device design based on how we employ vibration. We aim to elicit sound perception via extra-tympanic conduction (ETC) at specific sites on the human torso, paired with vibrotactile stimulation of the skin. Commonly described as bone conduction, we refer to contact-based sound transmission as "extra-tympanic", because there is speculation that soft tissue is involved in transmission mechanisms [20]. Notable past investigations of ETC are primarily based on the anatomy of the skull [21], but research has also shown the potential for sound perception via more distant sites of stimulation on the body such as the neck and back [20]. By testing the limits of ETC and the resulting tactile sensations elicited by vibratory stimulation, we explore the main objective of our research: build audio-tactile devices that challenge the common conception of sound perception and show that the body can be as much a part of listening as the ear.

3 Positioning our Work in Design Processes

In this section, we will show how we manifested our research objective in the form of design artifacts. The artifact, a concrete output of a design process, serves as an interface "between an 'inner' environment, the substance and organization of the artifact itself, and an 'outer' environment, the surroundings in which it operates" [8]. Building on this idea, in this section we will describe each design artifact first in terms of its surroundings (purpose) and substance (form). By detailing the purpose and form of each artifact, we position them within the processes of speculative and product design. Following this section, we will further illustrate the positive interactions between the two processes to demonstrate their reciprocity.

3.1 Speculative Design Artifact

Speculative Artifact Purpose The multimodal harness (see Fig. 1) was born from the motivation to challenge the status quo of listening experiences, one that



Fig. 1. The multimodal harness. Nine voice-coil motors (Atronika HapCoil) are integrated in the wearable structure inside hard plastic modules on the clavicles, spine and ribs. The velcro straps tighten the modules' contact against the body, whose vibrations penetrate the body to elicit ETC sound perception, and stimulate the skin for tactile sensations. Users receive earplugs and a noise-reducing headset (3M Peltor XEA) in order to protect them from all external noises created by the actuators and ensure they hear only via ETC.

assumes we need properly functioning ears to appreciate sound. This motive naturally led us to create an object that looks strange, even absurd. The notion of hearing through our skin and bones may also seem bizarre, but the multimodal harness makes this a real experience, while keeping it at arm's length from practical everyday use due to its inherent ergonomic constraints and cyborg aesthetics. Beyond its look, the experience of the multimodal harness is also an argument for its classification as speculative design. The act of putting on the harness requires the user to question their assumptions about sound perception. In order to hear, users must first become deaf: when using the harness, they cover their ears from all external, airborne sounds in order to ensure they are only hearing via extra-tympanic conduction. Instead of perceiving the sounds via one central point (the head), the user's torso is covered with vibrating modules that stimulate their skin, muscles, ligaments and bones. The harness is therefore a vessel for speculative debate, blurring the boundaries of auditory experience.

By using initial interfaces for multimodal effect design, we can create sensory effects that support our hypothesised mode of listening: sounds reach the ears from within the body, paired with accompanying specialised tactile sensations that expand, slide and dart across the outer skin's surface [2]. During demo sessions of these interfaces, users have commented that after an initial period of adjustment, they feel a rapid connection in their bodies, concentrating only on the sounds and sensations. In this direction of thought, the multimodal harness fits in an alternate timeline of our physical connection to sound... could we design

interfaces to envelop our bodies in sound in the way that headphones envelop our heads?

Speculative Artifact Form The multisided harness is *sci-fi-like* in its appearance, its strappy protruding structure inviting the user to expect an unusual sensory experience. We defined its form based on two key, albeit contradictory constraints: tight contact against the body, and user comfort. In order to optimize sound transmission and avoid signal attenuation, the point of contact with the body should be made of hard material, secured tightly against the user's body. Balancing good signal transmission and basic comfort therefore became a principal design challenge. We addressed this via the flexibility of the modules (see Fig. 2) and the ergonomic aspects of the harness structure, co-developed with costume design studio *Les Vertigedius*.

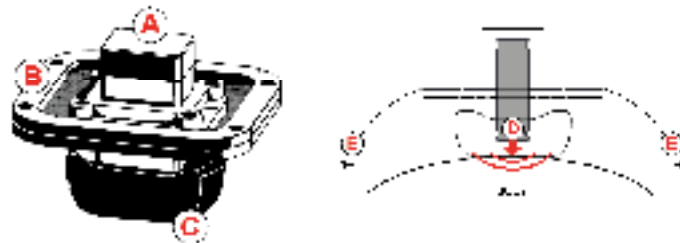


Fig. 2. The vibratory module. The module snaps onto extended fabric, tightened between the edges of the frame (B). A rounded, hard bottom (C) comes into contact with the body, transmitting the vibrations of the actuator to the user. The actuator's axis of vibration (D) is orthogonal to the body's surface. It "tweethes" within its structural frame, and is pulled against the body by straps attached at all four corners (E).

The technical aspects of the module allow the wearable device to adapt to nine points of stimulation on the clavicles, ribs, and spine. Velcro straps are attached to all corners of the modules, pulling them against the body. The voice coil actuators are connected to a multichannel audio-haptic card (AstroMedia HSD Mk-1). The card is wire-powered, and a USB audio port allows for wired connection to a computer for signal transmission. Our custom interfaces for audio-tactile effect composition are in a preliminary stage, and we need to conduct more perceptual research before we can fine-tune and calibrate the efforts to the body's sensitivity [2]. The harness cannot be worn for long periods due to its skin-tight fit, so today's use is limited to experimentation and demonstration.

3.2 Product Design Artifact

Product Artifact Purpose With *Ryann™*, we bridge the gap between our ongoing scientific investigation and the tangible value of our work to our research

partner, Actraalika, a growing deep-tech business specialised in vibrotactile integration and product development. By adapting to this industrial context, we find ourselves in what is probably a common situation, as "the majority of design research is paid for by the development industry" [22]. To adapt, we identified a use case that fit our initial results and the company's haptic expertise: tactile-augmented listening experiences. *Ryann*TM was imagined as a tactile listening device that will build on things consumers have already experienced about audio technology and haptic accessories, but in a slightly different way. To make new technology more easily acceptable, that degree of difference should sway users' perception of the product towards an improved existing experience rather than one that is totally new and unusual [23]. If successful, *Ryann*TM may allow us to inject an aspect of our research into society at large, communicating that sensory experiences of sound are diverse and arguably under-served by today's dominant audio technology.



Fig. 5. The product design artifact. A preliminary illustration of the future *Ryann*TM device, designed for tactile augmentation of listening. The device integrates three positions of vibrotactile stimulation on the upper neck and clavicles.

Product Artifact Form We designed *Ryann*TM in order to consolidate results from our prior research with simplified formal aspects of the multimodal harness (see Fig. 5). The device is to be worn around the neck, targeting three of the most sensitive positions for ETC as found in our prior psychophysical study [1]. On both clavicles and the upper neck, we integrate three vibs-on-coil actuators to transmit the vibratory signals. Vibrations on both clavicles allow for stereo-type effects, and a third point of stimulation on the neck adds potential for tactile effect diversity. The vibratory effects could therefore make sound accessible to all hearing profiles, either via tactile stimulation or in combination with ETC. In contrast to the multimodal harness, *Ryann*TM's future design will not require users to wear earplugs. To improve ease of use and comfort, this feature combined with other ergonomic aspects of the product (positioning on the body, lightness, number of actuators) will change the potential perceptual experiences in comparison to the multimodal harness. Future user testing with prototypes will help Actraalika to prioritise key features and design better algorithms for

acoustic signal transformation into vibratory stimuli, displayed by *Hyam*SM. We defined these features not only based on ergonomics and comfort, but also to draw comparisons to existing products on the market: neck-worn speakers are now sold by prominent acoustic companies such as Bose¹ and Sony². Future users' familiarity with such existing devices may ease the acceptance of *Hyam*SM as a product designed for listening, despite obvious formal differences from classic headsets.

4 Positive Project Impacts

Through a retrospective view on the artifacts' development, we can give a few insights about the complementarity of the speculative and product design processes. Their reciprocal nature can be demonstrated in terms of three main positive project impacts: it advanced a common objective, defined the product concept, and built mutual understanding between our commercial and scientific partners.

4.1 Positive Impact 1: Advancing a common objective

Though their purposes and forms are different, the process of creating the two design artifacts has taken our research objective in a common direction. The act of wearing the multimodal harness forces the user to challenge their assumptions about sound perception and helps to imagine another evolutionary path of personal listening devices. However, its speculative purpose constrains its use to experimentation: it is heavy, wired, requires the use of earplugs, and users can realistically wear it only for short periods of time due to the tight fit. Finding its roots in the same research objective, *Hyam*SM offers a compromise between idealism and practicality. The product concept suggests a more easily acceptable, ergonomic and less time-consuming solution to the industrial development of novel audio-tactile wearable technology. Such a product could already introduce ETC and tactile sensations of sound to the upper neck and sleeves, and potentially pave the way for more of the body in future listening devices.

4.2 Positive Impact 2: Defining a product concept

In Fig. 4, we illustrate how the "problematic" nature of the speculative artifact helped define the product concept in terms of industrial considerations: the user, the scale of development, the market, and project timelines. We first identified the most inspirational aspects of the multimodal harness to define *Hyam*SM's future characteristics: uni-size, lightweight, simplified development and use, and familiar appearance. Without the multimodal harness at hand, we would not have had these points of comparison that helped guide the definition of a user-centered product.

¹ Bose SoundWear Companion speaker

² Sony SRS-N87 Wireless Neckband Speaker

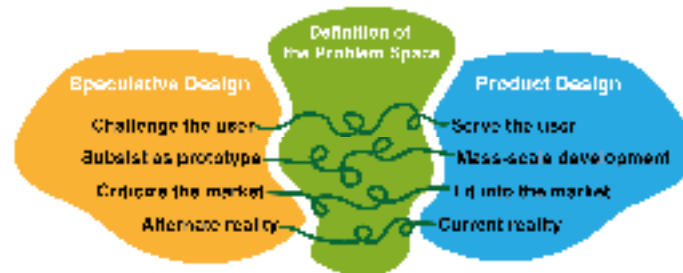


Fig. 4. In our project, the speculative design process influenced the product design process due to the problem space which naturally emerged between them. This problem space was built on contrasting purposes, as shown in the figure. The most “problematic” aspects of the multimodal harness revealed how Ryan™ must be different in order to be commercially practical.

4.3 Positive Impact 3: Fostering mutual understanding

Certain key moments in each artifact’s development demonstrate the interactions between the two design processes (see Fig. 8). To be able to respond to our industrial partner’s commercial requirements for our project, we needed to understand their expectations and facilitate their understanding of our research: something best done through a collaborative activity. We therefore started the Ryan™ project during a workshop with colleagues. This resulted in an initial design concept, sketched while we finalized the first multimodal harness prototype. As we developed initial prototypes of the Ryan™ product, we also developed the second prototypes of the harness. By developing the prototypes at the same time, we were able to maintain close contact with Astronika’s mechanical and electronics design teams. Through our research, we also created another connection with Astronika’s co-development partner, Leo Vertuguilho. The consistent internal communication and integration of our project in our partner’s external network helped to assimilate the speculative research in the industrial context, building mutual understanding and accelerating both artifacts’ development.

5 Conclusion

Through all of these aspects of our case study, we demonstrate that the two parallel design processes had a reciprocal relationship: the interactions between them propelled both speculative and product development, and advanced our research in body-based listening experiences. The industrial environment that gave life to our work has helped to ground our speculative design approach and emphasize the importance of a practical output: an objective of commercial product design. The two design artifacts are interdependent despite their contrasting purposes: the scientific context for developing the multimodal harness could not have existed without the commercial context for developing Ryan™, and vice versa. While speculative artifacts like the multimodal harness don’t

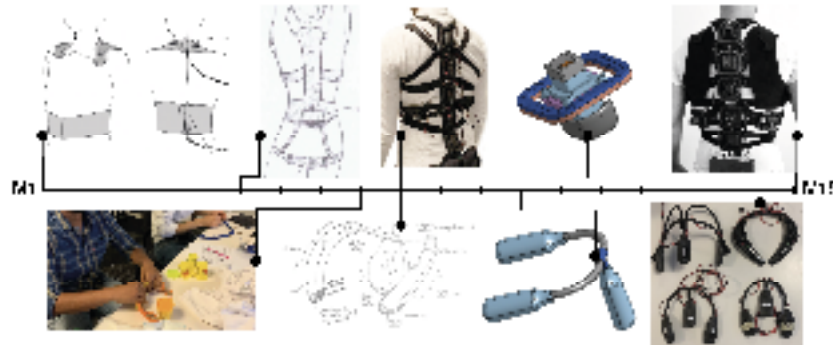


Fig. 8. Overlaid 18-month timeline of speculative (top) and product (bottom) artifact development. Images are taken from project records. The two processes overlap phases of brainstorming, sketching and prototyping occurred in parallel and provided momentum for both artifacts' development.

target commercial use, they give the design researcher the freedom of imagination. This creative liberty may seem to be at odds with the controlled nature of the scientific method and time-sensitive commercial development, but without it, neither design artifact would exist. Through this case study, we hope to have illustrated the value of a peaceful coexistence between uninhibited creativity (speculation) and practical constraint (commercialization) in an industrial environment. In future work, we will extend this analysis to other audio-tactile device development, with the hopes to expose commonalities and explore the diversity of speculative methods in multidisciplinary product design projects.

Acknowledgements This research is part of a CIFRE industrial PhD contract, funded by Antraxia SAS and the ANRT. We thank James Auger, Frédéricus Pain and Pablo Arias for their contributions through insightful discussion. We also thank all of our colleagues and our co-development partner Les Vertigardes for their sustained partnership.

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Vibratory Detection Thresholds for the Spine, Clavicle and Sternum*

Claire Richards^{1,2,3}, Nicolas Misdariis¹, Roland Cahen², Damien Faux³, and Vincent Hayward³, *Fellow, IEEE*

Abstract— We sought to determine the vibratory detection thresholds at several points on the upper body that are associated with bony structures. Stimuli were pure tones generated by a voice-coil transducer at eight locations along the spinal column, the clavicle, the sternum and the skull, a point of comparison to past threshold studies. Owing to the transmission properties of mechanical waves in the body, we hypothesized that the detection thresholds would increase with distance from the skull and would depend on frequency in a manner that could reflect the integration of somatosensation and audition.

I. INTRODUCTION

Hearing through bone conduction is a well-researched topic which has been studied mostly on the skull [1]. A similar effect, however, has yet to be explored for other regions of the body. Many behavioral and neural correlate studies, e.g. [2], investigated different aspects of integration between touch and hearing. Here, we conducted a study on detection thresholds at eight points on the upper body (spinal column, clavicle, sternum, skull) which were candidates for efficient transmission of mechanical waves to the inner ear. The tested frequencies from 50 to 4000 Hz overlap the auditory and tactile sensitivity ranges. The results of this study could serve as a baseline for the design of audio-haptic devices to be worn on the upper body [3].

II. METHOD AND APPARATUS

We selected the extra-tympanic stimulation points for their proximity to bone structures in close connection to the skull and thus to the inner ear. We created a stimulating apparatus comprising a vibrotactile actuator (Actronika HFBA9534), a force sensor (FSR) to monitor contact with the skin surface, and an accelerometer to monitor the stimulating signal. The apparatus was fixed to the skin via self-adhesive hydrogel patches that ensured near perfect transmission of vibrations. An electronic interface collected the data and digitized it for computer processing. The psychophysical experimental method—one-up two-down adaptive staircase—was adopted from previous studies of bone conduction hearing thresholds at points on the skull [1]. A related study investigated the effects of masking conditions on bone conduction hearing thresholds on the mastoid [4]. Python code generated the signals, collected the data and participants' responses (“Yes”-I hear / “No”-I don't hear). The procedure was approved by the relevant ethics committee of Sorbonne Université.

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III. RESULTS AND DISCUSSION

Fig. 1 shows the data for a typical participant in arbitrary units of intensity. Due to the extremely high sensitivity dynamic between the skull and upper body, we exclude the skull point (mastoid) from this figure. At the frequency of 3950 Hz the low sensitivity suggested an effective frequency cutoff for signal detection at most tested body regions. With increasing distance from the skull, sensitivity was reduced at 915 and 1900 Hz. We observed consistently high sensitivity between 100 and 440 Hz, but not at 50 Hz, frequencies centered around the peak vibrotactile sensitivity of the Pacinian corpuscles (250 Hz). This result may be due to an effect of multimodal integration within the overlapping sensitivity ranges, and/or the physical properties of the mechanical waves propagating within the musculoskeletal structures of the body (100-440 Hz corresponds to 330-75 cm wavelength). During future work, we will develop an adjustable, wearable device permitting simultaneous, pattern-based vibrotactile stimulation of points evaluated during the current research.

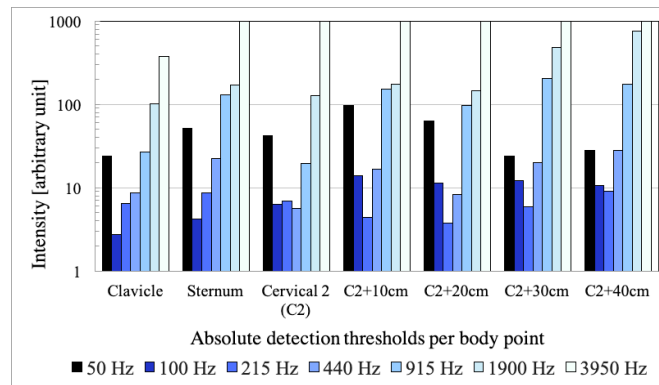


Figure 1. Vibratory detection thresholds of a single subject. Starting at the neck (C2), each descending point on the spine is 10 cm apart.

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AVIS

COMITÉ D'ÉTHIQUE DE LA RECHERCHE

> RÉFÉRENCES ADMINISTRATIVES

Protocole n°	:	CER-2020-74
Nom du protocole	:	RICHARDS-BoneConduction : Bone conduction reception : upper body sensitivity mapping
E-mail pour la correspondance	:	claire.richards @ inscm.fr
Protocole évalué en séance du	:	11/12/2020

AVIS : FAVORABLE

> COMMENTAIRES

Le Comité d'Éthique de la Recherche a noté les différentes modifications et informations apportées par les porteurs du protocole et émet un avis favorable.

Les investigateurs faisant appel aux services du CER-Sorbonne Université s'engagent à lui signaler tout évènement non anticipé survenant en cours d'étude. Ces éléments seront utilisés aux fins d'amélioration des futurs services et conseils que le CER-Sorbonne Université pourra donner.

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OUTCOME – INSEAD INSTITUTIONAL REVIEW BOARD

Date: June 16, 2022

To: Claire, Richards (IRCAM/SO); Nicolas, Mindarin (IRCAM/SU)

Protocol: Distinguishing parallel sensations: A study of audio-tactile bimodal judgment

Protocol ID: 2022-52

Your IRB application “Distinguishing parallel sensations: A study of audio-tactile bimodal judgment” reference number 2022-52 was approved today, under the condition that you include your name and institutional e-mail in the instructions and consent form to participants, in case they want to contact you for further information, or withdraw from the study. This is a requirement under GDPR.

If this protocol is used in conjunction with any other human use, it must be re-reviewed. The IRB requests prompt notification of any complications or incidents of noncompliance, which may occur during any human use procedure. In case any new data is collected, all data including the consent forms, must be retained for a minimum of three years past the completion of this research and must be destroyed when no longer needed for research purposes. Additional requirement may be imposed by your funding agency, your department, or other entities.

You are required to use your institutional / university email address in the consent and debriefing forms.

In the published version of your study, please include an acknowledgement that the study has been approved by the INSEAD Institutional Review Board, and – where relevant – that the data collection has been done at the INSEAD-Sorbonne Université Behavioural Lab.

Please use the reference number stated above for any further correspondence, amendment relating to this study.

Best regards,

The INSEAD Institutional Review Board

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OUTCOME – INSEAD INSTITUTIONAL REVIEW BOARD

Date: July 17, 2022

To: Claire Richards, (IRCAM/SU); Scott Aker (Denmark Technical University); Nicolas Misdariis (IRCAM STMS Lab -Sorbonne Université)

Protocol: **Evaluation of audio-tactile congruences for a body-based musical interface**

Protocol ID: **2022-35**

Your IRB application “Evaluation of audio-tactile congruences for a body-based musical interface” reference number 2022-35 was approved today, under the condition that you include your name and institutional e-mail in the instructions and consent form to participants, in case they want to contact you for further information, or withdraw from the study. This is a requirement under GDPR.

If this protocol is used in conjunction with any other human use, it must be re-reviewed. The IRB requests prompt notification of any complications or incidents of noncompliance, which may occur during any human use procedure. In case any new data is collected, all data including the consent forms, must be retained for a minimum of three years past the completion of this research and must be destroyed when no longer needed for research purposes. Additional requirement may be imposed by your funding agency, your department, or other entities.

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Please use the reference number stated above for any further correspondence, amendment relating to this study.

Best regards,
The INSEAD Institutional Review Board
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iNsO4L (iNsOund for Live) toolbox

Roland Cahen, Claire Richards & Nicolas Misdariis

iNsO Tools for AudioHaptic body spatialisation

©2022 Centre de Recherche en Design (CRD) ENSCi les Ateliers - ENS Paris-Saclay,

User manual

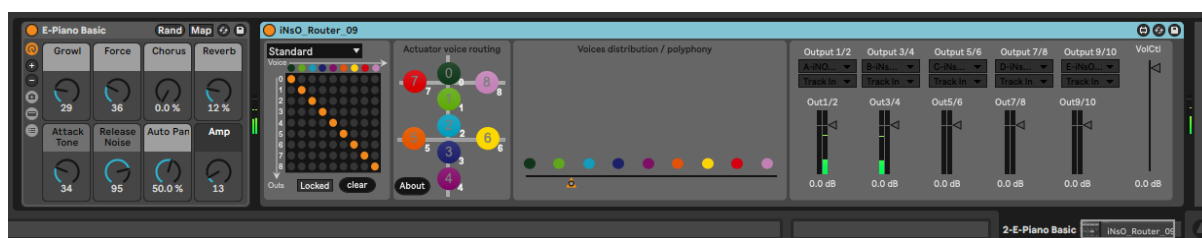
Body spatialisation concept

Sound spatialisation usually refers to a listener situated inside a speaker's array, all sound positions being calculated to the listener. In the "body spatialization" paradigm, the listener's head is outside of the array of actuators. While haptic perception is localized on different body positions, audio perception is perceived via extra-tympanic (bone/soft-tissue) conduction through the central conduct of the cervical (neck) vertebrae. In order to ensure spatialized sound transitions from one actuator to another with a minimum of gain loss, basic multichannel panning is used along 1-dimension linear paths. For these reasons, AudioHaptic (AH) signal paths are the main concept and setting of iNsOund.

iNsOund architecture in AbletonLive: iNsO_Router

Ableton Live only allows stereo in and out tracks. Therefore, multichannel spatializers must be split into two-channel buses. Max for Live (M4L) allows to create wormholes with more than two channels, but which must be routed to stereo outputs. In addition, it is not possible to directly address physical channels, and any routing must look up AbletonLive's existing channels, outputs which are available according to the present audio clients.

Each input track, midi-instrument or audio, can therefore host an *iNsO_Router* device which allows to spatialise the incoming signal onto the harness. This device must be added to the track after (on the right of) a chosen instrument.



iNsO_Router has 1 input (audio or instrument) and 9 outputs routed separately to 5 stereo Return tracks.

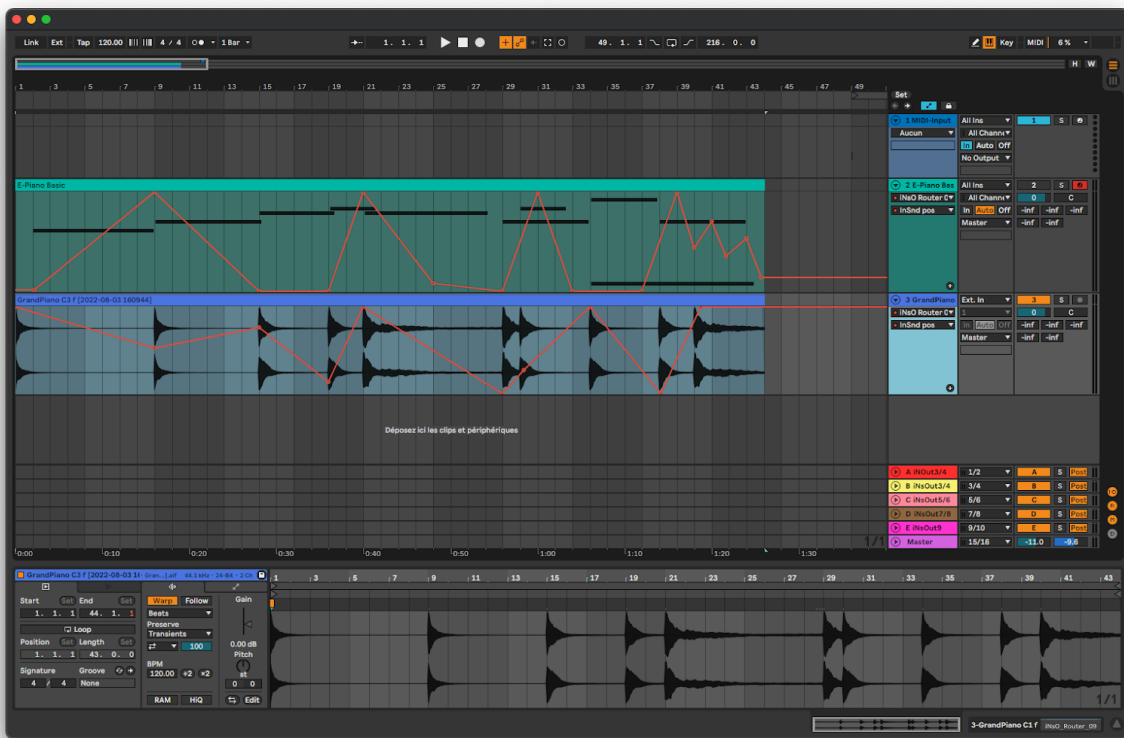
The 5 return tracks can be freely named but have preferably specific names in order to be easily recalled. They are named (A) *iNsOut1/2*, (B) *iNsOut3/4*, (C) *iNsOut5/6*, (D) *iNsOut7/8*, (E) *iNsOut9*.

(A B C D E F) letters are automatically created. Return tracks must be respectively routed to Ext.Out $\frac{1}{2}$, $\frac{3}{4}$, $\frac{5}{6}$, $\frac{7}{8}$ and 9/10.





The simplest way to start is to try and copy the given model session “iNsO_Model.als”.

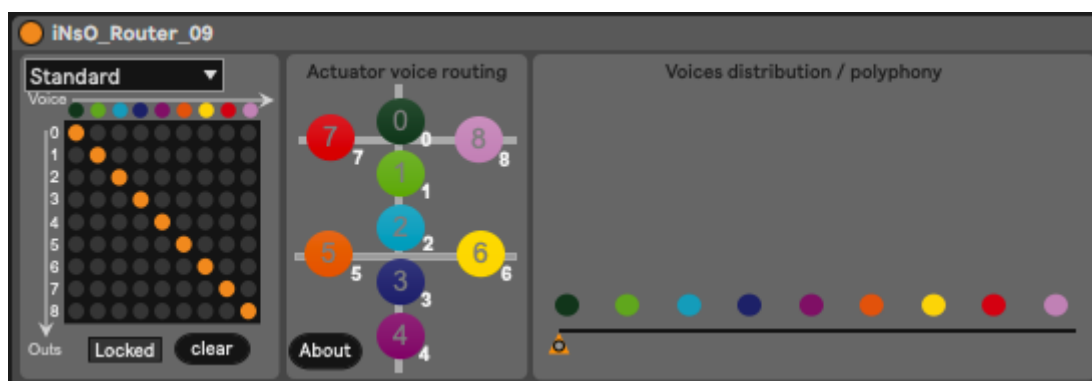


Installation

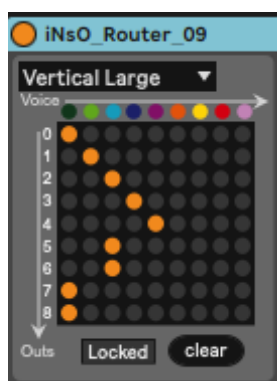
MaxForLive devices

iNsO_Router

Actuators are numbered from 0 to 8 , as represented by the “Standard” distribution/path : 0 to 4 down the spine, 5 and 6 on the Left and right sides on the ribs, 7 and 8 on the Left and Right clavicles. This distribution is symbolized on the Harness Cross view. The Path Polyphony view shows the actual path places and polyphony. Colors represent the channel rank on the path.

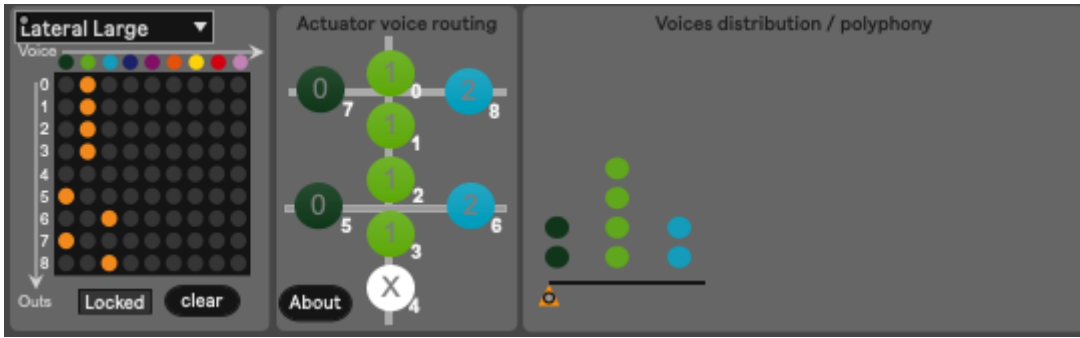


Matrix



The matrix allows AH signal paths preset recall and editing. As physical outputs (actuators) are represented vertically, places or ranks on the path are represented horizontally. One place/rank can be affected to one or several outputs (actuators). In the following case, the same signal is send to several actuators at the same places, here to enlarge the haptic surface of a lateral shift as well as increasing the sound volume.

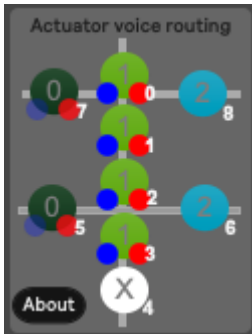




HarnessCross view

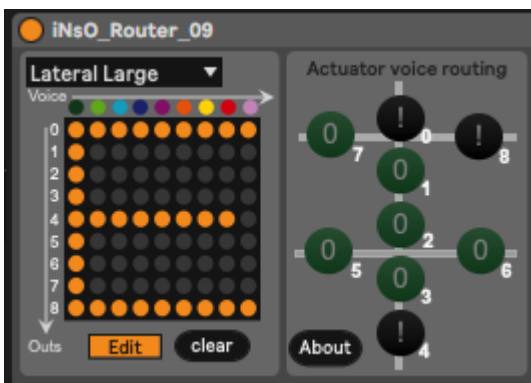
The HarnessCross view symbolizes the actuator positions and what signal they receive. White numbers represent the actuators numbers. Actuators 0 to 8 correspond to physical outputs 1 to 9.

Blue spots indicate the probable haptic volume and red spots indicate the probable audio volume. These indicators are rendered through filters created to approach Claire's experimental evaluations.



Clicking on an actuator's icons allows it to change position on the path. Place in path will be incremented at each click. Matrix Edit must be active (unlocked) to modify routing.

The X on white icon indicates that no signal is sent to this actuator.



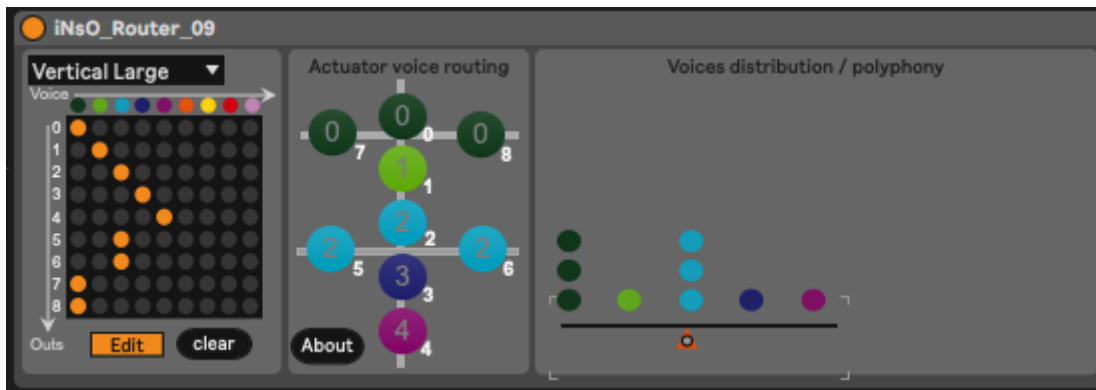
Repeating the same actuator in several places on the path doesn't quite make sense yet; the icon turns black with an exclamation mark to signify an error.

PathPolyphony view

Path is horizontal and polyphony vertical.

The slider routes the incoming signal to each path position and its corresponding outputs/actuators. This slider can be automated and edited in Live using standard automation. Positions and movements can also be controlled from an external MIDI

controller. It is preferable to control each iNsO_Router placed on different Live tracks with independent controls.

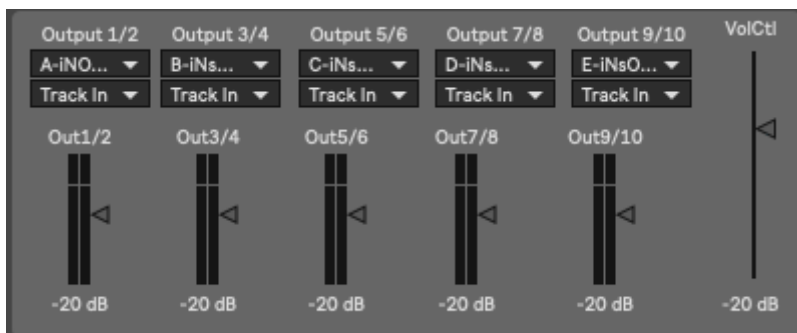


Output routing

The output routing should in fact not exist, but is necessary for AbletonLive to be aware of the existing outputs.

Therefore, it should always be set the same way, which is:

Output 1/2 -> Return A-iNsOut1/2, Output 3/4 -> Return A-iNsOut3/4, Output 5/6 -> Return A-iNsOut5/6, Output 7/8 -> Return A-iNsOut7/8, Output 9/10 -> Return A-iNsOut9/10.



Levels

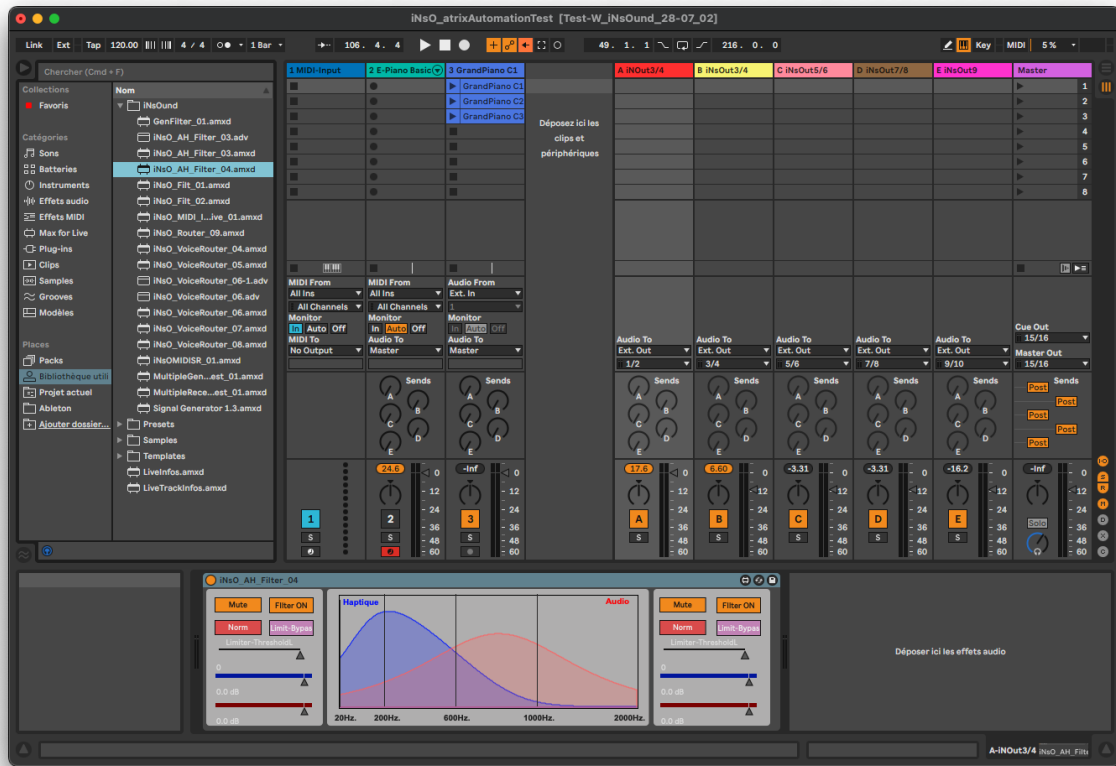
The levels are quite sensitive. Be careful to *start low* (e.g -20dB) not to damage actuators because some of the Live instrument's gains can easily be overloaded.

The VolCtl fader can be automated in Live and controlled from an external MIDI controller.

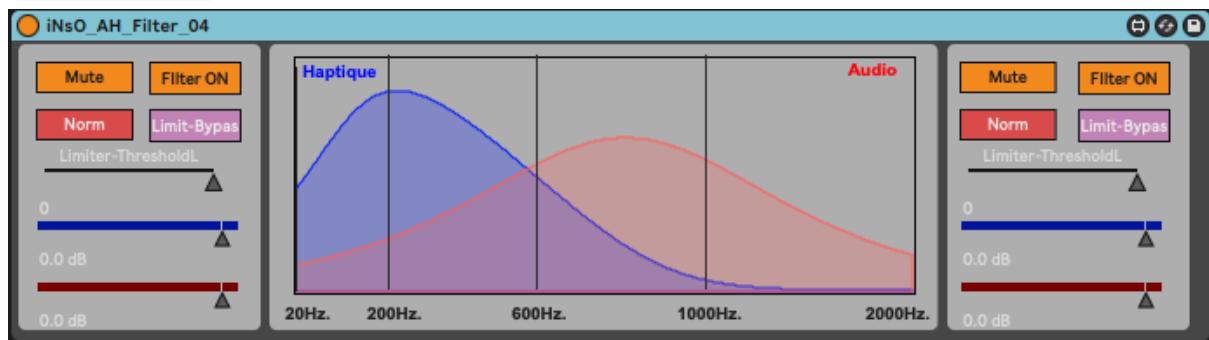


iNsO_AH_Filter

iNsO_AH_Filters are meant to be placed on each Return/Output stereo track



They allow to balance Haptic/Audio sensation using filters calculated to approach Claire Richards 's experimental results.



Each Individual output can also be muted to stop all audio going to this actuator.



The filter can be activated or deactivated (Bypassed)



Normalization allows to maximize signal to 100%



Limiter limits signal to 0dB.



Utilities

GenFilter

A small Monophonic MIDI instrument, allowing to make simple tests

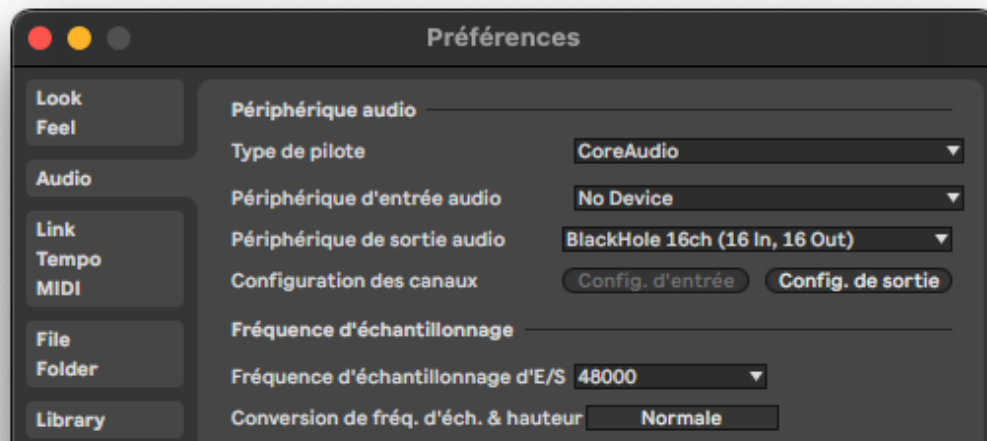
iNsO_MIDI_InOutSendReceive_01.amxd

A tool to insert in an input MIDI track allowing to route MIDI signal to all AbletonLive tracks, including audio tracks.

AudioHaptic Framework using third party applications

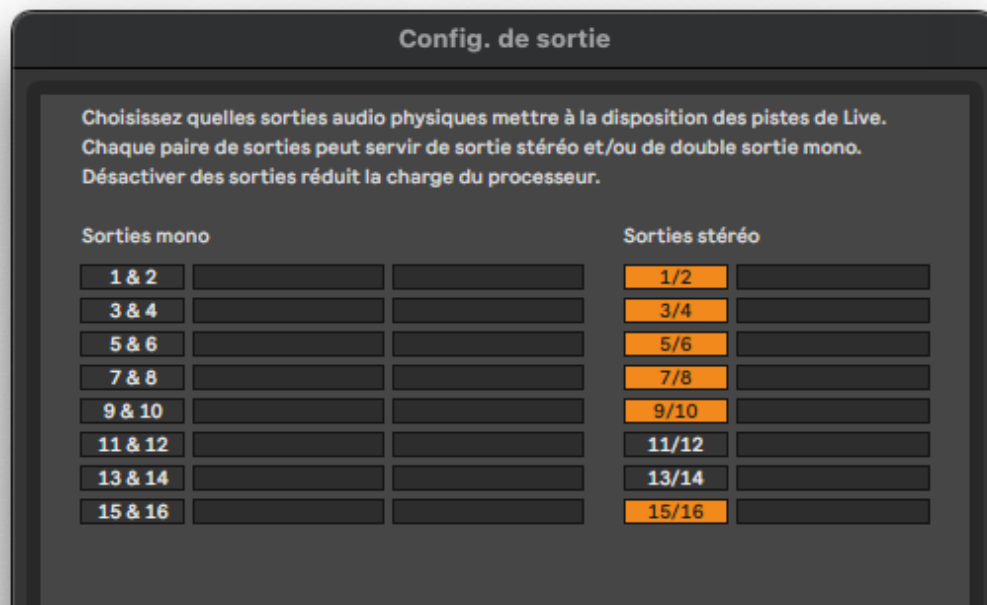
A more practical ControlRoom configuration than direct Live output to the harness can easily be achieved using third party applications. In order to switch from playing AH signals through the harness or through speakers, The easiest solution we found was by sending audio to an multichannel bus such as [Blackhole16ch](https://github.com/ExistentialAudio/BlackHole) for Mac (<https://github.com/ExistentialAudio/BlackHole>) in conjunction with [LoopBack](#) from [Rogue Amoeba](#).

Therefore Live Audio Output should be set on Blackhole 16ch.

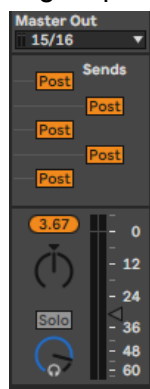


Here is how outputs should be configured:

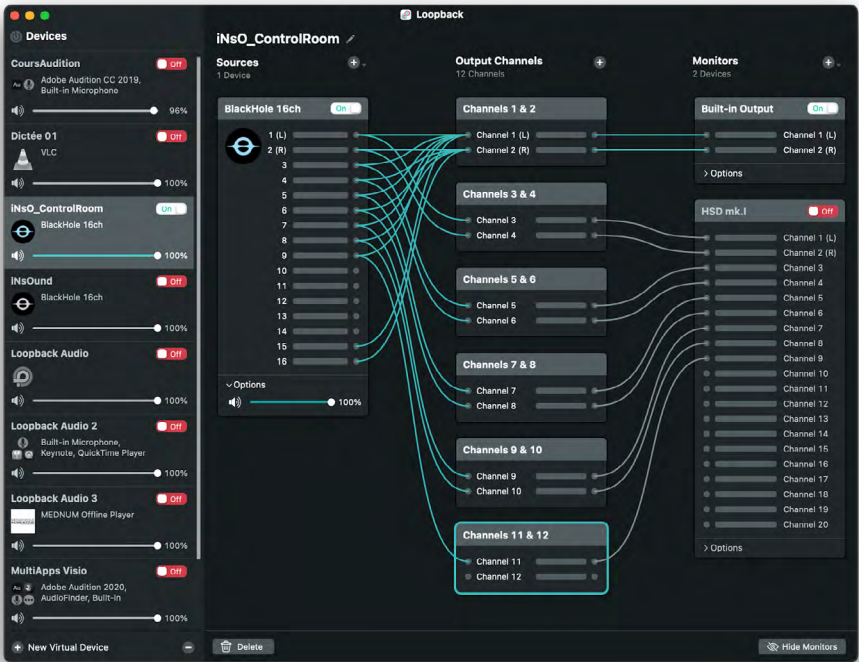
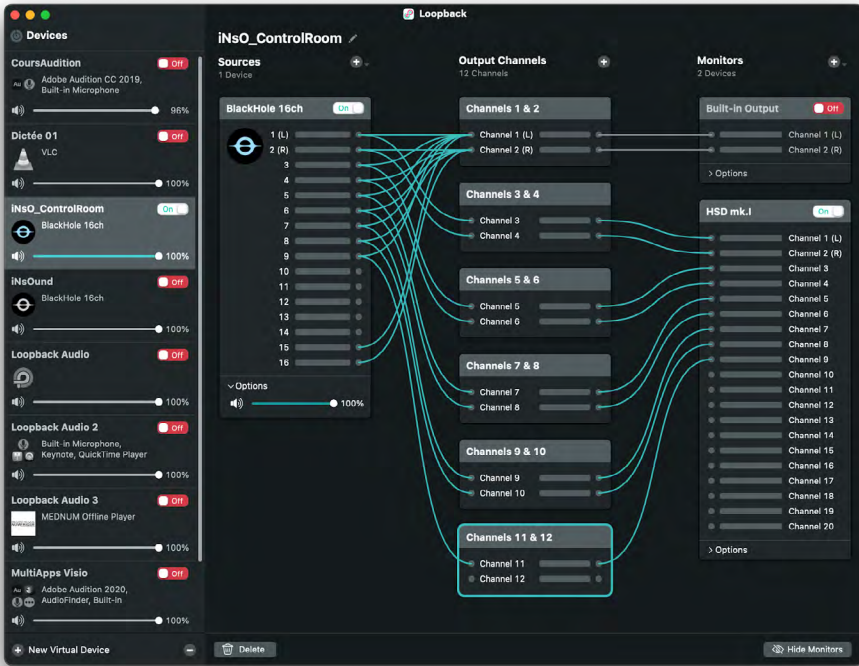
5 outs ($\frac{1}{2}$, $\frac{3}{4}$, $\frac{5}{6}$, $\frac{7}{8}$, 9/10) are used by iNSO for the harness by pairs of two (because of AbletonLive bus and channel polyphony limitations). For output 9/10, only output 9 is used.



Outputs 15/16 are used for audio monitoring, especially for headphones monitoring.



LoopBack allows switching from audio monitoring to harness configuration. The audio monitoring config. can be routed to any secondary multichannel or stereo monitoring device. In the following example, audio monitoring is achieved through Built-in audio Output and reduced to stereo.



Composition of audio-tactile études: Follow-up questionnaire

This questionnaire, filled in after the composition process, provides some first-hand insight into Alberto's process, experience and impressions while creating the audio-tactile études.

1. How did you use Ableton and Max for Live for multichannel distribution (spatialization) and audio-tactile composition?

I ended up using Roland's Device for the looser parts, so that I could use a kind of spatialisation device to move continuous streams of sound. For the more precise and punctual parts I programmed a spatialiser/sampler with Max/MSP so that I could work out every single detail and control the movement of the sound in each part, and I assigned different buses from Ableton Live for playback, modulating everything using the DAW's return tracks.

2. How were you able to interpret the medium of audio-tactile perception, in your own personal style? What did you learn about your style while composing for this new tactile medium?

Compared to my style, I did not change my patterns and timbres too much. More than anything else, I was able to think about the perception of the usual sound differently and internally. Another aspect was the handling of the timbre designed for a given reproducer and no longer for any classical speaker or vibrating transducer.

3. What were the most difficult parts of the composition process?

Definitely the rendering of sound and mirage. On a strictly artistic level, I consider them studies investigating precise aspects of the audio-tactile experience. The biggest problem was definitely sound design and the difficulty of getting the sound right. Finally the question I asked myself was "but am I writing music or something else?", this could be the beginning of a new chapter in my personal research.

4. What were your favorite parts of the composition process?

The perception is new and impossible to imagine. Thinking of sound as a force, as something that squeezes and stretches you is a truly incredible thing. Being able to understand that high sounds move through the body differently from low sounds is also something expected but when composed it really gives you the opportunity to think about your inner acoustic space.

5. Was the frequency bandwidth (max 2000 Hz) a limitation in your process?

At first I thought so, but shortly afterwards I thought of this limitation as a merit to be valued rather than thinking of it as a limitation. Above all, working with pure sounds or at least those with little spectral variability allowed me to think about new sounds and the relationship between them over time.

6. Do you have any comments or recommendations about the wearable device design?

The only flaws in my opinion are the uncomfortableness (because it is very tight) and the subjectivity of the listener. We all hear differently, so perhaps a self-calibration system should be included. In terms of design, I don't think it's too much of a problem to wear this exoskeleton, also because, as already mentioned, what it does is a new thing and will certainly have a future.

Multimodal Harness:
1st Iteration



Multimodal Harness:
2nd Iteration



